

# URBAN MODELLING FOR RESOURCE PERFORMANCE ANALYSIS: ESTIMATING CITIES' RENEWABLE ENERGY POTENTIAL

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## ABSTRACT

A preliminary methodology based on the urban metabolism approach (Fernández, 2007) is developed to explore the relationships between urban configuration and some measures of urban sustainability. The goal of this study is to establish a standardised method for the analysis of urban resource performance that can be applied to different cities around the world. For this, physical descriptors of urban morphology are combined with land-use variables, to identify representative typologies of urban clusters. Subsequently, the resource performance of each typology is evaluated in terms of material intensity, energy demand, and, what is the focus of this paper, renewable energy potential. The preliminary findings of two case studies suggest that there is a strong inverse relationship between building density and the renewable energy potential of cities.

## INTRODUCTION

This paper presents the methodology and preliminary results from case studies used in an on-going research project, with a specific focus on the estimation of renewable energy potential within cities.

### **Analysing renewable energy potential (REP)**

The rapidly increasing world urban population predicted for the next decades (United Nations, 2009), and its related urban growth, suggest that cities will continue to become even more energy intensive than they are today. Furthermore, the finite nature of fossil fuels and their impacts on climate change pose a major challenge; a shift towards cleaner and renewable energy resources is now becoming imperative. Currently, most of our renewable energy is produced in high capacity, large-scale plants located outside cities. However, urban expansion and the need for more agricultural land to provide food for city-dwellers are likely to raise the pressure on freely available land. Thus, generation of renewable energy within the city boundaries is expected to increasingly grow in the coming decades, as the energy from fossil fuels becomes scarcer and more expensive (MacKay, 2009).

It is well established that the most efficient ways for supplying energy (in the form of electricity, heating or cooling), are those that minimise the distance between production point and end-user (Abu-Sarkh et al., 2006). Thus, distributed energy resources (DER) across a city are an efficient way of supplying energy for the built environment, and will be a crucial part of the EU efforts towards supplying 20% of the final energy consumption from renewable sources by 2020 (European Renewable Energy Council, 2008). In order to achieve this goal, different renewable energy resources – such as solar, wind, geothermal, environmental heat, and biomass – can be exploited within the city (Barret, 2009). However, the implementation of renewable energy technologies (RET) involves various requirements and constraints, such as specific spatial and land-use characteristics or microclimatic conditions (Yamaguchi et al., 2008; Yun and Steemers, 2009; and Cheng et al., 2006). Consequently, in order to take advantage of cities' renewable energy resources, it is important to understand how the urban configuration can facilitate or hinder the viability of different RET to be implemented.

Previous research has focused on analysing REP from an engineering- and technology-centred perspective, as well as on the optimisation of specific technologies at the building level. However, little work has been done on the integration of different renewable energy resources at the urban scale, from the perspective of urban planning and design. By performing this analysis at an aggregated level, it is easy to compare the REP across neighbourhoods in a city, and cities across the world, which can be helpful during planning and investment decision-making processes.

### **Objectives and expected outcomes**

The general objective of this project is to help improve urban environmental sustainability, by gaining a deeper understanding on how resources can be used most efficiently within an urban context. By developing a replicable method for the analysis of urban REP, this approach can be applied to different cities and neighbourhoods around the world. Using case studies from major UK cities such as London and Manchester, the long-term expected outcomes of the project are manifold: (1) to understand how

various RET may compete for urban space, and how they can be best integrated; (2) to estimate the REP of existing cities or neighbourhoods; (3) to develop a method for citywide REP mapping that can be used for diagnosis and design of existing and novel urban developments; and (4) to assess possible policy interventions for urban REP improvement.

## METHODOLOGY

With a top-down approach, a spatially explicit, standardised, and replicable method based on case studies is developed. The proposed methodology relies on spatial data that describes the urban fabric and that is available for many different regions throughout the world.

