Modelling the spatial energy diversity in sub-city areas using remote sensors

Javier Urquizo\textsuperscript{a,d}, Carlos Calderón\textsuperscript{b}, and Philip James\textsuperscript{c}

\textsuperscript{a} Newcastle University, Newcastle upon Tyne, United Kingdom, j.urquizo@newcastle.ac.uk
\textsuperscript{b} Newcastle University, Newcastle upon Tyne, United Kingdom, carlos.calderon@newcastle.ac.uk
\textsuperscript{c} Newcastle University, Newcastle upon Tyne, United Kingdom, philip.james@newcastle.ac.uk
\textsuperscript{d} Escuela Superior Politécnica del Litoral, Guayaquil, Ecuador, jurquizo@espol.edu.ec

Abstract:
Research in spatial energy 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. We argue that such techniques may also in the future be used in conjunction with results from more rigorous modelling. In this paper the thermal images are used to show the possible association between land use and surface temperature and domestic energy consumption.

Keywords:
Energy consumption, Microclimates, Surface temperature, Thermal images, Urban energy modelling, Vegetation.

1. Introduction
European building stock is highly diverse, particularly in local and regional places where there exists complex building forms affecting energy consumption; for example, in Newcastle upon Tyne United Kingdom (UK), there is a high proportion of bed-sits (bed-sits are not considered as a dwelling type in English House Survey) and regional building types, like the North East Tyneside flat, forming part of a terrace and horizontally divided as a semi-detached buildings. Tyneside flats have a usable floor area that is below the UK average and so it is difficult to impute values from other national data sets. Additionally, some of the worst problems in the housing condition are focalized in the inner core terraces as well as the outer estates, often where not so popular stock types (detached, maisonettes and one-bed old people's units) interact with high fuel poverty areas. In Newcastle, an area-based approach would allow more houses to be targeted in places where local area characteristics show energy inefficient elements, and may therefore potentially capture a greater number of fuel poor households per unit of cost. New governance mechanisms, such as the Local Strategic Partnerships [1], envisage an important role for area-based initiatives, which have a major impact on deprived areas (e.g. Newcastle West End is included as one of the six case studies). Also, Newcastle is one of the nine areas in the Housing Market Renewal Pathfinders [2] where “demand for housing is relatively weak; areas which have seen a significant decline in population, dereliction, poor services and poor social conditions”. The basis of the Pathfinder Housing Market Renewal programme in Newcastle is a robust evidential base for making programme decisions in which the importance of quantitative information (explicitly including understanding energy use) or ‘drivers’ for informing strategic interventions in the housing market has been established as one of the aspects of any assessment. This study aims to contribute to this evidence by estimating the energy use in sub-city areas through a bottom-up framework strategy. Furthermore, our framework would allow us to pose some questions about appropriate retrofit measures [3] in Newcastle and other matters related to energy consumption.

This paper argues that an area-based approach allows more houses to be targeted compared to the existing self-referral method, like the Green Deal\textsuperscript{1}. The Green Deal scheme would be more

\textsuperscript{1}The Green Deal scheme provides finance to make energy-saving improvements in a home and finds the best way to pay for them.
appealing to the owner-occupied sector [4] if additional energy efficiency measures could be bundled into a house renovation plan. As an example of acceptance, by 31\textsuperscript{st} December 2013 [5] 129,842 Green Deal scheme assessments had been made in Great Britain, of which 75% of the valid assessments were on owner-occupied properties. The relevant improvements recommended were boiler (upgrade) (13.2%), cavity wall insulation (13.2%), loft insulation (15%), micro generation (16.2%), and solid cladding (10.6%), and usually two to three improvements were recommended per assessment.

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

This paper uses an innovative area-based approach for mapping and monitoring heat loss from a group of buildings using imagery from an airborne thermal remote sensing and a building-based energy consumption framework to reduce energy consumption.

2. Approaches for reducing the energy consumption

In the United Kingdom, the approach to reduce energy consumption is to identify which measure and its combinations i.e. the building fabric and energy supply systems that are capable of making a significant contribution and the marginal value in the available policies and technologies. Shorrock and Utley [6] estimate that in Britain the overall heat loss of the average dwelling was reduced approximately by 31\% between 1970 and 2001. Fig. 1 shows the contributions of various building fabric elements to the heat loss of the average dwelling.

