Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 122 (2017) 493–498

Energy Procedia

www.elsevier.com/locate/procedia

CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale, CISBAT 2017 6-8 September 2017, Lausanne, Switzerland

All the way to the top! The energy implications of building tall cities

Ian Hamilton[a]*, Stephen Evans[a], Philip Steadman[a], Daniel Godoy-Shimizu[a], Michael Donn[b], Homeira Shayesteh[a] and Graciela Moreno[a]

[a]*UCL Energy Institute, Unversity College London, 14 Upper Woburn Place, London WC1H 0NN, UK*
[b]*University of Victoria, Wellington 6140, NZ*

Abstract

Density of urban form may be achieved under a variety of morphological designs that do not rely on tallness alone. Tall buildings have implications on the broader urban environment and infrastructure that lower buildings would not have, e.g. wind effects, sight-lines, or over-shading. They may also have an impact on energy use for reasons of buildings-physics, construction, and occupant practices. This study uses a statistical approach of neighbourhood level data to analyse the impact of building morphology (e.g. height, volume and density) on energy demand in 12 local authorities in London. The research shows that areas marked by tall buildings use more gas after adjusting for exposures surface area, volume, number of residents and other features. The implication for energy policy and planning is building taller without increasing density may have an energy penalty.

Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale

Keywords: Type your keywords here, separated by semicolons ;

* Corresponding author. Tel.: +44-203-108-5982.
E-mail address: i.hamilton@ucl.ac.uk

1876-6102
Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale
10.1016/j.egypro.2017.07.302

1. Introduction

At the extreme, achieving a high urban density relies on buildings being closer together and taller. However, while tall buildings may be a necessity in areas of highly constrained land availability (e.g. Hong Kong or Manhattan), they are often also driven for other reasons such as prestige, profit motivation, economics of productivity and creativity among others. However, tall buildings by themselves are not necessary to increase density in most cities. Instead, density of urban form may be achieved under a variety of morphological designs that do not rely on tallness alone [1]. Many cities have restrictions on over-shading, massing, street setbacks, and sightlines that impact on the height of building form or its development location. London, for example, has all of these requirements and has led select areas of the city to experience high-rise growth. In London's case, there are cultural and visual sensitivities to tall buildings that have prioritized the creation of a skyline aesthetic where such buildings are 'deemed to be appropriate' but is recognized that tall buildings would not necessarily prevent suburban sprawl nor achieve higher densities than those of mid- or low-rise development [2].

Tall buildings have implications on the broader urban environment and infrastructure that lower buildings would not have, e.g. wind effects, sight-lines, or over-shading.[3,4] Several older cities around the world have experienced intense development overtop aging infrastructure that have meant significant investment is needed to maintain service and minimize the impact of increasing density and building height. They may also have an impact on energy use due to reasons of building-physics (e.g. wind exposure, temperature differences, unobstructed solar gains), infrastructure and construction (e.g. ventilation methods, heating system types), and occupant practices (e.g. window opening, lighting). There are also challenges around the embodied energy of building taller with the addition of more floors relating to higher embodied energy compared with lower buildings [5,6].

From a city level energy performance perspective, what might the impact of building height, at equivalent levels of density, have on energy demand? A recent study for London found that there was a positive relationship between energy demand in non-residential buildings and building plan depth, with areas characterized by deeper plan buildings using more electricity [7]. However, the study did not look at height of buildings for equivalent densities.

In this study we focus on London, which is an example of city with considerable growth pressures (estimated 10 million people by 2036)[8], has an urban form with a range of building heights, and is characterized by areas with considerable variation in urban density. London offers an interesting setting to examine the relationship between urban density and energy demand. In this study, we focus on the following research questions:

- How does building height vary across London?
- How does energy demand vary in areas characterized by different building heights?
- Do areas with taller buildings use more / less energy than areas characterized with less-tall buildings?
- What neighbourhood-level built environment factors affect energy demand in areas of tall / less-tall buildings?