The work is organised in two steps, as illustrated in Figure 1. In the first step, spatial and empirical geo-referenced data is analysed using Geographical Information System (GIS) to establish a method for characterising typical urban configurations within the city. According to shared aggregated descriptors of urban form, the city is organised into various groups of neighbourhoods with similar urban configuration. Each group, or ‘urban cluster’, represents typical characteristics of zones with relatively homogeneous urban texture and provides detailed information that can be used for further analysis.

In the second step of the methodology, the relationship between urban configuration and resource performance is investigated using the urban clusters previously identified. For this, urban configuration is described as the combination of urban morphology and land-use, while resource performance is measured using three main criteria: (1) material intensity of buildings and urban infrastructure, (2) energy demand of buildings and transportation, and (3) the potential for renewable energy generation within the city boundaries.

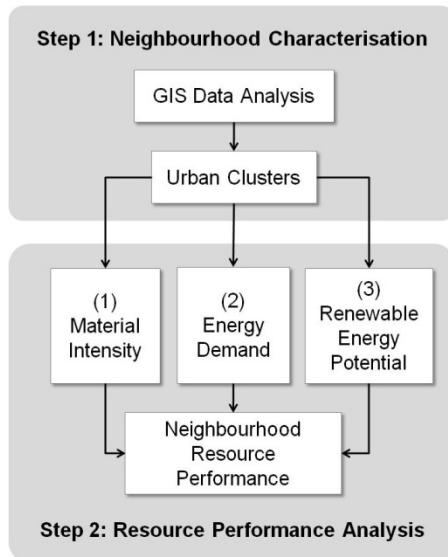


Figure 1 Steps of analysis

### Step one: neighbourhood characterisation

The characterisation process helps improving the understanding of cities’ morphology by identifying homogenous neighbourhood types and isolating their main shared physical characteristics. In this process, the first step is to determine a systematic method for characterising urban configuration at the neighbourhood scale. This is done using urban modelling and GIS to extract simplified parameters that are representative of the various urban typologies existing in the city. The objective is to explore how these physical descriptors can be related to resource performance. With a top-down approach, the aggregated parameters used reflect different aspects of urban configuration, such as the average size of buildings and the space between them, which can be in the form of public or private green areas, public spaces, and roads. The specific parameters utilised in the clustering process are detailed later, together with the description of case studies. The data clustering process is carried out using the  $k$ -means algorithm for cluster analysis. This method works by partitioning a data set of  $n$  observations  $(\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n)$ , where each observation is a  $d$ -dimensional real vector, into  $k$  number of clusters or sets ( $k \leq n$ )  $\mathbf{S} = \{S_1, S_2, \dots, S_k\}$ , where  $k$  is chosen based on graphical observation. Accordingly, each observation will become part of the cluster with the nearest mean, so that the within-cluster sum of squares (WCSS) is minimised:

$$\arg \min_{\mathbf{S}} \sum_{i=1}^k \sum_{\mathbf{x}_j \in S_i} \|\mathbf{x}_j - \boldsymbol{\mu}_i\|^2$$

where  $\boldsymbol{\mu}_i$  is the mean of points in  $S_i$ .

The software used for the clustering analysis is R, with the package Stats. The implementation of  $k$ -means is the default MacQueen implantation, which works by iteratively partitioning the data until it reaches convergence (MacQueen, 1967).

### Step two: resource performance analysis

The methodology of analysis and preliminary results for (1) and (2) in Figure 1 are out of the scope of this paper and presented elsewhere (Quinn, Wiesmann and Sarralde, 2011). The focus of this paper is on (3). The specific methodology for REP analysis is organised in three stages, as presented in Figure 2. In the first stage (a), reported in this paper, a city-level and top-down approach is used to estimate the REP of cities. For this, a variety of REP indexes are proposed according to the urban descriptors contained in the spatial data. These indexes are then calculated for the whole city and for each of the urban clusters identified in the neighbourhood characterisation process. In the next stage of research (b), this simple analysis will be followed by a bottom-up approach for the validation of results at the neighbourhood scale, using the Output Area (OA)

UK geographies as the smallest reference size for neighbourhood boundaries. For selected representative sample areas, an optimisation analysis will be conducted by contrasting empirical energy demand data with the net capacity for renewable energy generation. Furthermore, in the last stage of research (c), the results will be evaluated using regression modelling to establish relationships between REP and urban configuration. Finally, different urban design and policy scenarios for REP improvement will be tested, applying possible lessons learnt from the previous analyses.