![Fig. 1 Heat loss of the average dwelling [6].](image)

Fig. 1 shows that the mean heat loss has fallen approximately by 115 W/K in the average house, and approximately 40\% reduction is in insulation of roofs. Also in Fig. 1, there is a small reduction in walls, windows and ventilation (mainly air leaking) by 2001 presumably to the fact that most walls (solid or cavity) remain uninsulated and there is a significant housing stock with single glazing in windows. We argue that an interesting application of thermal remote sensing is detecting and monitoring heat loss from buildings in urban areas i.e. area-based sites targeted for repair and re-insulate roofs so to conserve energy.
Airborne thermal infrared sensors are widely used for military applications, later advances in the sensor technology made them available for remote sensing tasks in cities. Thermal sensors employ one or more internal temperature references for comparison with the detected radiation, so they can be related to absolute radiant temperature. Airborne thermal remote sensing is an attractive option for identifying areas of high surface heat exposure. Airborne thermal remote sensing gives an excellent spatial picture of the urban landscape for a snapshot in time, allowing a comparative analysis of areas of high surface temperatures. The advantage of airborne thermal remote sensing is the ability to observe high resolution surface temperatures, allowing the identification and analysis of individual landscape elements, therefore to relate surface temperatures to different land surface building types and features, and also have demonstrated that vegetation cover and urban geometries are important controls of surface temperatures. However, for most of the thermal remote sensing data, other auxiliary data can be accessed to assist in processing, analysing and interpreting the imagery, like estimations of energy consumption per building. Correlations between surface temperature and energy reductions would help to further understand the role of building features in urban domestic sector. In this paper a measure of the waste heat at different temperatures is then analysed and coloured maps are produced for buildings areas.

For energy consumption estimations of individual buildings, we use the Newcastle Carbon Route Framework (NCRF) [7, 8]. NCRF is a building-based energy framework comprised of city-wide individualized spatial per-dwelling records in a PostGIS spatial database, which later were imported to an ESRI geo-database for further spatial analysis. Every spatial per-dwelling record is keyed on the Unique Topographic Identifier (TOID) and associated with their Unique Property Reference Number (UPRN). This allows a common set of attributes to be displayed as either the building outlines or the property parcels identified in the UPRN.

Our energy consumption process creates individual energy consumption estimates for each dwelling and aggregates these to sub-city areas. The process utilise a physic based approach to energy modelling based on BREDEM 12 methodology. In our case, this research uses 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 [9].

The most disaggregated level of spatial information in NCRF is about a single dwelling. The dwelling has a unique property identifier (its UPRN code) and the address information; both are part of the Local Land and Property Gazetteer (LLPG) and the aggregated National Land and Property Gazetteer (NLPG) data set. Local authorities in UK have statutory responsibility for the street name and property number and additionally inform Royal Mail of new buildings and address changes. NLPG data set is made up from each of the constituent LLPGs, and also joined-up national and regional services [10]. Gazetteer refers to those records in the data set where attributes have been added through incorporation of the LLPG records. The next level of hierarchy corresponds to a building as a building could have a number of dwellings. Every building is identified by a TOID. At the building level, two additional information were integrated: The Cities Revealed (CR) data (CR refers to those records in the data set where attributes have been added through incorporation of the Cities Revealed records) enables us to identify all residential properties by age and structure category through the Cities Revealed building class code compatible with Ordnance Survey Mastermap data [11]. The building Class provides a detailed perspective of the built environment, see Fig. 2. The Cities Revealed building classification data set provides building classifications and ages against MasterMap building outlines. In addition a further set of building

²A TOID is a unique reference identifier associated with every building within Ordnance Survey’s (OS) large scale topographic mapping.
³LAs are involved in all stages of the property lifecycle –planning, building, occupation and demolition.
⁴Characterized by coordination and coherence of though.
⁵Local and national statistics, social services, and others.
⁶Highways, counties, ambulance, fire, and police.
classifications were incorporated showing building use classification from the SCORCHIO\(^7\) project [12] (SCORCHIO refers to those records in the data set where attributes have been added through incorporation of the SCORCHIO records) that identifies the number of residential and commercial properties within the building.

