Urquizo J, Calderón C, James P. **A spatial perspective of the domestic energy consumption intensity patterns in sub-city areas. A case study from the United Kingdom.** *In: Ecuador Technical Chapters Meeting (ETCM 2016).* 2016, Guayaquil, Ecuador: Institute of Electrical and Electronics Engineers.

**Copyright:**

© 2016 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

**DOI link to article:**

http://dx.doi.org/10.1109/ETCM.2016.7750848

**Date deposited:**

20/03/2017
A spatial perspective of the domestic energy consumption intensity patterns in sub-city areas. A case study from the United Kingdom

Javier Urquizo1,2
1Facultad de Ingeniería en Electricidad y Computación Escuela Superior Politécnica del Litoral
Guayaquil, Ecuador
P.O. Box 09-01-5863
Email:jurquizo@espol.edu.ec

Carlos Calderón2
2School of Architecture Planning & Landscape
Newcastle University
Newcastle upon Tyne, UK
NE1 7RU

Philip James3
3School of Civil Engineering & Geosciences
Newcastle University
Newcastle upon Tyne, UK
NE1 7RU

Abstract—This paper explore the benefits of an bottom-up spatially enabled building-based energy framework in identifying districts, neighbourhoods, and community’s building aggregated areas with spatial expressions patters most similar to a given parameter within the energy profile. In districts, we argue that the hot spot cluster technique simplify the complexity of the urban extent of the energy consumption intensity which potentially signpost ad-hoc energy retrofit planning scenarios and flexible local distributed generation strategies. In neighbourhoods and communities, our results suggest that the number of heated rooms rather than the simple count of the number of rooms, as a proxy for the usable floor area, leads to a better density metric indicator, the space per person, which is more appealing to energy studies despite not being available in UK statistics as it should be. Additionally, certain geometry on the local construction of the UK’s city settlements lead to original building types, like the Tyneside Flats, that are both difficult to harmonize with existing national data sets, and to model; and, more importantly, to effectively assess the estimated energy savings that will result from potential measures. This represent a challenge not only to the government energy-efficiency national financing mechanism like the Green Deal but also for manufactures and suppliers, which have to provide specifications for a large number of architectural details. This modelling exercise is undertaken within the city limits and are set in the context of an unique identification of Local Land and Property Gazetteer (LLPG) in a Geographical Information System (GIS).

Index Terms—cities, climate change, decentralized target scenarios, hot spots, neighbourhood urban energy modelling, space per person, temperature controls, Tyneside Flats, urban patterns.

I. INTRODUCTION

The bottom-up simulation modelling approach methodology can be extended to include spatial differentiation [1] in the energy consumption of individual (and aggregated) buildings in a spatially enabled database area-based approach. In this spatial framework, the spatial distribution of aggregated buildings end-use energy consumption can be compared with current/future supply infrastructure or decentralized bounded low carbon generation to create a sub-city case scenario. Area-based case scenarios are used in evidence-informed energy efficiency and/or fuel poverty policies/practice which attempt to identify appropriate energy/carbon reduction targets in aggregated building stocks [2]. Examples include: the Energy and Environment Prediction (EEP) tool [3] developed to predict and account for reductions in CO₂ emissions in South Wales Local Authorities LAs. EEP uses a ‘100 house types’ (each described by five building characteristics) where similar houses are assigned to a particular cluster. The domestic energy, carbon counting and carbon-reduction model (DECoRuM) model [4] that was applied to 318 dwellings in Oxford using four categories for data reduction, uses the Building Research Establishment Domestic Energy Model BREDEM-12 (with 96 parameters) methodology in individual dwellings.

Using a case study from the United Kingdom [7], we develop a bottom-up spatial local energy end-use framework 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.

This paper understands the nature and extent of the energy consumption problem through the Annual Energy Consumption (use) Intensity (density) (AECI).1 The AECI is a term for benchmarking the comparative energy use of Buildings [8] that are different sizes, therefore, which performs better. The AECI can be used for comparing individual energy end-uses, as well as total energy use. The AECI is an appealing metric for energy efficiency measures as declines in energy intensity are a proxy for efficiency improvements provided energy intensity is represented at an appropriate level of disaggregation (buildings) to provide meaningful interpretation. AECI is calculated by dividing the total energy consumed by the building in one year (measured in kWh) by its total footprint area (measured

---

1Annual energy consumption intensity is the quantity of energy required per unit of area (kWh/m²), so that using less energy (electricity and/or gas) reduces the intensity.
in square metres). Intensity or density measures have been used in LAs, for example in Bristol [9], where the heat demand density (i.e. units of heat demand per square meter over a year) are used to evaluate the location and scale of opportunities for district heating. This paper’s main purpose is to relate evidence to arguments from the spatial characteristics of the three representative districts (Castle, South Heaton and Westgate) in Newcastle upon Tyne, United Kingdom (UK).