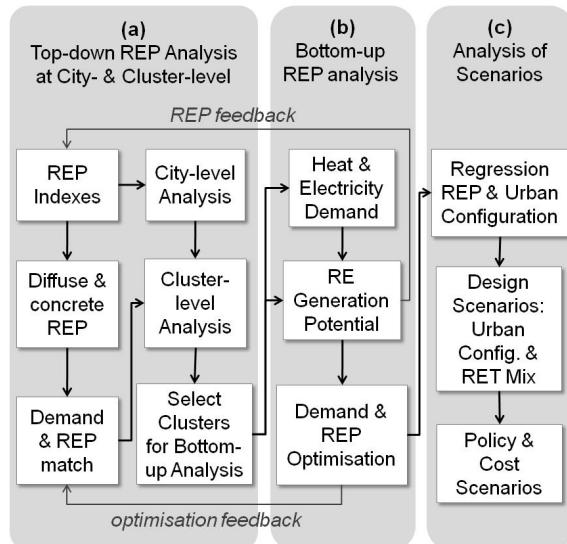


Figure 2 Methodology for REP analysis

### Calculation of REP indexes

The idea behind this mixed approach, inspired by previous research on City Renewable Energy Mapping (C-REM) for German cities (Genske, Porsche and Ruff, 2009), is to develop a simple and straightforward method to estimate urban REP, without the need of detailed data for building simulation or time intensive RET optimisation modelling at the building level. Based on general

relationships between urban form and REP, the intention of this analysis method is to serve as a helpful first-diagnosis aid for designers and decision-makers at the local authority level, rather than a predictive tool for designing renewable energy generation systems. This method should help to understand how different RET can be best integrated in the urban context (in the case of the existing building stock) and how urban form can be optimised to increase REP (in the first design stages of new developments).

In this study, the potential for different RET is independently evaluated and expressed with nine different REP indexes, using aggregated parameters of spatial descriptors, land-use, and energy demand data, as detailed in Table 1. Moreover, in order to simplify calculations, some significant assumptions are made. For example, for index i, the result is divided by two, assuming that roughly half of the facades will have suitable orientation. For index ii, flat roofs are assumed, and the standard deviation of building heights is used to determine the likelihood of overshadowing by surrounding buildings. For indexes v and vi, wind availability is estimated as the degree of openness of an area, and calculated as the ratio of open space to buildings' density and heights. Finally, for index vii, the REP is estimated in terms of the degree of land-use mixture (domestic and non-domestic buildings), assuming that a higher mixture is beneficial for the balance between generation and demand profiles.

Following the approach used by Genske et al. (2009), the *total REP index* for each area of analysis is calculated, and the different REP indexes are organised into *diffuse* and *concrete* RET options, as shown in Table 2. The *total REP index* is calculated as the sum of all the REP indexes estimated for an area. A limitation of this analysis is that, although the indexes are normalised by their maximum observation, they are evenly weighted. Hence, they do not reflect the energy generation capacity, nor the type of energy they can produce (electricity, heating or cooling).