The initial data set was cleaned and restructured for this study and additional data layers were integrated. The LA provided dwelling level information about the social housing through the Your Home Newcastle (YHN) data. YHN\(^8\) is an Arm’s Length Management Organization (ALMO) responsible for managing council homes on behalf of Newcastle City Council. In 2009 YHN managed 28,950 council homes on behalf of Newcastle City Council, 1,800 homes on behalf of the Byker Community Trust and 330 homes on behalf of Leazes Homes. YHN also manage 1,500

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\(^7\)Sustainable Cities: Options for Responding to Climate Change Impacts and Outcomes (SCORCHIO).

\(^8\)The information in the paragraph is from the following source: URL: http://www.yhn.org.uk/about_us.aspx
leasehold properties on behalf of Newcastle City Council and the Byker Community Trust. YHN refers to those records in the data set where attributes have been added through incorporation of the YHN records. Calderon et al. [13] provides the details of the major data sets used to create the data as part of this study.

YHN council homes have an accurate build date taken from the deeds. YHN properties mainly consist of post-war, non-traditional buildings; however there are also a large number of pre-1919 terraces, semi-detached and flats in their housing stock. Where possible, NCRM YHN dates were used in preference to other building age data as it was deemed the most reliable. The additional attributes provided by the YHN records for 28,950 properties were added to the NCRM data set as part of this study.

An example of the problems faced in fusing multiple data sets is the building type classifications, of which WarmZone, Cities Revealed, LA Gazetteer and YHN all had different categories. In many cases this required looking for building market information or a small scale field work in order to map between categories consistently. A similar problem was found in building age classifications and categories which did not align perfectly and needed mappings to be created between categories. In the last four years, this paper found interesting research using the spatial diversity approach. Examples are Grafius et al. [14] who argue that in modelling ecosystem services an optimal balance must be sought between feasibility and capability i.e. a balance is important between scarce and detailed data. Reinhart and Davila [15] who argue that city-wide Geographic Information Systems (GIS) are increasingly accessible to the general public combined with LiDAR data or building heights as well as open semantic formats such as CityGML and used to generate extruded models of whole cities. In the UK, the Cambridge University [16] Energy Efficiency in Cities initiative (EECi) uses a bottom up' tool that brings together detailed data, expert knowledge, and energy simulation, the goal is to strengthen the UK's capacity to address energy demand reduction in cities. This paper proposes remote sensing techniques in conjunction with results from more rigorous building energy modelling framework to show the possible association between land use/land cover patterns on surface temperature and energy consumption in buildings at different scales.

Although the terms land use and land cover have been used interchangeably, it is important to remember that the two expression are not necessary synonymous. Land use [17-19] encompasses several aspects of people's relationship to the environment. By comparison, land cover [20-22] is represented by the natural and artificial compositions covering the earth surface at certain location. Land use is a cultural concept that describes human activities and their use of land, whereas land cover is a physical description of land surface [23]. Land cover can be used to infer land use, but the two concepts are not entirely interchangeable, as an example, Guérois and Pumain [24] use CORINE land cover classifications to derive built-up densifications and their evolution over time.

Thermal images allow to qualitatively observing ventilation leaks [25], conduction losses and thermal bridging [26]; defective services [27]; moisture condensation [28]; moisture ingress [29]; structural defects [30]; quantitative energy performance measurement [31]. Benefits include identifying problems without needing to gain access to buildings and being able to observe problems on large buildings more efficiently. Stockton [32] argue on such an application and finding show that aerial thermal images are well placed for detecting moisture over flat roof surfaces. Others suggest how aerial thermal images could be used quantitatively to determine energy loss from roofs [33], however limitations to this methodology such as roof shape & pitch, image blurring, internal temperatures, climate and emissivity could impact on and require consideration of for qualitative analysis [34]. A clear limitation to this methodology is that it does not seem possible to observe wall or fenestration defects, since these have not been reported on and could be due to the height and parallel angle of the camera from the plane to the building.

Urban areas tend to have higher air temperatures than their rural surroundings, as a result of gradual surface modifications that include replacing the natural vegetation with buildings and roads. This is because vegetation plays a significant role in regulating the urban microclimate and can influence domestic energy demand through solar absorption and the cooling effects provided by shade and
evapotranspiration (Akbari et al. [35] and Akbari and Konopacki [36]). This may mean that areas with a low residential density indicative of more open space require more energy to maintain the same temperature as higher density areas.

