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High-Rise Buildings: Energy and Density

Professor Philip Steadman of UCL sets out some of the existing evidence on density and energy usage for high-rise buildings and outlines his current research project on the subject.

Exactly a hundred years ago, in 1915, the monstrous Equitable Life Assurance Building was completed in lower Manhattan (*Figure 1*).

At 40 storeys it was not the tallest office building in the world, but it was the largest by floor area. It loomed over the surrounding streets, casting a seven-acre shadow and completely cutting off sunlight to at least three other tall buildings. The City of New York estimated that the total loss in value to surrounding properties was around a million dollars. The controversy provoked by the Equitable resulted in 1916 in the passing of the New York Zoning Ordinance, which severely limited the bulk of new buildings on their upper storeys, and created the well-known New York 'setback style' of skyscraper. The purpose was to preserve existing property rights and to allow some light and air to reach street level.

Figure 1: Equitable Life Assurance Building. New York, completed 1915, architect Peirce Anderson of Graham, Burnham and Co. Photo: New-York Historical Society

In 2015 a similar situation is looming in London, but without the protections of any direct equivalent to the New York Ordinance.

As is well known, large numbers of high-rise buildings are under construction or planned for London. A survey last year by New London Architecture showed that 236 buildings of more than 20 storeys are planned, of which 80% are residential.[1]

Today there are extra concerns about high-rise buildings, to do with their sustainability and use of energy. In this context a new research project at University College London's Energy Institute will try to answer two questions[2]:

1. Are high-rise buildings more energy-intensive – all other things being equal – than equivalent low-rise buildings?

2. Is it possible to provide the same total floor area on the same sites as high-rise buildings, but on a much-reduced number of storeys?

If the answer to both these questions is 'yes', then it would follow that energy could be saved by discouraging tall buildings and encouraging low-rise.

In many circles it is still believed that tall buildings are justified and unavoidable in order to achieve high densities when land is in short supply. This belief is even found in parts of the architectural and planning professions. Of course, if a building completely fills its site, then density can only be increased by adding more storeys. This is what happened in the Loop in Chicago and in Manhattan in the late 19th and early 20th centuries, and is still happening today in places that are highly constrained by their geographical boundaries like Hong Kong. But otherwise, taller buildings generally have larger sites so that they can be spaced apart to preserve standards of daylighting, ventilation, views and privacy. And London as a whole is not short of land. The densest borough in England and Wales, measured in terms of resident population per hectare, is Islington, which is predominantly low and medium-rise. Tony Travers of the London School of Economics has calculated that if the whole of Greater London had the same residential density as Islington, the population would be 20 million.[3]

1. Density and built form

Architectural researchers have studied the question of the relationship of different forms of building to the use of land since the 1930s. Some of the most important systematic work was done at Cambridge University in the 1960s by Lionel March and Leslie Martin (former chief architect of the London County Council). They made comparisons in purely geometrical terms between three simple generic forms of building: freestanding 'pavilions' or towers, elongated 'streets', and closed 'courts' *(Figure 2)*. They kept the depths of the forms constant; and they kept the spacing of the forms constant in relation to their height – the greater the height, the wider the spacing. They then varied the number of storeys and calculated the resulting densities.

They measured these densities not in terms of people per hectare but as floor space indices. The floor space index (FSI) is the ratio of the total floor area on all floors of a building, to its site area.