Table 1 REP indexes with their corresponding formulae

Index	Formula (variables aggregated to MLSOA)
i. Façade Solar	$\text{total non-built area (incl. roads, green and public spaces)} [\text{m}^2] / (\text{average façade area } [\text{m}^2] / 2)$
ii. Roof Solar	$(\text{domestic buildings' roof area } [\text{m}^2] + \text{non-domestic buildings' roof area } [\text{m}^2]) / \text{standard deviation of building heights}$
iii. Domestic Shallow Ground Source Heat Pump (GSHP)	$\text{total private garden area } [\text{m}^2] / \text{number of households}$
iv. Water Source Heat Pump (WSHP)	$\text{total water surface area } [\text{m}^2] / \text{total area } [\text{m}^2]$
v. Meso-wind	$\text{total non-built area } [\text{m}^2] / \text{total area } [\text{m}^2]$
vi. Wind	$\text{public green area } [\text{m}^2] / (\text{total area } [\text{m}^2] / \text{average building height } [\text{m}])$
vii. Combined Heat and Power (CHP)	$(\text{total domestic energy demand (incl. electricity and gas)} [\text{kWh}] - \text{non-domestic energy demand } [\text{kWh}]) / \text{total energy demand } [\text{kWh}]$
viii. Biomass	$(\text{public green area } [\text{m}^2] + \text{total garden area } [\text{m}^2]) / \text{total area } [\text{m}^2]$
ix. CHP & Biomass Combined	$(\text{CHP index} / \max(\text{CHP index})) * (\text{biomass index} / \max(\text{biomass index}))$

This limitation is explained by the fact that, at this stage of research, microclimatic conditions are yet to be taken into account. Rather, the REP indexes introduced reflect the general degree of RET viability for a given area, purely based on urban configuration. The aim of classifying RET into *diffuse* and *concrete* options is to establish an order of priority in which they should be considered, depending on their spatial and material flow requirements. *Diffuse* RET refers to those technologies that once installed will not ‘block’ any urban space that could be used for other purposes (e.g. buildings or infrastructure, urban agriculture, etc.), and that will not require any further material flows for their functioning. Examples of *diffuse* RET are photovoltaic panels (PV) installed on roofs or façades, or meso-scale wind turbines installed on rooftops. On the other hand, *concrete* RET refers to those options that use extra urban space and/or generate material flows, such as biomass fuelled combined heat and power (CHP) systems or macro-scale wind turbines, which might require a non-built safety area around them.

Next, the *energy demand & REP match index* is introduced (Table 2) to establish how well the REP and the measured energy demand will match their geographical location within the city. This follows the concept that proximity between generation and end-user is beneficial for distributed energy resources (DER). Hence, the total energy demand loads (including domestic and non-domestic gas and electricity) are mapped against the total REP index for each area. It is important to emphasise that, at this stage, the matching of REP and energy demand only accounts for the spatial characteristics involved, such as space availability for installing RET and the location where energy is required. A neighbourhood level optimisation analysis for demand and generation will be performed in the next stage of research. Finally, with the aim of having a standardised way for analysing cities, all calculations are implemented in the form of scripts, which ensures the replicability of the method (using free and open-source software R and Python (see references).

*Table 2 Total REP index, diffuse and concrete RET*

Index	Variables
Total REP	All REP indexes
Diffuse RET	Façade Solar, Roof Solar, Meso-wind, WSHP
Concrete RET	Domestic Shallow GSHP, Wind, Biomass, CHP & Biomass Combined
Demand & REP match	Total energy demand, total REP

## CASE STUDIES

Thus far, the methodology described here has been applied to case studies of two major UK cities:

London and Manchester. The data used and the preliminary results are now presented.

### Data sources

The data utilised for this study is publicly available for academic research and is organised in two levels of aggregation, based on the UK Census geographies: the Middle Layer Super Output Area (MLSOA) and Lower Layer Super Output Area (LLSOA), with a mean population of ca. 7,200 people (minimum 5,000 people) and ca. 1,500 people (minimum 1,000 people) respectively. The datasets utilised as input data for the calculations of REP indexes are summarised in Table 3.