2. Method

To address the above questions, an ecological study design is used to determine the variation in residential building height at the neighbourhood level and any association between indicators/measures of building tallness and energy demand. 12 local authorities in Greater London are used to examine the association between density and energy demand using data compiled on urban morphology, energy use and socio-economic features. They are Camden, City of London, Hackney, Hammersmith and Fulham, Islington, Kensington and Chelsea, Lambeth, Lewisham, Southwark, Tower Hamlets, Wandsworth, and Westminster. The study focuses on residential dwellings due to the constraints of available non-residential energy and socio-economic data. The study uses the lower super output area (LSOA) as the unit of analysis. An LSOA is a statistical geographic unit of analysis typically comprising an average of 650 households and 1500 people and is designed for both spatial compactness and social homogeneity. In this research, LSOA and 'neighbourhood' are used inter-changeably.

The study methods included:

- Calculating building height and density using detailed LiDAR data for all buildings within the study area;
- Classifying the height and density of the buildings in the local authorities to create a morphological description;

- Constructing a database of neighbourhood (LSOA) level information on building density and height, energy data, and characteristics of the buildings, occupants, and other land uses;
- Developing and testing neighbourhood level models to determine what urban features explain energy demand.

2.1. Data

The morphology data and its connection to 'buildings' used the 3DStock model of London [9]. 3DStock provides a simplified description (though with a resolution of 1m by 1m) of the 3D geometry of all buildings within the selected Local Authorities. A building within 3DStock is described using the 'Self Contained Unit' (SCU) [10]. From a morphology and energy perspective, a SCU is: 1) physically distinguishable; 2) bounded by a single building envelope; 3) having consistent properties, and 4) does not break up a premises. [10]

To create a 3-dimensional representation of the SCUs in the selected London local authorities, total height was obtained from the Environment Agency airborne Light Detection And Ranging (LiDAR) data to calculate the average height and the volume of a building footprint polygon [11]. Using these data 3DStock was used to create a prismatic block with a consistent plan shape, area and height. 3DStock provided an area and average height value for each SCU in the selected local authorities. These values were used to characterize the building (SCU) height and density for all the neighbourhoods (LSOAs) in the study area – described below.

The neighbourhood statistics data were drawn from the Office of National Statistics (ONS) Neighbourhood Statistics database. Table 1 summarizes the data used in this study to describe the non-morphological building and built form features, along with the socio-economic characteristics for the study neighbourhoods.

Table 1. Neighbourhood (LSOA) data accessed for the study.

Data	Description	Source	Period
Accommodation type	Number of households by the dwelling type (Whole House or Bungalow, Detached, Semi-detached, Terraced, Flat / Maisonette, Purpose-Built Block of Flats, Converted Flat, Mixed use Flat, Other, Shared Dwelling)	ONS - Census	2011
People	Number of residents by dwelling type	ONS - Census	2011
Heating systems	Number of dwellings by heating system type (None, Gas, Electric, Oil, Solid Fuel, Other, Two or More Types)	ONS - Census	2011
Energy	Counts, sum and average of domestic electricity and gas use	ONS - Census	2011
Population Density	Number of residents per hectare	ONS - Census	2011

2.2. Analysis

The morphology (i.e. area, height, volume, number of floors) for all the SCUs for each LSOA was characterized using the 3DStock SCU data. Summary statistics for all the SCUs within an LSOA were calculated and used in the subsequent regression modelling. The summary SCU statistics for each LSOA were then linked to their corresponding neighbourhood statistic data. For each LSOA, the energy data provides a measure of the total gas and electricity consumed (MWh/year) in the area and the mean of all the meters (kWh/meter/year). The analysis used stepwise linear regression modelling by a classification of neighbourhood tallness (i.e. total number of floors) to determine which variables were significant in predicting neighbourhood level gas use.

3. Results

Table 2 shows the variation in morphological features (footprint area, volume, estimated floor count, and height) of the individual SCUs classed as being domestic within the selected local authorities. The SCU morphology extremes are found within the denser central areas of London, i.e. the City of London, Camden, and Tower Hamlets (the location of Canary Wharf). The maximum height of a domestic classed SCU is 93m or approximately 31 storeys in the City of London. Figure 1a shows that the distribution of floor counts is widest within the City of London, Westminster and Southwark, areas that are marked by both large purpose-built blocks of flats (apartment buildings) built by the local authorities in the 1960's and 1970's and more recent residential and mixed use tower developments. Figure 1b shows a similar distribution of total neighbourhood level (LSOA) gas and electricity demand (MWh/year) across the local authorities, apart from the City of London which only has 4 LSOAs.

