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Metrics of urban morphology and their impact on energy consumption: A case study in the United Kingdom.

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Abstract: Energy policies implemented by local authorities and targeted at the domestic sector have focussed on interventions, which are usually selected after an optimization procedure. This paper identifies differences and similarities between three Medium Layer Super Output Area (MLSOA) districts in the United Kingdom (UK) and draws conclusions which prove to be useful to interpret other districts in the city and provide general rules for energy efficiency measures and distributed supply interventions in Newcastle upon Tyne UK, and potentially beyond. The core argument aims at provide an important link between the energy-reducing and energy-increasing effects of four urban morphology characteristics in 'place-specific' neighbourhoods. Our methodology explores the potential application of the close relation between four urban morphological characteristics and the spatial aggregated building energy end-use in the roll-out strategy of interventions. Our findings first indicate that the combination of shape and size of continuous building classes (in a building class the main residential buildings are grouped by their age and building type) and their extent using patch areas potentially simplify retrofit campaigns...

Metrics of urban morphology and their impact on energy consumption: A case study in the United Kingdom

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Abstract

Energy policies implemented by local authorities and targeted at the domestic sector have focussed on interventions, which are usually selected after an optimization procedure. This paper identifies differences and similarities between three Medium Layer Super Output Area (MLSOA) districts in the United Kingdom (UK) and draws conclusions which prove to be useful to interpret other districts in the city and provide general rules for energy efficiency measures and distributed supply interventions in Newcastle upon Tyne UK, and potentially beyond. The core argument aims at provide an important link between the energy-reducing and energy-increasing effects of four urban morphology characteristics in ‘place-specific’ neighbourhoods. Our methodology explores the potential application of the close relation between four urban morphological characteristics and the spatial aggregated building energy end-use in the roll-out strategy of interventions. Our findings first indicate that the combination of shape and size of continuous building classes (in a building class the main residential buildings are grouped by their age and building type) and their extent using patch areas potentially simplify retrofit campaigns. We argue that the whole continuous building class influences the building’s

thermal mass (the building massing) and their extent (the patch area or patch in short) and these are better descriptors for the energy use in the occupational phase of a building. Second, the building massing and the plot ratio (the ratio of the building floor area to the land area in a given territory) are a better descriptors of building density/mixing of land use and built form leading to the potential use of adequate distributed energy supply. Third, the way in which social and economic factors interact to shape area-based of household energy consumption leads to a possible better spatially-enabled policies for low income families; and fourth, the layout and orientation design of the neighbourhood may identify municipal sites for potential renewable energy projects. The use of the building massing and patch areas as spatial cluster operators simplify the complexity of aggregated building energy consumption by representing its spatial incidence through a smooth continuous surface. Additionally, building classes and its patch area extent show notable differences across different sub-city areas. Furthermore, the greater the number of building classes, the more diverse is the socio-economic make-up of a sub-city area.

Keywords: cities, climate change, neighbourhood urban energy modelling, decentralized target scenarios, urban morphology, building massing, patch areas, plot ratio.

1. The spatial energy end-use in cites

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 Cooperation and Development (OECD)¹ argues that by 2008 half of the world's population lived in cities, and by 2030 cities will house 60% of the world's population -equivalent to the total global population in 1987 (OECD, 2008, pp. 137). Detailed analysis from the International

¹ The OECD is an international economic organisation of 34 countries, and was founded in 1961 to stimulate economic progress and world trade.

Energy Agency² (IEA, 2008, pp. 44) shows that global energy use in the residential sector increased 19% between 1990 and 2005. The second reason is that the LAs 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 (SEAPs) (Covenant of Mayors, 2010). 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. the Directive 2010/31/EU (2010) on the energy performance of buildings) into local actions.

In the United Kingdom, the Department of Energy and Climate Change (DECC), as part of the implementation and monitoring of local energy strategies, reports estimates of electricity and gas consumption data at various scales below local authority (LA) level. DECC reports individual dwelling energy consumption in the National Energy Efficiency Database (NEED) as part of the energy efficiency statistics, and aggregated dwelling energy consumption in the sub-national energy consumption statistics. Aggregated data are in two geographic areas: Middle Layer Super Output Area (MLSOA) and Lower Layer Super Output Area (LLSOA).³

Our work supports analysts working on distributed energy supply programmes in sub-city areas where DECC published data does not geographically match policy and energy needs through the use of common values for the Unique Property Reference Number (UPRN), the address, and the building Topographic Identifier (TOID). In the UK, The UPRN identifies a Basic Land and Property unit (BLPU) whereas a TOID is a unique reference identifier associated with every building within Ordnance Survey's large scale topographic mapping. UPRN, address and TOID have made possible the use

² IEA is an autonomous intergovernmental organization established in the framework of the Organisation for Economic Co-operation and Development (OECD) in 1974, serving as an information source on statistics on the international oil and energy sector.

³ These statistics are experimental.

of different combinations of thematic and spatial resolutions and their interaction with the aggregated domestic energy consumption estimation. Our work investigates how the energy consumption changes at different aggregates of domestic homes according to different local area characteristics. Energy planning at decentralized level would be to prepare an area-based Distributed Target Scenarios (DTS) to meet energy needs using a bottom-up approach and disaggregated data (Hiremath et al., 2007, pp. 735).

The energy and carbon saving potential varies between cities, reflecting their particular landscape, the physical characteristics of the building stock, the heating supply systems, and the household's real characteristics. These differences need to be understood via a domestic energy model; one common characteristic of cities is that the local area's aggregated demand for energy use provides economies of scale (less infrastructure unit cost per capita) as well as additional energy savings due to minimised distribution losses. However, one key activity often overlooked when quantifying interventions in DTSs is the implementation of the roll-out strategy. This paper explores the relations between aggregated building's energy consumption and a possible roll-out strategies using four characteristics of the urban morphology in building aggregates covering spatially contiguous sub-city areas. In cities, the concept of spatially enabled database allows data integration to ensure multi-sourced thematic data and interoperability. Thematic information may be integrated through key identifiers (UPRN and TOID) and the result is a comprehensive, spatially enabled database embedded in the building energy estimations.

Using a case study from the United Kingdom, Calderón et al. (2015) developed a bottom-up spatial area-based local energy end-use framework that sets out the sub-city energy aggregated planning direction, the Newcastle CarbonRoute Framework (NCRF). NCRF utilises Newcastle CarbonRoute Map (NCRM) (Calderón et al., 2012) and adds on the energy modelling aspect through linking with the English House Survey (EHS) as input to the Cambridge Housing Model (CHM). This provides the means to produce building level energy consumption estimates which in turn can be analysed both spatially and aspatially (e.g. by building type). NCRF establishes the single dwelling as the unit of detail. CHM Outputs are also adjusted to match the Digest of UK Energy Statistics

(DUKES) data for gas and electricity use each year. This means that effectively it also includes a weather-adjustment. (Palmer et al., 2013, pp. 3). The key modification in CHM is the use of 19°C (292°K) as the baseline demand temperature for the living area for all dwellings -SAP uses 21°C.