*Table 3 Data sources*

Data set	Data source
UK Census (2001), Generalised Land Use Database (GLUD) (2005)	<i>Neighbourhood Statistics:</i> <a href="http://www.neighbourhood.statistics.gov.uk/">http://www.neighbourhood.statistics.gov.uk/</a>
Ordnance Survey MasterMap: Building Heights & Footprints	<i>University of Edinburgh's EDINA, Digimap collections:</i> <a href="http://edina.ac.uk/">http://edina.ac.uk/</a>
DECC: Electricity and Gas Consumption (2008)	<i>Department of Energy and Climate Change (DECC):</i> <a href="http://www.decc.gov.uk/">http://www.decc.gov.uk/</a>

### Cases analysed

The analysis was performed for two cities, at two different levels each. For each case, the number of observations (spatial divisions) is shown in Table 4. In order to select the most representative descriptors of urban configuration to be used in the clustering process, the pairwise correlations of a wide range of parameters were plotted for each case. This was done to identify any possible collinearity between different descriptors and to examine their trends across all observations. Finally, five non-collinear descriptors were selected for the *k*-means clustering: *population density*, *percentage of detached houses*, *plot ratio*, *average green area per household*, and *average building envelope area*. For this study, the number of clusters to be identified was set to three, all using the same five clustering parameters.

*Table 4 Number of observations for each case*

Case Study	MLSOA	LLSOA
London	1159	5256
Manchester	323	1504

### Cluster observations

The clustering patterns observed in London and Manchester are, in general terms, arranged in three radial bands, as presented in Figure 3 (from the London MLSOA case). As such, despite it being a simplification of the city’s structure, they still reflect the decreasing density gradient that exists from the city centre towards the suburbs. Figure 4 illustrates

typical portions of these clusters for the case of London MSA. The image on the left reflects cluster 1, a typical suburban situation with low-density, low-rise semi-detached housing and extensive private green areas. In contrast, the central image shows cluster 2, a typical medium-density, mixed-use and mid-rise urban structure, with clear distinction between residential and high streets, and some semi-public green spaces in the block's interiors. Finally, the image on the right reflects cluster 3, a typical high-density city centre with a predominant non-domestic use, mid- to high-rise, densely built blocks, a scarce presence of green and public spaces, and narrow street canyons.

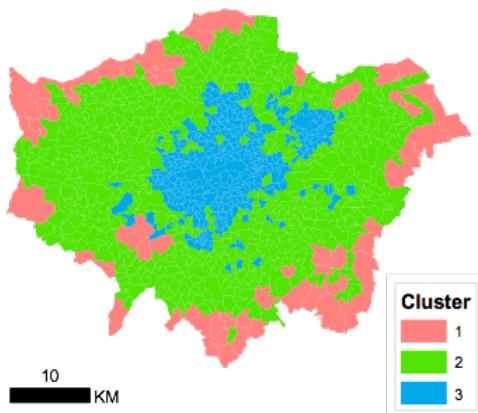


Figure 3 Clusters identified for London MSA

### Discussion of results

The preliminary results for the London and Manchester cases were consistent, presenting similar trends of REP indexes for each of the clusters observed. Hence, the results are illustrated using only the London MSA as a representative case.

Figure 5 shows the *total REP index* plotted against the three neighbourhood typology clusters previously identified. In Figure 6, these results are mapped to illustrate the heterogeneous distribution of the *total REP index* across the city. With the highest REP distributed along the edges of the city (matching cluster 1), and gradually decreasing towards the city centre (cluster 3), the location of each area relatively to the whole city structure seems to be an important factor. Since in London and Manchester, as in most