Section II shows that the hotspot spatial operator potentially simplifies the complexity of urban energy consumption by representing the spatial incidence energy consumption as a smooth continuous surface in districts (Middle Layer Super Output Areas MSOAs). Section III shows how specific variables affect patterns of energy consumption in communities inside neighbourhoods (Lower Layer Super Output Areas LLSOA). Section III.A shows the energy consumption issues around Houses in Multiple Occupation (HMOs) rented on a room-by-room basis and Section III.B focuses on the high density Tyneside Flats. The hotspots enable identification of similar patterns of energy consumption.

II. SPATIAL CHARACTERISTICS OF ENERGY CONSUMPTION PATTERNS IN DISTRICTS

The purpose of this section is twofold. Firstly, it attempts to observe the reasons and extent of AECI patterns within individual districts. Secondly, it aims at identifying differences and similarities between three districts and at drawing conclusions which may prove to be useful to interpret other districts in the city and provide possible general rules for energy efficiency measures in Newcastle upon Tyne, and potentially beyond.

This section uses the hotspot statistical method to quantify AECI spatial patterns. Hotspot is a statistical technique aimed at grouping point location entities together into relatively coherent clusters [10]. To minimize the subjectivity in the inter Middle Layer Super Output Areas (MLSOA) pattern analysis, the hotspot analysis uses the same legend classifications for all districts in the case study.

Figure 1, Figure 2 and Figure 3 present hotspot maps of South Heaton, Westgate and Castle, respectively. These figures provide a visual depiction of the spatial distribution of AECI within each of the MLSOA areas. The number of categories in the rating scale is the same in all the figures and serves to communicate not only similar AECI patterns but also patterns of low and high intensities. The maps use a bright red to show patterns of clusters of high-intensity (AECI) values whereas a dark red show patterns of clusters of low AECI values.

On the number of categories, [11] argue that little information appears to be gained by increasing the number of categories in rating scales beyond eight, and beyond six, if the number of categories is positioned to cover the whole range. Therefore, according to [11, pp. 38] “this finding is heartening for the advocate of seven” in the number of categories on the rating scale. This paper uses nine categories for allowing finer resolution in neighborhoods.

A possible wording for the rating scale could be: nine: very high; eight: much too high, seven: somewhat too high, six: a little too high, five: medium, four: a little too low, three: somewhat to low, two: much too low, and one: very low. However, a color code is more appealing to a Geographical Information Systems; therefore a color code is implemented as shown in all the figures of this Section. From the figures, the patterns in South Heaton are in the high range (up to 9,300kWh/year/m²), the patterns in Westgate are in the medium range (up to 6,000kWh/year/m²), and the patterns in Castle are in the low range (up to 4,000kWh/year/m²).

Fig. 1. Hot spots for South Heaton

The Figure 1 shows two delineated areas, the black rectangle corresponds mainly to patterns of high AECI in social housing with inefficient heating systems, whereas the red rectangle shows patterns of high AECI.

The black rectangle shows an area of high AECI which is made up of three-storey mid-terrace (and end-terrace) with three bedrooms dwellings in Heaton Close, Grafton Close, Langhorn Close and Tynemouth Close. This is a zone of inefficient warm air heating systems and standard boilers in an area of dwellings with small footprints (around 40sqm). Warm air units were popular at the time of the construction of these buildings (1965-1975), but became less popular when conventional gas boilers decreased in size, and became easier to install.

2 MSOAs are the UK Office of National Statistics aggregated areas that on average have a population of 7,200.
3 LLSOAs are the UK Office of National Statistics aggregated areas that typically contain 4 to 6 OAs with a population of around 1,500.
to install. The density of the built form facilitates the use of more efficient combined heat and power systems (CHP).