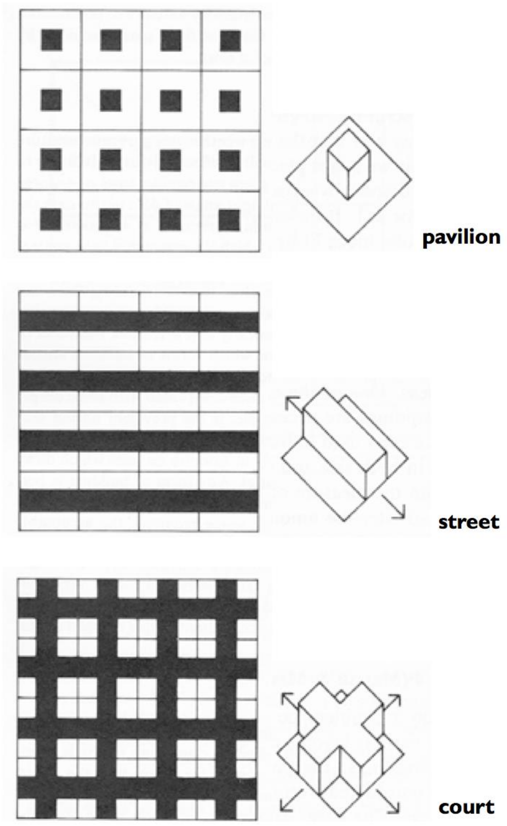

Figure 2: Three generic building forms – 'pavilions' (or towers), 'streets' and 'courts' – analysed by Martin and March in their work on densities. The repeated patterns are to be imagined as continuing indefinitely. From Martin and March (1972) p.36

What Martin and March found in broad terms was that for a given number of storeys, the ‘courts’ always achieved higher densities than the ‘streets’, which in turn always achieved higher densities than the ‘pavilions’ (towers) *(Figure 3).*

Put another way: the floor area provided in a given ‘court’ building would need more storeys in a ‘street’ form, and even more storeys in a ‘pavilion’ or tower form.

These counter-intuitive results arise because as the buildings get taller, they must be set further apart, and take up more land. Also, to put it somewhat loosely and figuratively, a free-standing tower ‘uses’ the land on each side of the building just once to obtain its light and air; while within a courtyard, the same land is ‘used’ four times.

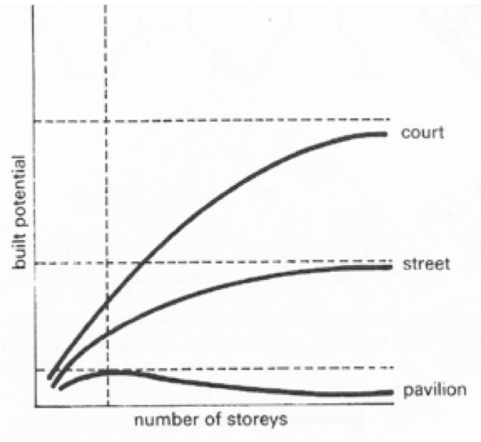

Figure 3: The relationships, for Martin and March’s three schematic forms of building, between number of storeys (horizontal axis) and density measured as floor space index FSI (vertical axis). Densities are always greater at any given height in ‘courts’ than in ‘streets’, and always greater in ‘streets’ than in ‘pavilions’ (towers). From Martin and March (1972) p.37

More recently two researchers at the Technical University Delft, Meta Berghauser Pont and Per Haupt have looked at the same issues, not with theoretical models but by measuring large numbers of actual Dutch housing developments.[4] *(Figure 4).*