other European cities, building density increases from the suburbs towards the centre, it can be inferred from these results that lower building density is beneficial for REP. Higher building density means that less portions of land are freely available for installing RET. However, this may not necessarily mean that the final RE output will be lower, since it will depend on what types of RET can be installed. While high density can be detrimental for some types of RET, it can as well be beneficial for others. For example, a high-density area might not be optimal for installing wind turbines or domestic shallow GSHP, but it can be very good for the installation of building mounted PV, due to a larger proportion of envelope area. Although these results might indicate that some important trade-offs are involved in the assessment of building density and REP, there is clearly an inverse relationship between building density and the variety of RET that can be considered for any given type of neighbourhood. Following on this, Figures 7 and 8 respectively present the *diffuse* and *concrete REP index* for each cluster. Similarly as in the case of *total REP index*, in both cases the distribution goes gradually from highest in cluster 1, to lowest in cluster 3. Furthermore, when comparing both indexes for each cluster, it can be observed that the mean values for *concrete REP* options are in all cases higher than the ones for *diffuse REP*. This difference is especially high in the case of cluster 1, where the *concrete REP index* is a factor of two higher than the *diffuse REP index*, which is probably due to the higher spatial requirements related to most of the concrete options. On the other hand, *diffuse* options will be generally more viable in clusters of the type 3, where the lack of freely available space will make the use of existing façades, roofs and water streams a more attractive alternative.

Another element analysed was the actual energy demand of each MSA, in order to establish the ratio to which the location of high demand corresponds with the location of high REP, and vice-versa. The driver of this analysis was to identify zones of the city where the demand would be more likely to be supplied locally (and therefore more efficiently), as well as zones that might be over- and under-supplied. Figure 9 shows the distribution of the *demand & REP match index* across the city.



Figure 4 Examples from clusters for London MSA: left: cluster 1, centre: cluster 2, and right: cluster 3

Although with less variation between clusters than the previous indexes analysed, the results for *demand & REP match index* show the same trend as observed before, where cluster 1 (suburban low-density) has the highest values. However, the distribution of the index across the city does not follow the pattern of radial bands previously identified. Instead, a scattered pattern is observed, with some high value areas distributed in all clusters, including the very centre of the city, in cluster 3.

There are different possible interpretations for this result. One possible reason for high value areas around the edges of the city is that industry, which is associated to high levels of energy demand, is often located between residential suburban areas, which in turn have higher *total REP indexes*. On the other hand, a reason for high match in the city centre can be explained by the presence of mixed land-use patterns, such as buildings with domestic and office spaces, which have a lower energy demand (relatively to industry, for example) and match well with relatively low *total REP indexes*.

Nonetheless, from the analysis of these results it can be established that, in some cases, cities are more likely to be energetically self-supporting in the suburban neighbourhoods than in the city centre. This is clear from Figures 10 and 11, which respectively illustrate some mismatch between the location of London's highest total energy demand areas and the areas with highest *total REP indexes*.

However, it should be said that the idea of energetically self-supported suburbia is more likely to be possible when only considering the energy consumption related to buildings. As it is well established, low-density suburban areas tend to be linked to higher energy consumption levels for transportation than compact cities, which is another important trade-off to be considered for the assessment and planning of energy efficient urban developments.

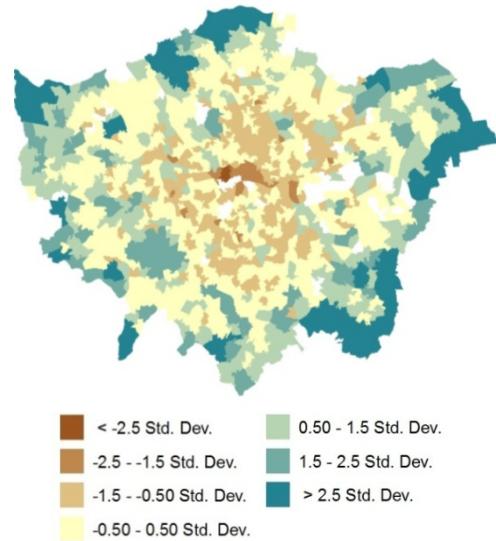


Figure 6 Total REP index (standard deviation, London MSA)