The dwelling definition includes a dwelling-house and a flat. In general, a dwelling-house does not include a flat or a building containing a flat. However, dwelling-houses do include single storey bungalows. The bottom-up spatially enabled database provides information not only on the magnitude but also the extent of neighbourhood variations (Chaix et al., 2005) i.e. indicating a significant correlation between dwellings with similar energy profiles in neighbourhoods in which these dwellings are in close proximity to each other. Bahu et al. (2013) argue that the introduction of the spatial dimension to our understanding of all aspects in the energy model involves a ‘paradigm shift’⁴ that extends the traditional tabular energy consumption aggregates to a modern spatially enabled energy model.

Results from our component matrix show higher correlation (association) between dwelling size, building form and number of floors (principal component one PC₁); and between age and wall construction (principal component two PC₂) as seen in Figure 1. The total variance table informs the cumulative proportion of variance criteria that can be met with two components. Also, PC₁ and PC₂ satisfy the criteria of explaining almost 60% or more of the total variance (see Figure 2).

Component Matrix ^a		
	Component	
	1	2
age	-.156	.823
number of floors	.879	-.006
dwelling size	-.693	-.073
wall construction	.193	.824
building form	.888	-.080
heating	.337	-.015
Extraction Method: Principal Component Analysis.		
a. 2 components extracted.		

Figure 1: Principal Component Analysis matrix

⁴ A fundamental change in approach.

Total Variance Explained			
Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	2,217	37	37
2	1,369	23	60

Figure 2: Factor analysis total variance explained

The urban morphology, which refers to the spatial configuration of urban land use within an urban area, has profound influences on the energy consumption of a city. In recent years, there has been an increasing amount of literature about this topic. Examples include: Rode et al. (2014), Touchie et al. (2013) and Delmastro et al. (2015). Our study extends these recent studies by considering several spatial metrics to quantify the urban morphology. Urban morphology can affect the residential energy use through three causal pathways: directly through electric transmission and distribution losses (T&D), and indirectly through the housing stock and the formation of urban heat islands (UHIs) (Ewing and Rong, 2008). This paper is concerned with the indirect impacts. Furthermore, Camagni et al. (2002) argue that different urban morphologies may give rise to diverse social, ecological and environmental activities.

Although the spatial metrics quantify the urban morphology characteristics, we attempt to characterize aggregated buildings by means of adapting, expanding and integrating four basic individual metrics into quantified drivers of energy consumption in aggregated buildings using three-dimensional (3D) structures: first, the building massing using a patch area extent when referring to energy settlement pattern; second, the building massing and plot ratio when referring to urban density (intensity); third, socio-economic characteristics when doing an area-based household energy characterization, and, four, the layout and orientation design of the neighbourhood when referring to a building's window area distribution, shading from neighbouring buildings and energy production from solar thermal and photovoltaic systems, depending on available roof surfaces i.e. both energy consumption and production taking advantage of energy efficiency and renewable energy. Section 1.1 is the case studies selection and Sections 1.2, 1.3, 1.4 and 1.5 expand the traditional urban metrics into meaningful spatial 3D metrics

for energy consumption studies.

1.1. Case studies selection

In this paper we have followed the Local Authority's criteria for selecting three suburban residential MLSOA (districts) areas in Newcastle upon Tyne, UK (South Heaton, Westgate and Castle), see Figure 3, which represent the city's diverse demographic and housing stock/ownership.

Figure 3: Newcastle MLSOAs: South Heaton, Castle and Westgate

Additionally in the UK, every MLSOA is divided in several inclusive LLSOAs (neighbourhoods). As an example, Figure 4 shows the LLSOAs associated with South Heaton MLSOA. LLSOAs were built using data from groups of SOAs (typically four to six). They have an average of roughly 1,500 residents and 650 households.

Figure 4 shows the five LLSOAs maps associated with the South Heaton MLSOA.

Figure 4: South Heaton LLSOAs

1.2. Absolute Settlement patterns

Coombes and Raybould (2001) argue that there are at least three key dimensions to consider in modern settlement patterns: size, concentration, and accessibility. The sub-city case study areas have interesting settlement patterns. For instance, South Heaton has an area of 102 hectares (the smallest in the city) and shows a high concentration of late Victorian/Edwardian terraced houses, which are the most noticeable house type. South Heaton has become a very popular residence for students attending the city's two universities and its college, and this is reflected in the high number of Houses in Multiple Occupation (HMO) (nearly 300) which have easy access to/from the city centre through metro stations and local buses. 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. Castle has an area of 2,179 hectares (the biggest in the city); the sixties/seventies semi-detached and detached houses are the most important house types. Inside Castle, Newcastle Great Park is identified as a neighbourhood growth area for approximately 500 new homes (NCC, 2012). Figure 5 shows the representative buildings in the case study selection.

South Heaton			
Age	Type	Class	Percentage
Late Victorian/Edwardian 1870-1914	Lower 3-4 storey and smaller flats, detached and linked	26	48.9%
Late Victorian/Edwardian 1870-1914	Low terraces, 2 storeys with large T-rear extension	28	12.2%
Late Victorian/Edwardian 1870-1914	Low terraces, small	29	12.0%
Castle			
Age	Type	Class	Percentage
Sixties/seventies 1964-1979	Standard size semis	83	24.0%
Sixties/seventies 1964-1979	Low terraces, small	80	10.6%
Sixties/seventies 1964-1979	Smaller detached houses	86	10.2%
Westgate			
Age	Type	Class	Percentage
Recent years 1979-photo date	Non residential building	132	35.2%
Sixties/seventies 1964-1979	Lower 3-4 storey and smaller flats, detached and linked	77	12.1%
Recent years 1979-photo date	Lower 3-4 storey and smaller flats, detached and linked	96	7.6%

Figure 5: Representative building types for the case study selection

It follows the name and the area in parenthesis of the LLSOA in South Heaton (see Figure 4): 8303 (336,318 sqm), 8359 (111,071 sqm.), 8360 (246,613 sqm.), 8361 (97,805 sqm.), 8362 (114,261 sqm.) and 8364 (171,027 sqm.). Neighbourhood maps enable us to visualize smaller objects like the city streets which provide a more detailed depiction of the area. At this level, the area patches showing the individual building massing characteristics (shape and size) become visible.

Figures 6 to 8 use the spatially contiguous building classes –the patch area- in the MLSOA case studies and the estimated energy consumption (gas, electricity and combined). Figure 6 corresponds to South Heaton, Figure 7 to Westgate, and Figure 8 to Castle.