The red rectangle shows Victorian houses in linear terraces with patterns of high AECI. The uninsulated solid wall structures of terraced houses also have additional problems of airtightness and ventilation. The appropriate measure is to bring those terraces up to requirements for modern standards of energy such as those used in BREEAM (BRE Environmental Assessment Methodology).

Figure 2 shows patterns of AECI in Westgate which has values that are not as high as South Heaton. However, zones such as Elswick (inside the black rectangle) have inefficient electric heating. In particular, the 71 social housing mid-terraced (and end-terraced) houses of Mill Farm Close and Quarry Bank Close use an Economy 7 tariff. [12] suggests that there are opportunities in replacing the electric heating with low and zero-carbon technologies, e.g. replacing the electric heating with a ground source heat pump could provide space and water with a combined annual coefficient of performance between 3 and 4.

Figure 3 shows that the natural landscape dominates the Castle area. The low density Castle area forms pockets of residential development in a spatial cluster based approach. Most of the properties are small terraces, semi-detached and detached dwellings with private gardens and private parking and the predominant pattern is low AECI. The black rectangle in Figure 3 shows the Dinnington area of high intensity (relative to the rest of Castle). [13] and [14] suggest that medium to low density housing may enable a greater saving in CO₂ emissions because of the greater amount of space for the collection of renewable energy.

Moving away from the clusters, the houses become sparse with emphasis on large houses in large plots (see red rectangle in Figure 3). The LIDAR⁴ image (see Figure 4) shows that gardens and trees dominate the Dinnington area. The LIDAR image has a 50cm planimetric accuracy for 1km of flight altitude.

As a consequence of the low density array in Castle areas, there are opportunities for off-grid generation, using a diverse and independent renewable energy provided on-site. An appropriate measure in the Dinnington area (in the Figure 4) could

⁴Airborne Light Detection and Ranging.
be a solar collection project.

In summary, the areas of high energy consumption can be visualized according to the graduated colour intensity. The analysis from Figure 1, Figure 2 and Figure 3 maps has led to the identification of areas where energy reduction is a priority. These areas have conditions to favour large scale, more economic and effective forms of low and zero-carbon technologies generation, such as CHP with district heating. Two priority areas were identified in the case study areas: the pre-1919 housing with poor building envelope, and small area dwellings with inefficient heating systems. Both areas have high individual average gas consumption and AECI and are in South Heaton.

The figures throughout this section re-iterate the key messages of this paper, which is that local area characteristics are important in understanding the energy consumption estimates in the sub-city areas.

III. SPATIAL CHARACTERISTICS OF ENERGY CONSUMPTION PATTERNS IN COMMUNITIES

This section aims at providing an overall estimation of the relationship between individual dwelling characteristics affecting energy consumption patterns in communities. This section shows the spatial patterns in energy consumption in communities using two specific built forms: the HMOs rented on a room-by-room basis and the small usable floor area Tyneside Flats. Also in this section are the patterns of dwelling AECI on the use of heating systems and controls. The aim is to present an evidence-based analysis and discussions of ‘plausible’ measures to reduce energy consumption in communities.

This section uses the hotspot statistical method results as the background in all the figures. This potentially makes it easier to spot correlated patterns between inefficient measures and high energy consumption.

A. Spatial characteristics of HMOs energy consumption patterns - the space per person

HMOs play an important role by providing affordable shared-housing mainly for three spatial patterns of the market demand: people in lower income, student housing, and migrants. High concentrations can have a detrimental effect on the local environment as well as impacts on social cohesion and services within an area. However, the requirements for getting a licence to change the use to HMO vary in terms of the size and spatial location of the property. These issues will be clarified next.

The 2004 [15] first introduced the definition of a HMO and in 2010 two specific changes in the England planning regulation were introduced: the [16] and the [17] to allow the Class C3 family dwelling houses to be changed to the recently established Class C4 known as HMOs without the need for planning permission, making such a change a ‘permitted development’. However, under the [18], local planning authorities can remove permitted development rights using an ‘Article 4 direction’. In order to manage the growth and distribution of HMOs, Newcastle city Article 4 direction (established on 1 October 2011) required an application to be submitted within identified areas covering eight wards (South Heaton and Westgate among others), including a total of 17,895 households, see Figure 5 for the spatial characteristics of the Article 4 direction. It took effect on 25 November 2011 and required that an application for planning permission be submitted for a change of use from C3 (family housing) to C4 (small HMOs). All HMOs included in the article 4 directions are subjected to city licensing, and for the licence to be granted the HMO must comply with certain standards. The number of HMO licences in South Heaton and Westgate, respectively, are 283 and 46. There is no HMO licensing in Castle. HMOs are in one of the older areas of the city, and it is therefore expensive to renovate and raise to modern standards.