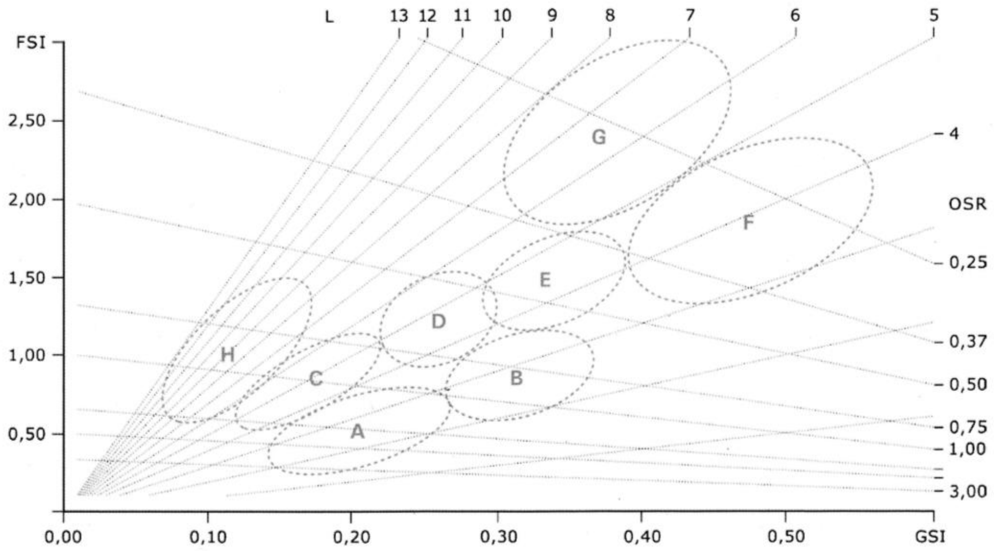

Figure 4: The ‘Spacemate’ diagram of Meta Berghauser Pont and Per Haupt. The vertical axis plots density as floor space index (FSI). The horizontal axis plots ground coverage (GSI) as a fraction. The diagonal lines correspond to different numbers of storeys, from 1 to 13. The ellipses enclose groups of Dutch housing development with distinct morphological characteristics, as given in the key. From Berghauser Pont and Haupt (2002) p.56

A *Low-rise spacious strip developments [i.e. ‘streets’ or terraces]*
B *Low-rise compact strip developments [i.e. ‘streets’ or terraces]*
C *Mid-rise open building blocks [i.e. courts]*
D *Mid-rise spacious building blocks [i.e. courts]*
E *Mid-rise closed building blocks [i.e. courts]*
F *Mid-rise compact building blocks [i.e. courts]*
G *Mid-rise super blocks [i.e. courts]*
H *High-rise developments [slabs and towers]*

They measured densities again as floor space indices (FSI). And they measured the fraction of the ground area covered by buildings, the *ground space index* (GSI). They plotted the resulting values along with numbers of storeys on a diagram they call 'Spacemate.' FSI is shown on the vertical axis. An FSI of 1 means that the total floor area is equal to the site area. GSI is shown on the horizontal axis. A value of GSI of 0.5 means that half the land is covered. The diagonal lines mark numbers of storeys, from 1 to 13.

Berghauser Pont and Haupt find that actual housing estates are clustered in different areas of the diagram (the ellipses) depending on their heights and built forms. Thus group H contains 'high-rise' slabs and towers on 8 to 12 storeys. Groups A and B are terraces on 2 to 4 storeys.[5]

The remaining groups C to G are closed courts on 3 to 8 storeys, and with courtyards of varying sizes relative to the buildings' heights.[6] These differences in courtyard size can be seen in the varying extent of ground coverage (GSI).

What these Dutch results demonstrate in terms of densities is that the more compact terraced streets on 3 and 4 storeys in Group B have roughly the *same* density (FSIs around 1) as the high-rise blocks in Group H on 10 storeys. Meanwhile the densest courtyard developments on 5 and 6 storeys in Group G achieve more than *double* the density (FSIs above 2) of the high-rises. Martin and March's theoretical results are confirmed empirically. The answer to the density question posed by our research proposal is therefore 'yes', depending on the sizes and shapes of sites available for specific projects.