Every figure shows four maps:

- (a) a spatial representation of the buildings in their spatial-topological aggregation of contiguous building classes occupying patch areas. Patches are defined as spatially

Figure 6: Building types for South Heaton LLSOA 8362 at scale 1:3,000

consistent areas with similar thematic features forming basic homogeneous entities that describe or represent a landscape. The term spatial topology (Schneider and Behr, 2006) deals with spatial properties of geometric objects, independent of their extension, type, or geometric form. Two important topological properties of objects are the number of dimensions an object has (i.e. a building is a three-dimensional object) and the relationships that exist between objects. All topological properties are invariant to any continuous deformation of space (Sharma, 2006). Algebraic topology is a subfield of topology. Algebraic topology concerns mappings from topology to algebra (May, 1999). The algebraic topology simplifies analysis functions, as an example, joining adjacent areas (aggregate) with similar properties. It is important to note that in this study the aggregation is on the dwelling vector data formats. The dwelling is composed of a border, which separates the interior from the exterior of the surface;

Figure 7: Building types for Westgate LLSOA 8440 at scale 1:8,000

Figure 8: Building types for Castle LLSOA 8294 at scale 1:3,500

- (b) a representation of the annual gas intensity of individual buildings;
- (c) a representation of the annual electricity intensity of individual buildings;
- (d) a representation of the combined energy (gas and electricity) intensity of individual buildings.

The legend on map (a) is unique and shows the existing continuous building classes in the case studies, and the legend on maps (b), (c) and (d) show the annual intensity (kWh/m^2)⁵ in a coloured quantile⁶ classification. The quantile classification contains an approximately equal number of features in each class and is well suited for NCRF because the estimated energy data is linearly distributed across the whole case study. The fact that the quantile classification is unique for the whole case study (South Heaton, Westgate and Castle) allows a quantitative benchmark of three different (but representative in each case study) building types and the fact that the contiguous building classes legend is unique allows individual classes to be discriminated in the case study areas.

The first element of the urban morphology is the shape and size of the contiguous building classes (the building massing) forming patch areas. The patch areas were created for each building class using two spatial overlay operators,⁷ which are the dissolve operator and the union operator. Initially the dissolve operator⁸ is applied to each building in order to remove any lines that form shared walls between adjacent dwellings of the same building class. The union operator⁹ is then used to combine the dissolved buildings

⁵ Annual energy consumption intensity is the quantity of energy required per unit of area (kWh/m^2), so that using less energy (electricity and/or gas) reduces the intensity.

⁶ Quantile assigns the same number of data values to each class. There are no empty classes or classes with too few or too many values.

⁷ This combines sets of features from two layers to create new features with inherited attributes from each layer.

⁸ This removes boundaries between adjacent polygons that have the same values for a specified building class.

⁹ This joins two layers together visually with the new attribute table consisting of shared/overlapping areas.

together in a patch area. The result of this process is that each patch area contains a record of the number of dwellings that fall within a specific building class.

The representative building classes for the areas are depicted in maps (a) of the figures 6 to 8. In South Heaton LLSOA 8362 neighbourhood, the Victorian/Edwardian linear terraces are of class type 26 (the ‘lower 3-4 storey and smaller flats, detached and linked’) and 28 (the ‘low terraces, two storeys with large T-rear extension’), as shown in the map in Figure 6. In Westgate LLSOA 8440 neighbourhood, the representative building class is ‘recent year’ 132 (tall non-residential mix use buildings), as shown in the map in Figure 7. In Castle LLSOA 8294 neighbourhood, there are three representative classes: the 82 (the standard semis), 84 (the semi-types in multiples of 4, 6, 8, etc.) and the 86 (smaller detached houses), as shown in Figure 8.

We argue that geographic patches are virtual areas where strong building similarities are found in terms of construction typologies, therefore support the definition of a coherent set of solutions in energy efficiency, tackling both technological and non-technological barriers, maximising a business case potential for a group of buildings. Additionally, the patching mapping tool is not based on a fixed geographic region and therefore would strengthen a common energy-efficiency strategy to be pursued on a city level with regards to policies, decisions and measures in the UK.

In summary, patch areas add value to the energy retrofit projects in different ways: first, by organizing joint actions-demonstration on real-scale similar buildings classes; second, by applying a complete approach to the whole neighbourhood; third, by identifying solutions to common problems; four, by creating a framework of analysis and research approach to initiatives in the same type of building; and finally, increase the awareness about the retrofit projects among larger audience.

1.3. Spatial Urban Intensity (SUI) patterns

Stone and Rodgers (2001) argue that SUI is used to describe the overall condition of residential energy and CO₂ emissions land-use intensities i.e. high density urban areas (usually city centre) alter their climate in the form of elevated temperatures relative

to suburban (usually the peripheral areas. Additionally, the smaller dwelling sizes of higher-density neighbourhoods were found to emit less excess radiant heat energy per single-family household than households situated on larger lots due to the small pervious surface area.¹⁰ In municipal planning, density is typically expressed in terms of a single unit of land area, for instance, expressed in units (dwellings) per hectare. In our case studies, Castle is the lowest density (1.8 dwellings per hectare) district in the city and South Heaton is the largest (43.48 dwellings per hectare).

NCRF results show the residential density in Castle neighbourhoods is uniformly low (see Figure 8) and in South Heaton neighbourhoods the residential density is uniformly high (see Figure 6). Density units are kilowatt hours per square meter per year (kWh/year/m²). However, in Westgate neighbourhoods the relation between the residential density and the estimated energy consumption is complex (see Figure 7) as two LLSOAs have small residential density: Westgate LLSOAs 8395 (4.65) and 8397 (5.00) and have annual energy consumption of 14,464,975 and 10,572,029 respectively; three LLSOAs have medium residential density: Westgate LLSOA 8440 (20.72), Westgate LLSOA 8439 (29.01) and Westgate LLSOA 8399 (34.16) and have annual energy consumption of 47,831,713, 13,556,309 and 23,328,186; and one LLSOA has high residential density Westgate LLSOA 8394 (62.04) and has an annual residential energy consumption of 8,486,769. In summary, the consumption is greatest in Westgate LLSOA 8440, which has middle residential density, and smallest in Westgate LLSOA 8394, which has high residential density amongst Westgate neighbourhoods. Density units

¹⁰ Pervious surface area (the plot area devoted to lawns) was found to have the greatest direct effect on excess parcel heat production. The pervious surface area is an independent variable significantly related to residential surface heat emissions, as the pervious surface area expands, net thermal emissions increase as well, see figure 4 in Stone and Rogers (2001). Urban structures absorb a large quantity of thermal energy during the daylight hours and slowly re-emit this stored heat during the late afternoon and into the night. Because every excess watt of energy emitted from a parcel theoretically contributes to the formation of a surface heat island, a measure of thermal efficiency must be based upon the total rather than the average quantity of energy released per parcel.

were (dwellings/hectare) and annual energy consumption are (kWh/year).