There are three other difficulties associated with assessing energy in an HMO: first, the government’s official definition of fuel poverty is not directly applicable in cases where energy bills are part of the rent or the bills are shared between multiple households. Second, Energy Performance Certificates (EPC) are not required for HMOs rented on a room-by-room basis because the European Energy Performance of Buildings Directive only requires EPCs for self-included dwellings, and third, the 2009 EHS survey only considers self-included dwellings.

Being rented on a room-by-room basis raises an important issue in energy modelling, as every rented room is a heated room. Therefore, this section starts by setting out differences in measures of density such as ‘population density’, ‘dwelling density’ and ‘space per person’ as a measure to describe indoor space. Further, if the number of rooms is a valid proxy for useable floor area in dwellings. Finally, there are

5Family houses, or houses occupied by up to six residents living together as a single household, including a household where care is provided for residents.  

6Class C4 (HMO) covers small shared houses or flats occupied by between three and six unrelated individuals who share basic amenities. This would include small bed-sit forms of accommodation. Houses in multiple occupations where more than six unrelated people sharing are called ‘sui generis’ and are not generally considered as class C4.
also arguments on the need for modellers and statisticians to consider both the ‘space per person’ as a better driver in domestic energy consumption studies and the ‘not self-include dwelling’ as a significant dwelling from the North East England housing stock. Space per person is defined as the dwelling size of a habitable unit divided by the household size. It is a measure of how much ‘private’ indoor space people consume [19].

This section uses the HMOs in the high density South Heaton LLLOAs 8359 and 8362 in the analysis.

Figure 6 shows four maps of South Heaton housing stock using a yellow graduated energy consumption intensity background. The map (a) represents HMOs with four rooms (in cyan), and increases in terms of the number of bedrooms is described in three adjacent figures: in (b) map HMOs with five rooms, in (c) map HMOs with six bedrooms, and in (d) map HMOs with seven and eight rooms.

Fig. 6. HMOs with a differing number of rooms in South Heaton LLLOAs direction areas at scale 1:4,000

The Figure 6 seems to suggest that there is a difference in the number of rooms for the similar useful floor area occurs through those LLLOAs e.g. the red rectangle shows in the four maps (a, b, c and d - the linear terraces along Rothbury Terrace and Meldon Terrace) a decrease in the average of useful floor area per room and what is more important a decrease in the ‘space per person’ [19]. This means a change of use in South Heaton which impacts the social condition of the household and the increases the number of rooms heated. The increase of the number of rooms in turn increases the ‘Heating behaviour’ defined by the combined set point temperature, number of rooms heated and heating period [20].

[20, pp. 4] argues that the way people operate the space heating system in time, space and magnitude is through the following variables respectively: heating duration, number of rooms heated and set point temperature (assuming the presence of some kind of thermostat).

In the ‘space per person’ density value two other density concepts are often discussed: population density (South Heaton LLLOA 8359 = 132.61 number of people per hectare) and dwelling density (South Heaton LLLOA 8359 = 56.90 number of dwellings per hectare). This paper argues that neither population density nor dwelling density helps to understand the levels of ‘space per person’ as a contributing factor of the heating behaviour. This paper proposes the space per person as shown in the framework of Figure 7.

Figure 7 proposes the space per person as a combined measure between population density and plot ratio for two reasons. First, in municipal planning, density is typically expressed in units per hectare; however, density numbers can vary widely based on boundaries of the area studied. For example, extending the boundaries of a community to include more non-residential uses would affect the units-to-land ratio. A mixed-use urban neighbourhood would have a lower density than one that is primarily residential. Second, in population density, the diversity is introduced in many ways (e.g. offering different types of housing to accommodate various incomes or introducing non-residential uses to ensure a diverse population). Therefore, we propose the space per person as a better density descriptor for measuring energy performance as it includes the activity of the household members, turning the metric to a density of household diversity.

Additionally, measuring dwelling size (usable floor area or
how much ‘private’ indoor space people consume) by the number of rooms can also be misleading as houses with the same number of rooms can vary considerably in the similar usable floor space as Figure 6 seems to suggest.