We have made illustrative analyses of two current proposals for London. The first is Foster and Partners' scheme for 250 City Road, which consists of two towers on 36 and 41 storeys, plus other 7-storey buildings around courtyards *(Figure 5).*

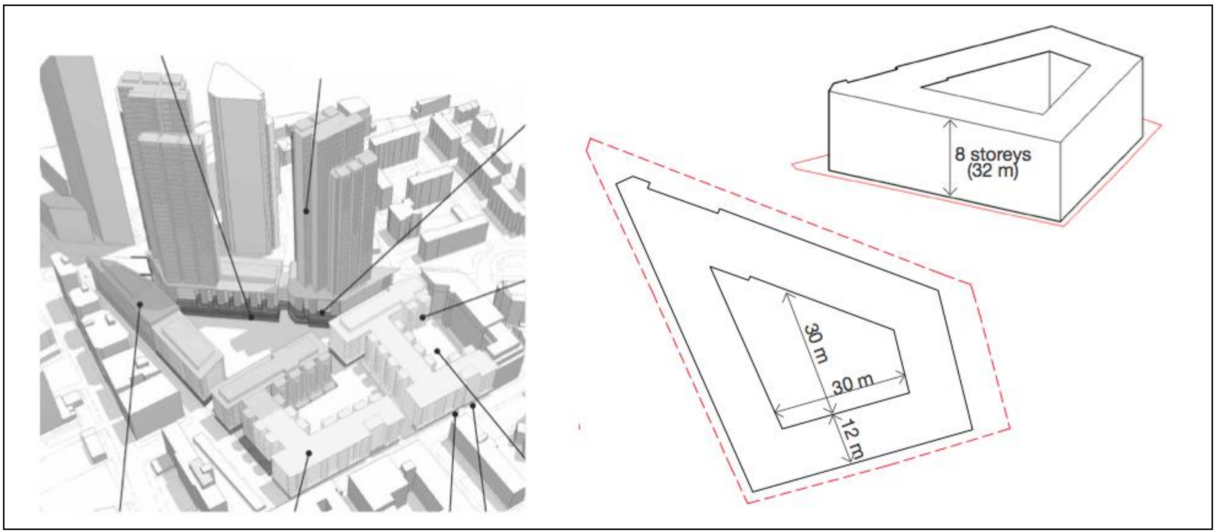

Figure 5: (left) Foster and Partners' proposal for 250 City Road, London, and (right) an alternative arrangement of the same floor area on the same site.

We find that it is possible to rearrange the same total floor area on the same site in a single large courtyard building on 8 storeys. The court is 30 metres across, and the plan depth is 12m comparable with the proposed buildings in Foster's scheme.

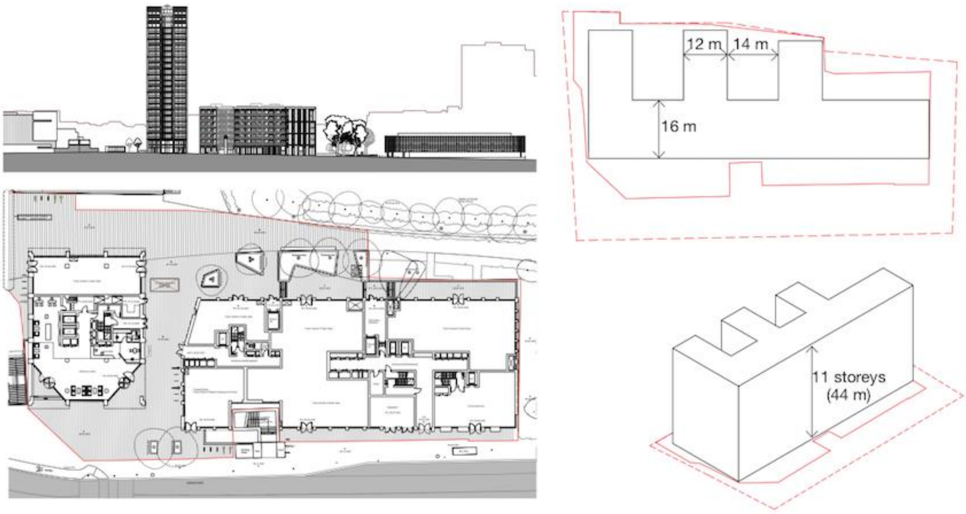

Figure 6: (left) Grid Architects' proposal for 100 Avenue Road, London, and (right) an alternative arrangement of the same floor area on the same site.