We argue that the cartographical (2D) descriptor approach of counting the number of dwellings per hectare, as used in the Planning Portal Glossary: D Portal (2015) is not a valid proxy of the annual energy consumption; instead, both a patch area¹¹ (3D) descriptor (as a measure of building massing) and plot ratio¹² area (as a measure of compactness of the urban fabric) are better proxies of energy consumption. The patch area counts the number of dwellings per contiguous building classes, and this takes into account the increase in building height, depth and shape (building massing), while the plot ratio area measures the availability of buildings in the built environment. To support our argument about the 3D density; using the information in figure 6 this paper will demonstrate that high consumption correlates with high building massing and plot ratio, and vice versa in the Westgate LLSOA 8440 extreme of the consumption in Westgate. Westgate LLSOA 8440 is in the city centre.

8440		Cities Revealed Building Classes												Total
		Early and Middle Victorian 1837-1870	Early and Middle Victorian 1837-1870	Early and Middle Victorian 1837-1870	Late Victorian 1870-1914	Late Victorian 1870-1914	World War 1- World War 2 1914-1945	Post war regeneratio n 1945- 1964	Post war regeneratio n 1945- 1964	sixties/seve nties 1964- 1979	sixties/seve nties 1964- 1979	Recent year 1979- photodate	Recent year 1979- photodate	
BLPU Class		12	13	15	26	29	41	57	58	76	77	96	132	
RD Residential dwellings	Count	22	17	12	172	7	54			6	42	27	189	548
	Gas	270,801	215,824	161,869	2,225,696	80,190	714,917			67,445	568,538	394,203	1,877,206	6,544,677
	Electricity	66,231	52,064	39,045	536,910	19,944	172,462			16,270	136,668	87,858	473,037	1,800,492
RD04 Residential dwelling terraced	Count	1	2										1	4
	Gas	13,489	30,299										13,489	57,277
	Electricity	3,254	8,962										3,254	15,470
RD06 Residential dwelling self included	Count	58			45			54	40	154		12	1634	1,997
	Gas	728,406			607,005			553,049	337,225	1,786,803		0	15,721,567	19,733,045
	Electricity	175,716			148,430			133,414	81,350	646,334		91,608	4,911,660	6,185,512
	E7 Meters	3			0			13	14	7		0	0	37
	Gas Meters	55			45			41	26	147		12	1,634	1,960
	E7	74,713			0			211,660	198,922	172,351		0	0	667,666
RD08 Residential sheltered accommodation	Count												31	31
	Gas												418,159	418,159
	Electricity												100,874	100,874

Lower 3 - 4 storey and smaller flats, detached and linked

Tall terraces 3 - 4 storeys

Low terrace small

Medium height flats 5 - 6 storeys

Non residential building

Figure 9: The Westgate LLSOA 8440

¹¹ Patch areas are contiguous building classes.

¹² Area domestic buildings/domestic built area

Figure 9 shows in the far right the total column, where all numerical values are added, i.e. the count of dwellings, and the annual gas, electricity and E7 consumption. In the left is the Building Land and Property Unit (BLPU)¹³ Class (LGIH, 2010, pp. 200-237), part of the Newcastle CarbonRoute Map Gazetteer. The representative BLPU classes are RD, RD04, RD06 (flats) and RD08, the flats being the most common use. The second and third rows show the dwelling age and the Building Classes both from NCRM Cities Revealed. The representative building class is the 132 mix-use building built since 1979. Therefore, associating the BLPU and Cities revealed class, the representative dwelling in LLSOA 8440 is the flat in mix-use buildings built since 1979. Even though the ‘lower 3-4 storey and smaller flats, detached and linked’ and the ‘medium height flats 5-6 storeys’ building types, respectively, are 20% and 10% of the stock; what makes this LLSOA have high energy consumption is the mix-use building type in 70% of the stock. This building type houses 1,634 residential self-included dwellings in 49 major buildings (just one building, the Newcastle’s 55 Degrees North mixed-use mainly residential development, on Pilgrim Street has a 1,771sqm of footprint area). This means that there is an increase of building’s engineering thermal mass, and, the modelled architectural building massing i.e. its three-dimensional geometric representation that possibly affect the energy consumption (we use the Cambridge Housing Model (CHM) which implements a BREDEM based energy model to compute energy estimates as it is the model used by DECC to underpin the 2012 Housing Energy Fact File and Energy Consumption in the UK). Unfortunately, the CHM model present a reduced number of thermal zones, for a quantification we need better models. The adjacent building class has a lot of internal mass therefore the increase in the air temperature is slow, then the internal conditions are generally dominated by the heat loads generated within the aggregated building envelope and these are typically heated by the conditioning heating systems, therefore, there is an increase in the energy consumption. The adjacent build-

¹³ The BLPU Class allows the LLPG Custodians in the UK to classify the type and use of land and property objects.

ing classes are presented in the Westgate LLSOA 8440 patches. The Westgate LLSOA 8440 also has a plot ratio of 0.81, the biggest value of any individual LLSOA in the case study areas; therefore there is a high availability of buildings in the built environment area. The Westgate LLSOA 8440 has the characteristics of a compact city, i.e. central area revitalisation and mixed-use development and services, and it is the compactness that inflates the energy consumption in dwelling aggregates.

In Westgate LLSOA 8394, the main building type is the ‘lower 3-4 storey and smaller flats, detached and linked’ in 87% of the stock, which has an average footprint area of 220sqm. The other building type is the ‘small low terraces’ in 13% of the stock with an even smaller footprint area less than 40sqm. Domestic gardens comprise 32.47% of the total area, which means the plot area is 0.42. The Westgate LLSOA 8394 total area is the smallest amongst the Westgate LLSOAs (66.4sqm). The reason for the low energy consumption is that the low rise buildings have a small floor area (low building massing) and low plot area. This neighbourhood has the characteristics of a residential area.

In summary, this section has shown that the cartographical (2D) descriptor approach of counting the number of dwellings per hectare is not a valid descriptor of the annual energy consumption; instead, both a patch area descriptor (as a measure of building thermal massing) and plot ratio area (as a measure of the compactness of the urban fabric) are better proxies of energy consumption.

1.4. Socio-economic urban patterns

Since 2009, the Newcastle city Council has been able to identify, locate, and attain evidence of where some of the most vulnerable socio-economic groups within the city. The Experian data is provided by Rowntree (2009) in the form of a number and a percentage of households within each of the broad socio-economic classification groups and types. These numbers act as descriptors of the areas this study attempts to analyse and are intended to be indicative of the socio-economic patterns of the districts. Experian data shows that Castle has middle income younger families living in modern houses; South Heaton has students, young couples and singles living in small, old flats, and

Westgate has low income persons living in social housing and young, educated persons living in temporary accommodation.