Table 2. Summary statistics of footprint area, volume and external exposed surface area for all domestic classified SCUs within the selected London local authorities

		All SCUs in Selected London Local Authorities											
		SCU footprint (m2)			SCU volume (m3)			SCU floor count (N)			SCU height (m)		
Local Authority	N	Mean	Std	Max	Mean	Std	Max*	Mean	Std	Max	Mean	Std	Max
Camden	24,938	139	516	53,465	1575	14,498	2,066,835	3	1	20	10	3	60
City of London	615	656	1656	25,558	14492	37,769	509,726	6	3	31	18	8	93
Hackney	23,144	97	230	23,964	900	2,614	227,198	3	1	17	8	2	51
Ham & Flhm	33,397	86	242	28,966	818	5,133	734,456	3	1	23	8	3	68
Islington	28,743	98	193	13,547	1003	3,110	210,910	3	1	23	9	3	69
Knsgtn & Chels	23,586	121	313	26,658	1582	6,203	482,373	4	1	27	11	4	80
Lambeth	41,250	87	118	5,292	702	1,277	56,074	3	1	19	8	2	56
Lewisham	65,741	77	168	26,352	595	2,009	364,171	2	1	23	7	2	69
Southwark	37,188	96	194	16,447	949	4,195	625,356	3	1	24	8	3	73
Tower Hamlets	13,517	175	517	26,455	2296	11,776	902,815	3	2	25	9	5	76
Wandsworth	61,565	86	203	32,311	727	2,266	277,360	3	1	21	8	2	62
Westminster	21,611	203	532	16,146	3153	11,673	452,147	4	2	31	12	5	92
All	375,295	104	290	53,465	1092	6,265	2,066,835	3	1	31	8	3	93

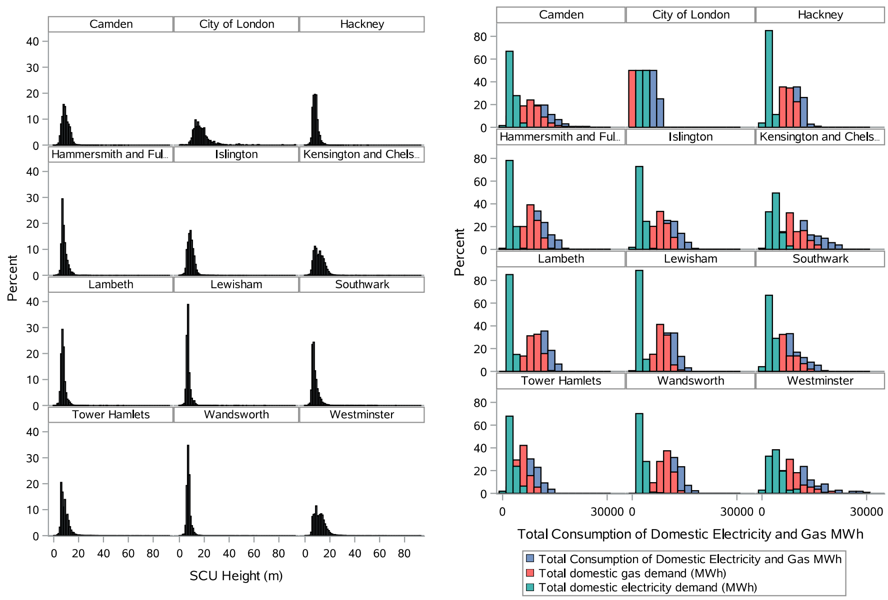

Fig. 1. (a) Distribution of SCU height (m) and (b) total LSOA energy use (MWh/year) in selected Local Authorities.

Figure 3 shows the simply comparison of total neighbourhood gas and electricity demand classed into five levels of a measure of neighbourhood domestic SCU tallness, i.e. the total number of floors within an LSOA. There is an increase in total gas demand as the total floors increase. However, there is no apparent relationship between total electricity use and total floors, suggesting that taller areas do not use more electricity. The relationship for gas may reflect the fact that areas with more floors would also have an increase in exposed surface area.