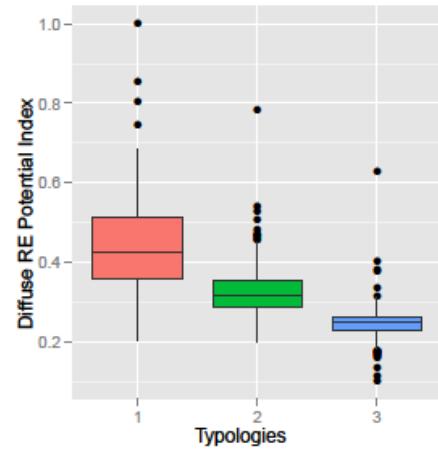


Figure 7 Diffuse REP index per urban cluster (London MSA)

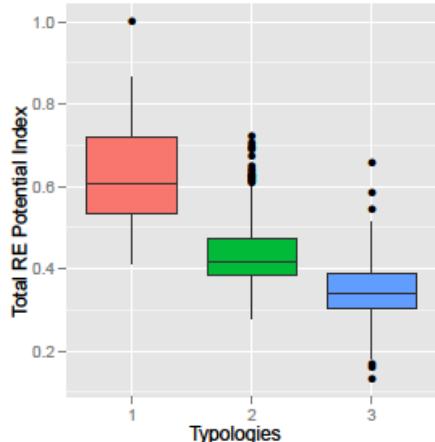


Figure 5 Total REP index per urban cluster (London MSA)

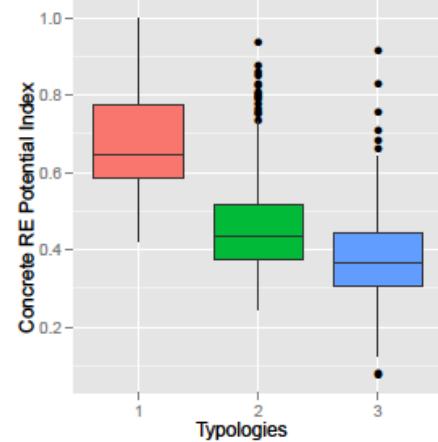


Figure 8 Concrete REP index per urban cluster (London MSA)

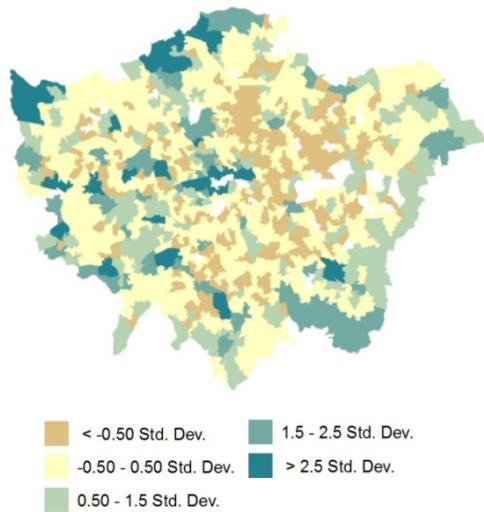


Figure 9 Demand & REP match index (standard deviation, London MSAOA)

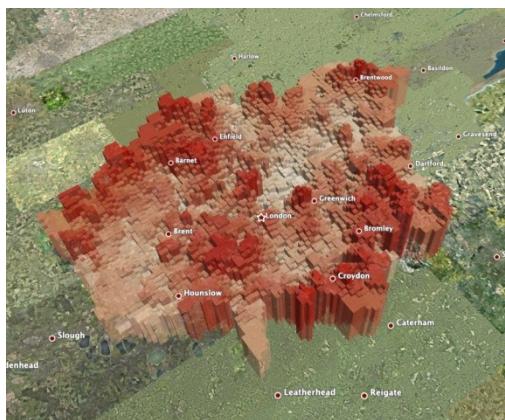


Figure 10 Total energy demand for London MSAOA



Figure 11 Total REP index for London MSAOA

Another factor to consider is that, although some suburban areas might be able to produce enough energy for their own demand, this may not be the case for the whole city. In some cases, it will be necessary to ‘import’ energy into the city centre or into highly populated areas, where the REP is too