We propose to expand the socio-economic patterns into a social landscape (Clift et al., 2015). The social landscape affects the home energy and emissions. Buchs and Schnepf (2013) argue that household characteristics like income, household size, education, gender, worklessness and rural or urban location differ in the home energy total emissions. Thus, the aggregated energy consumption is strongly affected by both the population density and the number of households; also, some vulnerable groups in a household composition are likely to be sensitive to energy consumption, for example, Castle’s ageing population and flexible working practices make people more likely to work from home. These groups with more pensioners and more flexible working practices mean an increased proportion of dwellings are heated between 9am and 5pm on weekdays. This also affects electricity use. The number of people living in households increases hot water use and the use of appliances, while heating energy usually correlates more strongly to the size of buildings, whilst household size makes only little difference to heating demand (Palmer and Cooper, 2013, pp. 20-21). Also, differences in household composition do affect poverty rates: households including most particularly children, the elderly and lone parents. The number of people living in households increase the hot water use and the use of appliances, while heating energy usually correlates more strongly to the size of buildings, and household size makes little difference to heating; The low-income households, who spend proportionately more of their incomes on energy, are affected by energy cost rises. Their demand for energy tends to be more elastic than wealthier households, meaning that they tend to use less energy if prices rise.

In the fuel poverty indicator, the key elements in are: income, fuel prices and fuel consumption (which is dependent on the lifestyle of the household and the dwelling characteristics). The approach is to increase the energy efficiency to reduce the energy consumption. However an interesting fact for households in fuel poverty and for homes that start off below acceptable standards of ‘comfort’, the relationship to energy demand is not direct, as more than half of any efficiency improvement is taken in the form of

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3 higher internal temperature (Henderson et al., 2003, pp.334). In tenure, owner occupiers
4 have the highest combined (gas and electricity) and gas consumptions, Local Authority
5 has the second highest combined. Households in private rented dwellings consumed the
6 most electricity. Electric heating was found to be more predominant in the private rented
7 than in other tenures. Joerges and Muller (1983) argue that housing tenure has been
8 found to be the most influential demographic feature on household energy consumption.
9 In building types, the highest consumptions were found in buildings with lower com-
10 pactness that have higher potential for heat loss such as detached and semi-detached.
11 Smaller buildings in the private rented sector have particularly high electricity consump-
12 tions, caused by the large proportion of electrically heated dwellings in this category. In
13 building age, combined and gas consumptions are at their highest in older dwellings and
14 decrease as the construction date becomes more recent. Electricity consumption was
15 roughly comparable across the range of construction dates.

16
17 CRMF shows that in Castle, using the 2001 UK Census data (number of people
18 living in the households UV51) plotted against residential density, it can be seen that
19 the relationship does not follow standard occupancy rates, that is, as residential density
20 increases the population does not increase at the same rate that standard occupancy
21 would suggest it should (see Figure 10 for Castle).

22
23 In addition, the census data show that there is a high proportion of pensioners
24 (Household Composition KS20) living in owner occupied houses (Tenure KS18). This
25 may partly explain the relationship between density and population but has the added
26 effect of potentially underestimating energy consumption, as older people tend to have
27 a non-standard heating regime due to being in the house during the daytime demand
28 (Palmer and Cooper, 2013, pp. 20-21). Also, in Castle MLSOA has seen its population
29 fall by 13% in the last 20 years (NCC, 2007, pp. 113-115), which may suggest that more
30 socially mobile groups are leaving the area.

31
32 From Figure 11, Figure 12 and Figure 13, it can be seen that in Castle the represen-
33 tative income band is the lowest 20%. In South Heaton it is a moderate concentration
34 of quintile 2 and in Westgate it is a moderate concentration of lowest 20%. Palmer and

Figure 10: Number of people living in households in Castle

Cooper (2013) argue that low-income households spend proportionately more on energy, and there are a lack of resources to improve energy efficiency. However, there is high sensitivity to price rises in energy (Palmer et al., 2008). The graph seems to suggest that as the low household income increases, there is a decrease in the energy consumption.

Figure 11: Economic structure: income, understanding energy consumption in Castle

From Figure 14, Figure 15 and Figure 16, it can be seen that in Castle the representa-

Figure 12: Economic structure: income, understanding energy consumption in South Heaton

Figure 13: Economic structure: income, understanding energy consumption in Westgate

tive socio-economic type is lower managerial and professional and in South Heaton/Westgate it is full time students. The socio-economic profile impacts are on energy use of appliances, lighting, and cooking where low income households tend to have fewer appliances than average, and use those appliances less than average. While the energy efficiency of some products has greatly increased over the past few decades, the increase in the number of energy using products (particularly consumer electronics) to be found in the

average home has made a major contribution to the rise in domestic energy consumption.

Figure 14: Economic structure: socio-economic, understanding energy consumption in Castle

Figure 15: Economic structure: socio-economic, understanding energy consumption in South Heaton

Most low income people living in Westgate are in social housing, spending proportionately more of their incomes on energy, and thus affected more by energy cost rises. Their demand for energy tends to be more elastic than wealthier households, meaning that they tend to use less energy if prices rise.

Figure 16: Economic structure: socio-economic, understanding energy consumption in Westgate

In summary, this section provides additional evidence with respect to housing that is potentially of significant value as a policy tool for energy efficiency and fuel poverty. 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. For instance, the results of this paper support the idea that the framework could be used to test the effect of a range of possible future revisions to the Building Regulations or future revisions in the Energy Company Obligation (ECO) Carbon Saving Community Obligation (CSCO) (e.g. extend from the bottom 15% to the bottom 25% most deprived areas, based on the Index of Multiple Deprivation (IMD)).