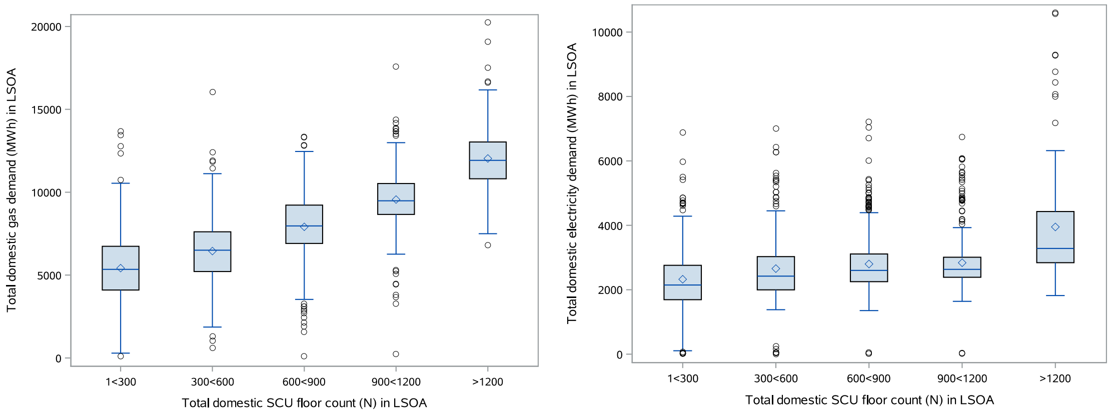

Fig. 3. Total a) domestic gas and b) electricity use (MWh/year) classed by sum of all domestic SCU floors (N) in LSOA.

Table 4 shows the results of the linear regression modelling for the LSOA height classes (only the lowest, middle and highest are shown here) to illustrate how SCU morphology features predict gas use differently within taller and less-tall areas. The results show that in less tall areas (Model 1), building height and volume were not significant predictors of total gas use, while areas of tallness (Model 5) shows the reverse. The addition of 1 metre of height in lower built form areas adds 0.06 MWh/year compared to 0.9 MWh/year in tall areas, after adjusting for volume and the deviation of height within the LSOA. The results also show that both volume and external wall area are significant predictors of gas use within tall areas, while the percentage of electric central heating is less significant.

Table 4. Model statistics of total LSOA gas use (MWh) and LSOA built form features

	Model 1 - <300 floors				Model 2 - 600-900 floors				Model 5 - <1200 floors			
Parameter	**Est**	**SE**	**|t|**	**Pr > |t|**	**Est**	**SE**	**|t|**	**Pr > |t|**	**Est**	**SE**	**|t|**	**Pr > |t|**
Intercept	1347	1027	1.31	0.1909	707	747	0.95	0.3448	116	1213	0.1	0.9238
External wall area (m2)	0.01	0	2.03	0.0433	0.04	0	7.38	<.0001	0.05	0	5.12	<.0001
SCU volume (m3)	-0.002	0	-2.93	0.0038	-0.002	0	-2.87	0.0043	-0.01	0	-5.4	<.0001
SCU height (m)	0.06	0	0.17	0.869	0.31	0	1.36	0.1741	0.90	0	3.58	0.0005
SCU height deviation (m)	11	23	0.46	0.6437	163	78	2.08	0.0384	743	232	3.2	0.0018
Domestic built area (m)	154	16	9.35	<.0001	87	13	6.89	<.0001	36	24	1.54	0.1259
% Flats	1089	1041	1.05	0.2965	2150	541	3.97	<.0001	896	1028	0.87	0.3856
% central heating other	-11064	791	-13.99	<.0001	-13873	931	-14.91	<.0001	-42779	6475	-6.61	<.0001
% central heating electric	-7474	659	-11.34	<.0001	-9943	796	-12.49	<.0001	-2957	3577	-0.83	0.4103
Residents (N)	2	0	8.3	<.0001	1	0	5.49	<.0001	2	1	2.7	0.0081
N	230				384				116			
R-Square	0.80				0.71				0.76			
Root MSE	1033				1064				1193			
Mean Gas (MWh)	5399				7912				12035			

4. Discussion

London's domestic built form is predominantly low-rise, with a mean of 3 storeys for SCUs across the 12 local authorities examined within this research. However, there is considerable variation in height, with a mean of 8m and a maximum in most local authorities above 60m. There are few areas in London marked by street after street of high-rise residential buildings; instead, these types of buildings are dispersed among the city. The diversity of domestic built form also means that when undertaking an ecological style analysis, the 'within-neighbourhood' variation in height will play an important role. Because LSOAs are used for undertaking the UK Census, their boundaries are defined for spatial compactness and social homogeneity and are not necessarily ideal for classifying the morphology of the built form. The implications of this for analysing neighbourhood level energy use can mean that built form areas are split across these boundaries, potentially obscuring the nature of the relationship.