low to meet the energy demand. This is illustrated through Figure 14, which shows a strong inverse relationship between REP and population density. These results are well in line with previous research by Barret (2009), who showed that the potential for the energy demand to be met by a city’s solar resources decreases with an increased proximity to the city centre. Those findings are supported by this research (Figure 12), which shows the relationship between total energy demand and plot ratio for all of London’s samples, and Figure 13, which illustrates the relationship between *total REP index* and plot ratio (hence expanding Barret’s results to a variety of RET, rather than only solar resources). For this analysis, plot ratio is used as a measure of aggregated building density, expressed as the buildings’ total floor area (including all levels of all buildings in a MSAOA) divided by the area of the site, which in this case is calculated as the surface of the whole MSAOA. As plot ratio increases, so too does population density and hence the total energy demand. However, in the case of *total REP index* the opposite happens, where REP decreases as the plot ratio increases.

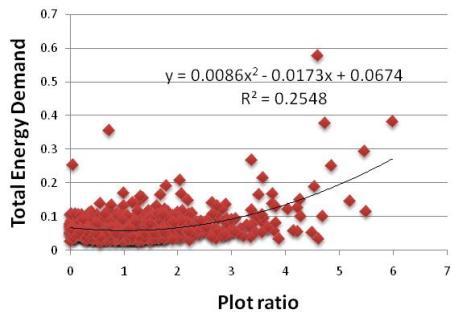


Figure 12 Total energy demand vs. plot ratio

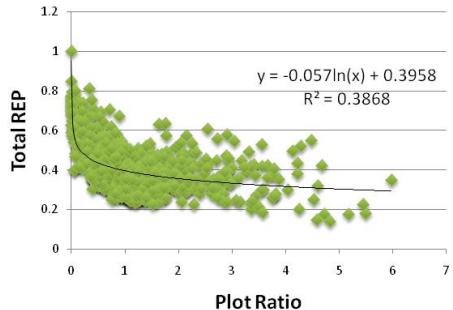


Figure 13 Total REP index vs. plot ratio

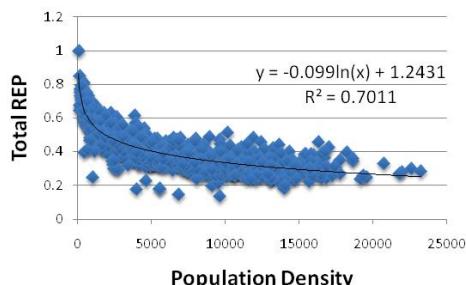


Figure 14 Total REP index vs. population density

## **CONCLUSIONS**

A new methodology for assessing cities' resource performance from an urban metabolism perspective has been introduced and partially tested using the UK cities of London and Manchester as case studies. The specific methodology presented in this paper has led to preliminary findings that show a consistent relationship between urban configuration and the renewable energy potential of cities. Furthermore, the utilisation of renewable energy potential indexes, based on parameters for describing urban configuration, has helped to identify zones of high and low potential for renewable energy implementation within a city. So far, this method has shown to be effective as a simple way for analysing resource performance of cities at an aggregated level, reducing the need for complicated and time intensive building simulation methods at a first stage of diagnosis. However, at this point, this method is not intended to be used for detailed and predictive planning of energy generation strategies, and the results have yet to be validated with a bottom-up neighbourhood level analysis in order to establish their level of accuracy.

Nevertheless, the findings on the relationship between building density and REP are especially significant, adding to the current discussion on the benefits and disadvantages of planning a compact city versus green suburbia, in the search for increasing the energy efficiency of cities.

## **FURTHER RESEARCH**

At the current stage of the study, priority was given to achieve a first complete iteration of the proposed work process and to test the general structure of a new methodology. The REP analysis will be brought into a second phase, in which a bottom-up approach will be used for testing and validating the assumptions made in the first phase. This will be done using simplified calculations and heuristic rules (when possible), drawn from calculations used in commercial software such as RETScreen and CitySim.

## **ACKNOWLEDGEMENTS**

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