1.5. Layout, orientation and building surrounding in neighbourhoods patterns

The fourth urban morphology characteristic is the street layout and building orientation design of the neighbourhoods. The street layout determines the building orientations. The resulting building orientation affects the energy consumption for heating and electricity depending on building's window area distribution and shading from neighbouring buildings. The The resulting building orientation affects the energy consumption for heating and electricity depending on window area distributions and shading from neighbouring buildings. The neighbouring buildings in the urban context reduce solar

1 radiation and daylight availability to individual buildings. Building orientations also
2 affect the solar collection capacity (solar thermal and photovoltaic systems), especially
3 in low density Castle, but in the case of photovoltaic systems, the energy production
4 depends on available roof surfaces. Therefore, building orientations can fundamentally
5 influence both energy consumption and micro-generation energy supply.
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8 The urban morphology also affects the individual dwelling's energy consumption in
9 other ways. In South Heaton and Westgate (mainly compact linear terraces and tall
10 multipurpose tower blocks) there is an actual heat flow in either direction between two
11 adjacent terraced houses or between the lower and upper levels in tower blocks, which
12 influences the energy consumption of individual dwellings. In addition, the air infiltration
13 between adjacent terraces and floors in buildings causes condensation, humidity and
14 difficulty in controlling indoor temperature and other heat losses.
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17 Rogers (2005) argues that towns and cities should be well designed, be more compact
18 and connected, support a range of diverse uses within a sustainable environment which
19 is well integrated with public transport and adaptable to change; for dwellings, Steemers
20 (2003) found that the energy implications of compact densification are balanced between
21 the benefits from reduced heat losses and the non-benefits of reduced solar and daylight
22 availability. Cheng and Steemers (2011), however, suggest that medium to low density
23 housing may in some cases enable a greater saving in CO₂ emissions than higher density
24 development because of the greater amount of space for collection of renewable energy.
25 Energy for heating is a function of house orientation, window area distributions, and
26 shading from neighbouring houses. Orientations of solar hot water (SHW) collectors
27 and photovoltaic (PV) arrays depend on available roof surfaces and house orientation.
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30 As a consequence of the low density array in Castle areas, there are opportunities for
31 off-grid generation, using a diverse and independent renewable energy provided on-site
32 provided there is an indication of the surface temperature. This study uses the thermal
33 infrared remote sensing method because the NCRM has a thermal image available. In
34 this section the thermal images are used to show the possible association between land use
35 and surface temperature. The thermal image was taken on Tuesday 2nd and Wednesday
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3rd March 2010, between 7pm to 11pm (those days were cold, dry and clear and people were most likely to be heating their homes). This image was then colour coded and the outline of buildings laid over the data. The colour code provides a heat loss profile for every building in the city. The rating and hence the colour on the map will be affected by a number of factors, such as: (i) whether the heating was turned on at the time the images were taken, (ii) how much heating was being used at the time (affected by the household composition) and whether there is a heating control in the dwelling, (iii) the type of building and building material used in its construction, (iv) whether the loft space had been converted for use as an additional room, (v) how much insulation there is in the property, especially in any loft space. At the end of the process, all domestic properties in Newcastle have been given a heat loss parameter of between 1 (low heat loss) to 5 (high heat loss) (NCC, 2010).

The neighbourhood chosen is Kingston Metro (Castle LLSOA 8294), a very uniform area, with almost 50% of standard semi-detached houses and semi-detached type housing in multiples of 4, 6, 8, and so on. These houses correspond to the 1964-1979 period. The analysis is shown in Figure 17.

Figure 17: Heat loss profile for every building in Castle LLSOA 8294

The LLSOA has a plot ratio equal to 0.3, see Figure 17. Map (a) represents a land cover raster image from Google EarthTM map (b) represents the OS MasterMapTM vector building outlines, map (c) represents the standard deviation of the classes in the buildings, and map (d) represents the average class (mean) recorded in the building. Map (d) shows a significant number of buildings in green (the likely class for the mean is 2) in the outer North West, where the vegetation is surrounding the buildings. The same type building then progressively turn to yellow (the likely class for the mean is 3) toward the centre of the image denoting that perhaps the inter-building effect is more noticeable than the vegetation.

In summary, research in spatial diversity using thermal images is an interesting and a useful notion, but further work is required to determinate whether it truly correspond to a dwelling's energy' consumption. Nevertheless, the technique is a simple and potentially powerful one, provided the appropriate attributes are correctly weighted. Such techniques may also in the future be used in conjunction with results from more rigorous modelling.

Section 2, 3, 4 and 5 provide various NCRM data-driven exercises that explores the potential application of the close relation between the morphological characteristics, the spatial aggregate building energy end-use and the roll-out interventions. Additional research considering a comprehensive range of building forms, age, regions, and retrofit measures would be presented in future works.

2. Retrofitting using the shape and size of the building classes forming patch areas

The first element of the urban morphology is the shape and size of the building classes (the building thermal massing) forming patch areas. We argue that morphological characteristics play an important part in the area-based building's energy efficiency. Figure 18, shows the Castle semi-detached 1965-1982, 50-75 sqm houses. The sample can be further separated into sub samples through analysis of the common variables (the y axis). This shows there is a wide range of modelled energy consumption within a single

property type and that these are closely linked to specific characteristics of the properties. The largest modelled energy consumption is made up exclusively of properties with uninsulated cavity walls and inefficient boilers. Potentially, understanding the local area characteristics at this granularity provides an opportunity for targeted retrofit campaigns and incentives.

Sample 9		Castle	House	Semi-detached	1965-1982	50 to 75sqm						
							Sample 9 - 1	Sample 9 - 2	Sample 9 - 3	Sample 9 - 4	Sample 9 - 5	Sample 9 - 6
							Housing Association					
							Private Rented					
							Local Authority					
Tenure	Energy Consumption		Owner Occupied									
Floor Area	C	↑	70 to 75sqm									
			65 to 70sqm									
			55 to 65sqm									
			50 to 55sqm									
Boiler Type	C	↑	Standard Boiler									
			Combi Boiler									
			Condensing Boiler									
			Condensing Combi Boiler									
			Warm Air									
			Room Heater									
Wall Type	C	↑	Solid									
			Cavity									
Insulation	C	↑	Un Insulated									
			Insulated									
Average Energy Consumption (kWh)							8,932	10,676	13,232	14,894	18,814	22,005
Subsample size							4%	54%	9%	1%	17%	15%
Cumulative quintiles							4%	58%	67%	68%	85%	100%

Figure 18: Planning retrofitting measures in semi-detached houses

Retrofitting measures could potentially be inferred from analysis of spatial aggregations of the NCRF framework by property type. For example, from Figure 18 (semi-detached houses in Castle) the sample composition corresponds to individual houses traceable to a local address. The energy efficiency of properties in the sample helps to understand appropriate retrofit measures for reducing energy demand. The semi-detached NCRM sample shown in Figure 18 and disaggregated against the fusion variables presents

uninsulated properties using a standard boiler with high energy consumption in sample. It is possible to decrease the energy consumption by 40% by changing the boiler type to a condensing one and insulating the walls, i.e. moving from left to right across sub samples and from top to bottom improving the energy efficiency.

Also, the NCRM data set composition in South Heaton suggest appropriate measures for reducing the energy demand. The local area characteristics leads interesting measures in the building envelope, e.g. the proportion¹⁴ of insulated (i) to total (t) solid wall properties in the complete city sample equals $i/t=258/7,654=0.033$, in South Heaton sample equals $i/t=12/1,010=0.012$ and in the Westgate sample equals $i/t=18/292=0.062$, i.e. only 1.2 percent of the Late Victorian/Edwardian terraces from 1870-1914, with solid walls in South Heaton being insulated and thus solid wall insulation retrofit measures may have a potentially large impact in South Heaton.