3. Modelling the spatial diversity

This paper has selected Castle, a Middle Layer Super Output Area (MLSOA) in the United Kingdom for the analysis. Castle is a low residential density MLSOA, which means the effects of microclimates are likely to be more influential than in high density areas (due to the urban heat island effect) meaning energy consumption is likely to be higher than the average. For a thorough explanation of how vegetation affect microclimates and the energy consumption see [37], [35] and [36]; and for quantification, one possible interpretation mechanism is from thermal images. NCRM spatial detailed data sets have both spatial and attribute information, and enable the analysis of detailed form and relationships. They are also sufficiently extensive to enable patterns to be generalised across sub-city areas. It is increasingly possible to link the socio-economic focus of geographical analysis to the geometric built environment approach [39]that is employed in local urban planning. Batty [40] has termed this link as “geography of the third dimension to geometry”, that is, the merging of iconic and symbolic urban models [41], and it opens up many possibilities for research.

Ong [42] argues that the primary cause of heat build-up in cities is insulation, the absorption of solar radiation by roads and buildings in the city and the storage of this heat in the building material and its subsequent re-radiation. Akbari, Pomerantz [35] argue that the uses of ‘cool’ surfaces, that is surfaces with a high albedo or reflective index, as well as planted surfaces are effective in reducing heat build-up. Plants also play a significant role in regulating the urban microclimate and can influence domestic energy demand through solar absorption and the cooling effects provided by shade and evapotranspiration, therefore more energy is demanded for maintaining the same internal temperature in the building. Additionally, all Castle Lower Layer Super Output Areas (LLSOAs) do not make the threshold (plot ratio of at least 0.3) were Directive 2012/27/EU [43] considers district heating directly feasible. Interestingly, Persson and Werner [44] classify areas based on plot ratio: plot ratio ≥ 0.5 as inner city areas, 0.3 ≤ plot ratio < 0.5 as outer city areas, and plot ratio < 0.3 as park areas and argue that “widely distributed park area settlements may prove unfeasible for district heating expansions, due to insufficient Linear Heat Density”. The microclimate is an important element not considered in energy modelling. Indeed, as an example, in the Cambridge Housing Model (Hughes CHM [9]), the only climate variable used is regionally based and the value is the same for the entire North East England in terms of Monthly External Temperature (ºC); monthly Average Wind Speed (m/s); and monthly Average Horizontal Solar Radiation (W/m²).

This paper presents our estimated energy consumption estimated in Calderón [7] for repeated property types by samples due that the Department of Energy and Climate Change (DECC) [45]. The Energy Act 2011 included provisions for the Green Deal. An Energy Company Obligation (ECO) integrated with the Green Deal, allows subsidy and Green Deal Finance to come together into one seamless offer. In this way, the Green Deal and the ECO will work in combination to drive the installation of energy efficiency improvements9, often referred to as measures10 . The Energy Act 2011 also made clear that the Green Deal may cover measures which generate renewable energy in a cost-effective way. For example, micro generation will use renewable sources of energy (such as the air, sun and ground heat) to generate energy and this ultimately results in fuel bill savings. Under the Green Deal households are always protected by the Golden Rule.11 There are 45 measures or areas of home approved to receive funding under the Green Deal, see Fig. 3.

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9 The term used in the Green Deal legal framework to describe the installation of a measure in a property.
10 Generic energy efficiency improvements which can be made to a property, for example, loft insulation, cavity wall insulation or a replacement boiler.
11 The Golden Rule means the charge attached to the energy meter in a property cannot be higher than the estimated savings for the package of measures in that property.
Fig. 3 Modelling the upgrade and technology options.
This paper groups those measures in seven functional categories, for modelling purposes, covering improvements in (i) the building fabric; (ii) space heating; (iii) electric; (iv) water heating; (v) community heating- CHP; (vi) heat from the earth, the air and newly dead biological matter burn in a boiler, and (vii) micro generation as shown in Fig. 3, and also included a change in the proportion in user behaviour and electric lightning in time as measures.

4. Results

This section shows energy data for repeated property types as a skewed distribution. Then, for comparative purposes, it is preferable to provide additionally to the mean and the median: (i) two outer centiles, such as the tenth and 90th; (ii) the first and third quartiles (25th and 75th centiles) that define the interquartile range, and (iii) the range of the sample, usually the fifth centile and the 95th centile, which is called the reference range 5%-95%, and is the difference between the two most extreme values. As an example, Fig. 4 shows the colour and shape pattern to a skew distribution.