In summary, there are a number of social and economic reasons in the local areas that means that some dwellings are more intensively occupied. The energy consumption in larger areas of South Heaton are underestimated because neither NCRF nor physical models take into account the fact that in shared houses all rooms may be heated, i.e. the whole house became a ‘living area.’ One possible solution is already in place in the [21] where any landlord operating a rental property where a boiler, or similar central heating system provides the heating for several tenant, such as houses converted into flats/bed-sits relying on the original heating system, “final consumers are provided with billing information that is accurate and based on actual consumption where it is cost effective and technically feasible to do so.”

Additionally, the ‘space per person’ as a useful density indicator and an important driver of energy consumption in neighbourhood energy studies is not available in UK statistics as it should be. This type of analysis is only realised through a detailed spatial database.

B. Spatial characteristics of Tyneside Flats energy consumption patterns. The small size purpose built flats

This section shows the spatial characteristics of a special building form in the north of England, and in particular in South Heaton, the Tyneside Flats (TF). The energy consumption patterns of the Tyneside Flats in the high density South Heaton LLSOAs 8359 and 8362 are used in the analysis.

In figure 8, each TF is an independent pair of purpose built flats in a terraced house, one above the other. Structurally, it is an unusual form of terraced housing because even though is a single fronted terraced house, behind the facade there are two and sometimes three flats, one above the other. Each flat has a separate front and back door, and backyards with no internal communication between the households. Tyneside Flats were built in the late 1800s as low-cost housing for the growing workforce; both flats are entirely self-contained and together comprise the whole building. The need for student accommodations has led to the conversion of lofts in upper Tyneside Flats, so as to provide extra student bedrooms. These conversions have resulted in a higher density than originally intended in the area.

Figure 8 represents solid wall properties (in cyan). The map is for South Heaton LLSOAs 8359 and 8362 housing stock using a yellow graduated energy consumption intensity background. The red rectangle shows a spatial pattern of high AECI in Tyneside Flats, mainly due to the higher density in small usable floor area buildings.

The TFs in the red rectangle inside Figure 8 are along Warton Terrace and mostly have loft conversions for an additional room-in-roof built into a pitched roof; this flat is better described as an ‘upper maisonette’ style flat. Both flats possess their own separate entrance from the ground floor level. The upper maisonette has roof heat loss and the lower flat has ground floor heat loss, but neither has both forms of heat loss. Most TFs have a small room for washing the dishes and share a backyard for drying clothes. Each property has a door leading into a back lane.

There are about 20,000 Tyneside Flats in Newcastle upon Tyne, with most having solid walls but the extension is cavity. Interestingly, the cavities are hard to treat because the cavity size is too small to pump insulation [22]. Having both solid and cavity in the building envelope makes the Tyneside Flat building type difficult to harmonize with other data sets and models; additionally, the building type is both purpose built and converted (because of the room-in-roof) at the same time; finally, like most pre-1914 properties, Tyneside Flats were usually built to rent, so the usable floor area is below the UK average and so it is difficult to impute values from other national data sets.

In summary, there are local area characteristics in the Newcastle stock such as the Tyneside Flat, that are difficult to harmonize with existing national data sets e.g. EHS, and to model effectively. The modelling methodologies potentially do not consider the appropriate thermal characteristics of old buildings. The spatial distribution of TFs shows high AECI in wide areas of South Heaton.

Understanding local area characteristics at various scales is important to be able to model local buildings successfully. In some cases, local area characteristics such as the TF can be very significant [23].

IV. SUMMARY AND DISCUSSION

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 relationship 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.

A spatially enabled energy model and rich thematic database enables integrated mapping practices, such as updating authoritative data with volunteered data sets, which may reduce their production costs. This study has also made possible the integration of records from the different geographies and semantics level to simple sets of rules. If we have spatially enabled models, this also makes possible the integration with detailed climatic data because there are detailed spatial records available.

Being rented on a room-by-room basis raises an important issue in energy modelling, as every rented room is a heated room. This sets out differences in measures of density such as ‘population density’, ‘dwelling density’ and ‘space per person’ as a measure to describe indoor space. Further, if the number of rooms is a valid proxy for useable floor area in dwellings. There are also arguments on the need for modellers and statisticians to consider both the ‘space per person’ as a measure to describe indoor space. Further, if the number of rooms is a valid proxy for useable floor area in dwellings.