In summary, patches are a sensible approach because it allows for ad-hoc energy retrofit planning scenarios and seeing patterns of base line energy consumption. Energy estimates using the physical properties of the building which would still be useful for retrofit evaluation or evidence based comparison of different strategies at an area level. It would even provide the means of implementing different energy efficient strategies with a great impact at the local level, rather than the more general approach made at citywide level.

3. Block-scale supply and demand matches using density/mixing of land use and building form

The second urban form variable is density/mixing of land use and built form. We argue that urban morphology play an important part in the area-based building's energy efficiency. Again, local area characteristics play an important part in the energy consumption. In some cases, these characteristics result in different building types hav-

¹⁴ A proportion is a statement indicating the equality of two ratios, where the denominator is the total while the numerator is a subpart of the total.

ing similar energy consumption, which suggests care must be taken when considering regional mean characteristics. This section uses a case study from Westgate.

DECC (2011) reports in 2009 that the Westgate LLSOA 8440 has an annual economy seven (E7) electricity consumption of 6,557,803 kWh, by far the biggest E7 consumption in the city, also the biggest LLSOA in the mix-uses building. The Westgate LLSOA 8440 also has a plot ratio of 0.81, the biggest value of any individual LLSOA in the case study areas; therefore there is a high availability of buildings in the built environment area. The following paragraphs frame the method for a proposed match of the heat demand/supply in city block by the replacement of the primary heating system. The main driver for the replacement of a primary heating system is the building regulations. The Department for Communities and Local Government DCLG (2014) building regulation 2013 part L encourages replacing an existing heating system by a significantly less carbon efficient one; the seasonal efficiency of the new equipment should have a 2 percentage points lower than the seasonal efficiency of the controlled service being replaced. In UK is measured as the Seasonal Efficiency of Domestic Boiler (SEDBUK) rating. The case study is in local small area of the NCRM Westgate' Elswick (see Figure 19) with electricity heat supply with a selected tariff (E7). The Elswick block heating system will pay for itself much more quickly (ETS, 2013) if it is replacing of the electric heating supply by a heat pump system.

For the heat pump, the overall efficiencies of the ground source heat pump (GSHP) are inherently higher than for Air Source Heat Pumps (ASHP), because (i) ground temperatures are higher than the mean air temperature in winter and lower in summer, (ii) the ground temperature also remains relatively stable, allowing the heat pump to operate close to its optimal design point, whereas air temperatures vary both during the day and the season, and might be low at times of the peak heat demand, and (iii) air has a lower specific heat capacity (the specific heat capacity, or specific heat, is the heat capacity per unit mass of a material) than water, so to supply the same energy more air must be supplied to the heat pump, which in turn requires more energy.

In summary, this paper provides a framework for integrating and consuming infor-

Figure 19: Elswick Westgate block re-engineering the heat supply

mation and the results seem to suggest an initial policy direction in area-based energy efficiency measures to reduce fuel poverty and consumption in households in any UK city.

4. Socio-economic area based policies

Analysis of the NCRM database shows that there is an important interaction between household composition, mobility, and energy use and interestingly fuel poverty. These

interactions are another example of how the social landscape could be used when having a sub-city energy model. This section uses case studies from Castle and Westgate.

From the UK Census Data, the number of people living in a house in Castle has decreased, and the household composition ‘one person living in household’ is now important. Furthermore, this person is usually a pensioner living in an ‘owner occupied house’ e.g. from the NCRM database, in Castle LLSOA 8308 32% are single person households with more than 50% of these being pensioners, 54% of the householders owning the house (although 64% of those who own the house have a mortgage or loan) and 64% of the household size is one or two people. Interestingly, 53% of the householders are in the lowest 20% quintile of income and the fuel poverty is 27% (average is 19% in England). The household size (mostly pensioners) suggests that the increased heating regime associated with pensioners does not fit with the heating regime of standard occupancy. The area faces issues regarding anti-social behaviour, lack of community buildings, effective bus services and accessible housing. The Castle LLSOA 8308 urban area is Hazlerigg which includes 1940 to 1950 council housing and 1950 private housing (mainly brick built semis). Hazlerigg is included in the Great Park initiative. The Castle LLSOA 8308 (urban) is listed in the small area geographies eligible for ECO CSCO support along with Castle LLSOA 8306 (rural) and Castle LLSOA 8307 (urban). In Castle LLSOA 8308, there is an opportunity for wall insulation and roof insulation in respectively 70% and 77% of the housing. Another possible solution is to extend the Warm Home Discount Scheme (WHDS) and the Winter Fuel Payment (WFP) to low-income families besides pensioners. Pensioners automatically qualify for the WHDS because they fall in the ‘core group’ and WFP is automatic if the householder is on the State Pension or another social security benefit.

The Xoserve database provides in ‘good faith’ information about households with ‘no record of a gas connection by either large or small gas transporters by postcodes’ (off-gas). A NCRM (group by LLSOA) analysis exercise reflects high percentages of off-gas households in Westgate (e.g. in Westgate LLSOA 8397 is 58%, in Westgate LLSOA 8440 is 67% and in Westgate LLSOA 8399 is 38%). The fuel poor in Westgate LLSOA

8397 and Westgate LLSOA 8440 are respectively 21% and 20.5% and respectively 64% and 61% of the householders are in the lowest 20% quintile of income. However, under the current ECO framework, delivery to fuel poor off-gas households is not always cost effective and therefore not a focus for most suppliers. One possible solution for the low income, off-gas households is to introduce a new energy efficiency fund. For these low income households this could be: grant aids directly from government, some of the proceeds of auctioning EU emissions trading scheme permits, or a UK carbon floor price which could be utilised to fund such grants.

5. Solar collection using layout and building orientation design

The fourth urban morphology characteristic is the street layout and building orientation design of the neighbourhoods. The street layout determines the building orientations. This is shown particularly in Castle neighbourhood in Figure 8 map (a). The resulting building orientation affects energy consumption for heating and electricity depending on window area distributions and shading from neighbouring buildings. The neighbouring buildings in the urban context reduce solar radiation and daylight availability to individual buildings.

Building orientations also affect the solar collection capacity (solar thermal and photovoltaic systems) generation, especially in low density Castle, but in the case photovoltaic systems, the energy production depends on available roof surfaces. Therefore, building orientations can fundamentally influence both energy consumption and micro-generation energy supply.

The urban morphology also affects the individual dwelling energy consumption in other ways. In the urban form of South Heaton and Westgate –mainly compact linear terraces and tall multipurpose tower blocks– there is an actual heat flow in either direction between two adjacent terraced houses or between the lower and upper levels in tower blocks decreasing the energy consumption of individual dwellings. But also, the air infiltration between adjacent terraces and floors in buildings causes condensation, humidity and difficulty in controlling indoor temperature and additional heat losses.

