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Urban heat and residential electricity consumption: A preliminary study

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ABSTRACT

The Urban Heat Island (UHI) is a well-documented phenomenon occurring in cities across the world resulting in city centres often being several degrees warmer than their surroundings. This local elevation in temperatures could potentially impact upon local energy consumption, with residents in the warmer central section of the city using more energy to cool their homes in summer and less energy to warm them in winter. This study uses a combination of Geographical Information System techniques and Remote Sensing data (MODIS LST and NDVI), as a preliminary investigation, to assess the spatial relationship between UHI, urban greenspace, household income and electricity consumption in Birmingham, UK. It provides simple and repeatable steps, based on freely available datasets, for urban planners, industry, human and physical geographers, and non-specialists to reproduce the analyses. The results show that, the present impact of the UHI is limited and instead highlights the dominance of household income over local climate in explaining consumption patterns across Birmingham.

1. Introduction

Energy demand in urban areas is an important facet of energy supply planning. In particular, increasing energy consumption by the residential sector is an issue that could endanger broader economic development since in itself it does not generate wealth and could limit the amount of energy available for other productive sectors (Pereira & Assis, 2013). The electricity consumption by sectors in the UK can be observed in Fig. 1, domestic consumption has maintained itself as the larger consuming sector almost throughout the whole period from 1965 to 2013.

Household size, income, building design characteristics and local climatic conditions are all key factors in determining residential energy consumption (Santamouris et al. 2007). Generally, small households need less energy due to a reduced transfer area, but they also have lower occupancy, and therefore, fewer appliances when compared with larger households (Pérez-Lombard, Ortiz, & Pout, 2008). Similarly, household income is an important factor, with a strong correlation evident between daily electricity consumption and earnings (Ghisi, Gosch, & Lamberts, 2007). This pattern is evident spatially, where areas with higher average per capita income consume considerably more energy; a direct result of the relationship between energy consumption and the purchasing power of families (Pereira & Assis, 2013).

With respect to climatic factors, the Urban Heat Island (UHI) is a potentially important localised phenomenon to take into account when assessing consumption in cities. The UHI is described as the difference in temperature between an urban area and the surrounding rural area of the conurbation. It is mainly caused by anthropogenic changes to the environment with a range of factors contributing such as urban geometry, density/population of a conurbation, replacement of vegetation cover by construction material (e.g. asphalt and concrete), changing surface's albedo and emissivity thus reducing evapotranspiration and increased emissions of anthropogenic heat (Oke, 1987). The overall result is that cities are generally warmer than their rural surroundings, reaching a maximum under “ideal” conditions (e.g., clear skies and light winds). For small cities, the effect can be minimal, for example, differences of 1 °C in Ljutomer, Slovenia (Ivajnšič, Kaligarič, & Žiberna, 2014) where as differences of more than 7 °C are not uncommon for large cities (e.g. Paris, France: (Lac et al. 2013). The subtle changes in temperature caused by UHI can impact on many aspects of everyday life, such as critical infrastructure (Chapman, Azevedo, & Prieto-Lopez, 2013), health (Tomlinson, Chapman, Thornes, & Baker, 2011) and energy consumption (Santamouris

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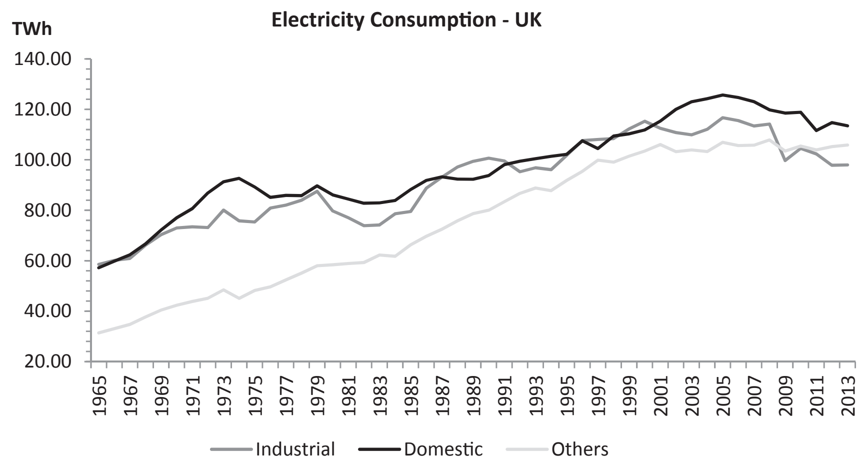

Fig. 1. Electricity consumption in the UK by sector. Others: Public administration, transport, agricultural and commercial sectors.

et al. 2001), with such impacts becoming exacerbated under heatwave events. It is hypothesised that the UHI should have a direct impact on energy consumption, particularly in the warmer core of the city (Akbari, Pomerantz, & Taha 2001; Hassid et al. 2000; Kolokotroni, Davies, Croxford, Bhuiyan, & Mavrogianni, 2010; Taha, Akbari, Rosenfeld, & Huang, 1988) where higher energy loads will be required for cooling in summer, and in winter consumption will reduce for heating. For example, in centrally located buildings in Athens (Greece), where the average UHI can exceed 10 °C, cooling loads can double in summer, whereas winter period heating loads can decrease by 30% (Santamouris et al. 2001). Therefore, by not considering the UHI, energy consumption and peak power should be significantly underestimated (Hassid et al. 2000).