There does appear to be a relationship between height of SCUs and gas energy demand. In areas marked by lower SCUs, the height relationship is not significant, but as tallness of a neighbourhood increases the predictive nature of height increases. As suggested above, this could be related to external area, but the regression modelling is adjusted for this factor. This means that there could indeed be something specific about the height of buildings, aside from exposed surface area, that relate to gas use. This might be the climate effects that are not experienced by lower built forms, such as increase wind shear and less over-shading. It might also be that aspects of the building design and operation result in more gas being used. For instance, it may be that due to the way the buildings are heated more gas is being used, such as centralized heating systems being operated by a building manager and their need to providing heat to tenants for a specified period. Interestingly, there appears to be no relationship between the total electricity use of the LSOA and SCU height. Electricity was not further investigated in this paper, but it is curious why increased height did not also result in greater electricity use.

5. Conclusion

The research shows that areas marked by tall buildings use more gas due to their being taller or some factor related to the tallness of buildings. This means that areas of city with lower buildings will use less energy than areas of tall buildings. The implications for energy policy and planning are that building taller without increasing density will have an energy penalty. However, it is the nature of an ecological style study that the associations (or lack thereof) described between built form tallness and energy are simply a means for developing hypotheses that can be further explored in subsequent analysis.

Acknowledgements

This work was supported by the EPSRC funded 'High-Rise Buildings: Energy and Density' (EP/N004671/1) and the EPSRC funded 'Research Councils UK (RCUK) Centre for Energy Epidemiology' (EP/K011839/1).

References

[1] Steadman P. Density and Built Form: Integrating "Spacemate" with the Work of Martin and March. Environ Plan B Plan Des 2014;41:341–58. doi:10.1068/b39141.

[2] Tavernor R. Visual and cultural sustainability: The impact of tall buildings on London. Landsc Urban Plan 2007;83:2–12. doi:10.1016/j.landurbplan.2007.05.010.

[3] Sarralde JJ, Quinn DJ, Wiesmann D, Steemers K. Solar energy and urban morphology: Scenarios for increasing the renewable energy potential of neighbourhoods in London. Renew Energy 2015;73:10–7. doi:10.1016/j.renene.2014.06.028.

[4] Mohajeri N, Gudmundsson A, Scartezzini J-L. Statistical-thermodynamics modelling of the built environment in relation to urban ecology. Ecol Modell 2015;307:32–47. doi:10.1016/j.ecolmodel.2015.03.014.

[5] Foraboschi P, Mercanzin M, Trabucco D. Sustainable structural design of tall buildings based on embodied energy. Energy Build 2014;68:254–69. doi:10.1016/j.enbuild.2013.09.003.

[6] Treloar GJ, Fay R, Ilozor B, Love PED. An analysis of the embodied energy of office buildings by height. Facilities 2001;19:204–14. doi:10.1108/02632770110387797.

[7] Steadman P, Hamilton IG, Evans S. Energy and urban built form: an empirical and statistical approach. Build Res Inf 2014;42:17–31. doi:10.1080/09613218.2013.808140.

[8] GLA. London Plan 2016. London, UK: 2017.

[9] Evans S, Liddiard R, Steadman P. 3DStock: A new kind of three-dimensional model of the building stock of England and Wales, for use in energy analysis. Environ Plan B Urban Anal City Sci 2017;44:227–55. doi:10.1177/0265813516652898.

[10] Taylor S, Fan D, Rylatt M. Enabling urban-scale energy modelling: a new spatial approach. Build Res Inf 2014;42:4–16. doi:10.1080/09613218.2013.813169.

[11] Ordnance Survey. OS Mastermap Topography Layer. Southampton, UK: 2016.