In summary, again, we reiterate the key message that local area morphological characteristics play an important part in the energy consumption.

6. Summary and discussion

This research is one of the first modelling exercises to be undertaken within the city limits set in the context of a unique identification of land and property (NLPG) in a spatially enabled database. The NLPG is updated on a continual basis by the local authorities in England and expected to be in the public domain in the near future. The present research confirms previous findings and contributes additional evidence that suggests that the spatially-enabled database allows common data integration (e.g. this study links secondary source either by UPRN code and/or address instead of using a grossing methodology that adjusts national dwelling to totals by region), gives geographic coordinates to all individual and group of buildings, provides tenure-based ownership aggregates (and a landownership aggregated areas), and finally supports area-based energy consumption planning.

The framework developed within this research extends our knowledge by testing different energy measures for the same property type and giving insights into community energy use. 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.

Spatial analysis of a city at different scales and through different variables is only possible through the development of energy enabled spatial databases like NCRM. Urban morphology can affect the energy consumption through three characteristics of the built environment: the continuous building class thermal massing and their patch area, the plot ratio (compactness) and layout and orientation design of the neighbourhood. The first two are better descriptors for a 3D residential density and that increase of both have a direct impact on the energy consumption in aggregated dwelling areas. Street layout and building orientation influence both the energy consumption and micro-generation supply.

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3 A key strength of the present study was that the NCRF will significantly increase
4 our theoretical understanding of the complex inter-relationships that exist, not only
5 between the various end-uses of energy within the demand side of the UK housing stock,
6 but also the spatial relationships that exist between a particular combination of urban
7 morphology metrics, climate, buildings (fabric and heating supply systems) and the
8 household characteristics in a sub-city area. Moreover, it must be acknowledged that
9 there is uncertainty in the model and the data, and sensitivity of key parameters in the
10 energy consumption.

11
12 In the social policy side, as early as 1994 energy suppliers have obligations in place to
13 improve the energy efficiency of the households through the Energy Efficiency Standards
14 of Performance (EESoP), specific obligations for a minimum amount of expenditure per
15 customer and targets for total reduction in energy consumption from delivered measures
16 followed shortly after. However, the Government should develop a model to ensure that
17 savings are focused on disadvantaged households who are least likely to be able to benefit
18 from pay- as-you-save type programmes, such as the Green Deal. But, we argue that
19 the Green Deal is at best a partial solution. The reason for a low penetration of efficient
20 boilers could be that the ECO and Green Deal self-referral is not using a good approach
21 in promoting an energy efficiency measure; potentially, an efficient method would be to
22 make area-based approaches rather than individual assessments.

23
24 We have shown that different urban patterns of urban development can potentially
25 affect the energy consumption, and, in the later sections potential applications in the
26 roll-out interventions, however, for the bigger picture, a quantitative implementation
27 strategy is needed which delivers whole-building measures, street-by-street to eliminate,
28 for instance, fuel poverty properly. This research will contribute to this aim by proposing
29 a methodology that uses a spatially-enabled database that is able to find those households
30 in fuel poverty in an area-based approach.

31
32 This paper has proven that the strength is the framework approach not necessarily
33 the model. The CHM model chosen might not necessarily be suited for energy estima-
34 tion in sub-city areas. Therefore, one interesting application for future work is to use

the framework developed in this study and fit it to a different hybrid model. This hybrid model could be integrated to the building's physical characteristics and the energy system. A hybrid model could consider –additionally to the physical characteristics– the interaction between household composition, household behaviour, the stage of the household social practice, and household income, all of which are critical to the energy estimates. Also, in the sub-city areas the scale problem arises when spatial data are aggregated into successively larger areal units. The detailed NCRF micro-simulation framework used for predicting the heating needs of a given building has limitations when taking into consideration the surroundings of a particular building. Indeed, shadowing and heat exchange in cities are non-negligible and ask for a broader scene description in the urban context. This problem is more important in heterogeneous than homogeneous study areas. On the other hand, broadening the modelling scale also opens opportunities to capture other aspects of urban energy use, such as energy distribution networks and shared use of power plants.

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South Heaton			
Age	Type	Class	Percentage
Late Victorian/Edwardian 1870-1914	Lower 3-4 storey and smaller flats, detached and linked	26	48.9%
Late Victorian/Edwardian 1870-1914	Low terraces, 2 storeys with large T-rear extension	28	12.2%
Late Victorian/Edwardian 1870-1914	Low terraces, small	29	12.0%
Castle			
Age	Type	Class	Percentage
Sixties/seventies 1964-1979	Standard size semis	83	24.0%
Sixties/seventies 1964-1979	Low terraces, small	80	10.6%
Sixties/seventies 1964-1979	Smaller detached houses	86	10.2%
Westgate			
Age	Type	Class	Percentage
Recent years 1979-photo date	Non residential building	132	35.2%
Sixties/seventies 1964-1979	Lower 3-4 storey and smaller flats, detached and linked	77	12.1%
Recent years 1979-photo date	Lower 3-4 storey and smaller flats, detached and linked	96	7.6%

Total Variance Explained			
Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	2,217	37	37
2	1,369	23	60

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Component Matrix ^a		
	Component	
	1	2
age	-.156	.823
number of floors	.879	-.006
dwelling size	-.693	-.073
wall construction	.193	.824
building form	.888	-.080
heating	.337	-.015
Extraction Method: Principal Component Analysis.		
a. 2 components extracted.		

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a) Image of Newcastle (2013) retrieved from Google Earth™

b) OS MasterMap™ building outlines

(c) The standard deviation of the classes in the buildings

(d) The average class (mean) recorded in the buildings

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Sample 9	Castle	House	Semi-detached	1965-1982	50 to 75sqm
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				Sample 9 - 1	Sample 9 - 2	Sample 9 - 3	Sample 9 - 4	Sample 9 - 5	Sample 9 - 6	
Tenure	Energy Consumption			Housing Association						
			Private Rented							
			Local Authority							
			Owner Occupied							
Floor Area	+	↑		70 to 75 sqm						
			65 to 70 sqm							
			55 to 65 sqm							
			50 to 55 sqm							
Boiler Type	+	↑		Standard Boiler						
			Combi Boiler							
			Condensing Boiler							
			Condensing Combi Boiler							
			Warm Air							
			Room Heater							
Wall Type	+	↑		Solid						
			Cavity							
Insulation	+	↑		Uninsulated						
			Insulated							
				Average Energy Consumption (kWh)	8,932	10,676	13,232	14,894	18,814	22,005
				Subsample size	4%	54%	9%	1%	17%	15%
				Cumulative quintiles	4%	58%	67%	68%	85%	100%

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