Fig. 4 Skew distribution legend.

Fig. 5 shows the skewed distributions in NEED on the left and NCRF on the right for two bungalow samples. Fig. 5 shows a decrease in heating gas consumption as the floor area becomes smaller for both NEED and NCRM.

Fig. 5 Skewed distributions for NCRF and NEED bungalow samples.

Fig. 6 shows the skewed distributions in NEED on the left and NCRF on the right for end-terraced properties.
We argue that the microclimate is likely to have affected the Castle results due to vegetation, which in urban areas plays a significant role in regulating the urban climate. It is an effective measure to create an “oasis effect” and mitigate urban warming at micro levels. Additionally, when vegetation is arranged throughout a city in the form of urban parks, the energy balance of the whole city can be modified through adding more evaporating surfaces by providing sources of moisture for evapotranspiration and more absorbed radiation can be dissipated in the form of latent heat rather than sensible heat [46]. Urban parks can extend the positive effects to the surrounding built environment.

Yu and Hien [46] argue that there are at least three ways to study the role of green areas in moderating an urban climate: (i) studies focused on surface temperature through the use of airborne or satellite thermal infrared remote sensors in, for example, the work of Yuan and Bauer [47], (ii) studies focused on in-depth field measurements at micro-level, and (iii) studies focused on numerical calculation to predict the thermal benefits of green areas in cities. This study uses the thermal infrared remote sensing method because the Newcastle City Council (NCC) has a thermal image available.

The thermal image was taken on Tuesday 2nd and Wednesday 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) [48].

The neighbourhood chosen for the microclimate quantification is Kingston Metro (Castle LL SOA 8294). Kingston Metro is 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 LL SOA has a plot ratio equal to 0.3, see Fig. 7.

Fig. 6 Skewed distributions for NCRF and NEED end-terraced samples.
Fig. 7 Heat loss profile for every building in Castle LLSOA 8294.
Map (a) represents a land cover raster image from Google Earth™, map (b) represents the OS MasterMap™ 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.

5. Discussion

Most physical energy models in the United Kingdom do not take into account the surface temperature; however, at the scale of the individual buildings detailed models exist, such as EnergyPlus™. Urban microclimate effects on energy demand were analysed by Yang, Zhao [49], who used an urban microclimate model and the building energy software EnergyPlus™ [50]. These models have to be supplied with suitable boundary conditions, which represent the urban microclimate. However, for this study, in order to consider interactions between energy demand, surface temperature, vegetation and the local urban microclimate, more complex tools are needed. The interactions between buildings and the landscape in low density Castle presumably create a real increase in energy consumption because there is an increase in the mean daily heat output from the heating system due to smaller increases in the outdoor air temperature due to heat island effects. One possible way to improve the weather data would be to spatially merge local area-based data with detailed weather data that is readily available. Urban microclimate is a key element during the design stages of sustainable and comfortable urban spaces, although the physics underlying the interaction of urban microclimate with buildings is complex to model.

Our energy estimation results does not consider the inter-building effect created by surrounding buildings. The energy consumption is underestimated in aggregated buildings because of the reduced solar radiance. However, this effect is complex and requires the modelling of a network of buildings. The Castle case study shows that the LLSOAs energy consumption may have modelling inaccuracies created by the nearby buildings. Physical building models would need detailed topological information (as provided by NCRM) in order to model inter-building effects effectively. For densifying urban environments, this is likely to be a relatively significant effect. Specifically, the role of inter-building effects must be examined as a number of researchers have suggested (e.g. Pisello, Taylor [51], Bueno, Norford [52], Yang, Zhao [49]). Also, urban form from the point of view of environmental performance in cities as addressed in Adolphe [53]; and, energy use and density as the results of Steemers [54] seem to suggest.

Finally, the cluster energy method is a process that suggests that the cluster size and composition not only reflect the energy efficiency of the Newcastle stock, but what was encouraging, the potential impact of applying certain retrofitting measures is possible. What was good from the cluster model district results is that they enable us to model aggregate energy consumption using a reduced number of variables. Also, in cities the scale problem arises when spatial data are aggregated into successively larger areal units. The detailed micro-simulation 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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