Green spaces are a widely adopted strategy to mitigate UHI intensity (Lambert-Habib, Hidalgo, Fedele, Lemonsu, & Bernard, 2013) since they reduce urban temperatures thorough evapotranspiration and shadowing. In modelling experiments carried out for Manchester, UK, it was found that a 5% increase in mature deciduous trees can reduce average hourly surface temperatures by 1 °C during summer (Skelhorn, Lindley, & Levermore, 2014). For example, the highest cooling loads in Athens are seen in the western area of the city where there is limited greenspace (Santamouris et al. 2001). In Manchester, it is proposed that if all vegetation was replaced with asphalt, then air temperature would increase by up to 3.2 °C at midday (Skelhorn, Lindley, & Levermore, 2014). Similarly, it was found in the USA that for an increase of 25% of tree cover in urban areas can result in a 40% annual residential cooling energy savings in Sacramento and 25% in Phoenix and Lake Charles (Huang, Akbari, Taha, & Rosenfeld, 1987).

The UHI can be largely subdivided into three different types: the surface UHI, the canopy UHI (i.e. 2 m) and the boundary layer UHI (Azevedo, Chapman, & Muller, 2016). Air temperature measurements are used to quantify both the canopy and boundary UHI, whereas land surface temperature (LST) is used for the surface UHI. Traditional ways in which canopy UHI are measured include station pairs (e.g. Wilby, 2003) or the use of transects (e.g. Smith, Webb, Levermore, Lindley, & Beswick, 2011). However, these usually have limited spatial (Muller, Chapman, Grimmond, Young, & Cai, 2013; Smith et al. 2011) and temporal resolution, and therefore there has been an ongoing challenge to quantify the intensity and spatial extent of the canopy UHI.

Due to the wide spatial coverage and availability of data, thermal remote sensing is one of the most popular techniques used for the evaluation of UHI (Azevedo, Chapman, & Muller, 2016; Dousset, 1989; Dousset, Laaidi, & Zeghnoun, 2011; Keramitsoglou, Kiranoudis, Ceriola, Weng, & Rajasekar, 2011; Roth, Oke, & Emery, 1989; Smith et al. 2011; Schwarz, Lautenbach, & Seppelt, 2011; Tomlinson, Chapman, Thornes, & Baker, 2012; Weng, Lu, & Schubring, 2004; Yuan & Bauer, 2007). The main advantage is that remote sensing provides a consistent, repeatable methodology for the end-user (Tomlinson et al. 2011). However, thermal remote sensing observes LST which restricts studies to just the surface UHI. Although LST plays a major role in urban climatological processes as surface temperature modulates the air temperature of the urban canopy layer, and therefore influences the internal climate of buildings and general thermal comfort (Voogt & Oke, 2003), it can only provide an indication of air temperatures and therefore the canopy UHI. Furthermore, remote sensing isn't ideal to evaluate the UHI in small cities, since the spatial resolution of the sensor can often be to coarse (Ivajnšič, Kaligarič, & Žiberna, 2014).

Vegetation abundance is an influential factor controlling UHI (Weng, Lu, & Schubring, 2004) and the Normalized Differenced Vegetation Index (NDVI) is often used to approximate vegetation abundance. The connection between NDVI and LST has been well established in studies, and a negative relationship between NDVI and LST has been shown and proven to be seasonally variable (e.g.Yuan & Bauer, 2007). Other studies which have included energy consumption data in the analysis (Akbari, Pomerantz & Taha, 2001, Huang et al. 1987), but no study has yet investigated all these factors along with income and socioeconomic data at the same temporal and spatial resolution (e.g. Pereira & Assis, 2013; Santamouris et al. 2007). Hence, this article aims to combine energy and income data with LST and NDVI data to assess the relationship between income, UHI,[1] vegetation and residential electricity consumption in Birmingham, UK. It also focuses on simple and repeatable steps, based on freely available datasets. The results could be used to inform current residential electricity consumption modelling due to the UHI effect.

2. Study area

Birmingham is the second largest urban area in the UK with an estimated population of over 1 million people (Birmingham City Council, 2014). It is a post-industrial city with a distinct range of land use zones (e.g. the central business district, eastern industrial areas with the majority of residential areas straddling this belt of

[1] Since LST data is being analysed, only surface UHI is being addressed, however the general term UHI will be used.