Figure 6 shows Grid Architects' proposal for 100 Avenue Road in Swiss Cottage, with an office block on 5 and 7 storeys and a residential tower on 24 storeys. This can be rearranged on the same site, with comparable plan depths to the Grid Architects design, in a branching slab on 11 storeys.

In the project we will carry out analyses of this kind for large numbers of projects. We will try to generalise the results and report them in design guidance for architects and planners. The analyses will not be intended as alternative architectural schemes, simply as demonstrations that other forms are possible. Clearly many design criteria besides density need to be considered in practice. Our purpose will be rather to show the ranges of geometrical possibility open to designers for any specified value of FSI, and for sites of different shapes and sizes.

2. Energy and building height

We know then from the start that the answer to our research question about density is (in most cases) 'yes'. What about the question relating to energy: do tall buildings use more energy than low-rise? The answer to this question is wide open at this point, although there are a few fragments of suggestive evidence. It should be emphasised that what follows is tentative and speculative. These are hypotheses, which it is the purpose of the project to test.

Many variables can potentially affect the energy use of tall buildings, only some of which would be directly related to height. First there are the activities in the building (e.g. office or residential) and how these affect the hours of use of the building and the extent and types of equipment, such as computers, water heaters and cookers. There is the use of energy in lifts. Then there is the use, or not, of air conditioning. The geometrical form of the building is important. Air conditioning can allow for buildings to be deeper. This can affect the amount of wall area for a given volume, hence the rate of heat loss. There can be important differences due to building construction, especially between glass curtain walls and solid walls, since rates of heat loss are greater through the glass. Finally there will be effects related to the local environments of buildings such as orientation, overshadowing, exposure to sun and wind, and climatic effects more generally. Our purpose in the project is to try to identify those effects that relate specifically to height. To do this we will have to devise methods for comparing energy use in buildings of different heights – *all other things being equal*.

There is some existing evidence on the relationship between height and energy use, but it is fragmentary. Joseph Lam and colleagues made a study in 2003 of 20 tall office buildings in Hong Kong.[7] These were all-electric air-conditioned public sector office buildings from the 1980s and 90s, and therefore comparable at least in those respects. The authors were not interested in the effects of height as such; but data published in their paper makes it possible to examine this relationship.

Figure 7: Electricity use in kilowatt hours per square metre (vertical axis) against number of storeys (horizontal axis) in 20 Hong Kong office buildings, plotted from data given in Lam et al (2004)

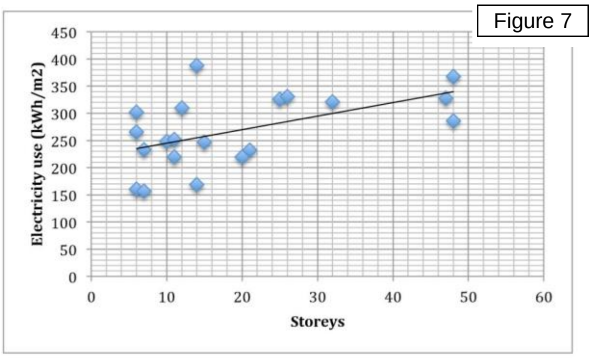

Figure 7 plots electricity use (in kilowatt hours per square metre) on the vertical axis, against number of storeys on the horizontal axis. There is a steady increase with height. Each additional storey adds on average 3 kilowatt hours per square metre.

Looking at the breakdown of the electricity consumption in more detail, the uses per square metre for lighting and (perhaps surprisingly) lifts do *not* increase with height. The biggest increase is in the energy used for heating, ventilating and air conditioning. The Hong Kong climate is hot and steamy, and we would expect heavy loads for air conditioning. But these are greater, per unit of floor area, the taller the building. The data show that the use of electricity by equipment – mostly computers – is also greater in the taller buildings, an effect that seems unlikely to be due to height as such. Despite the comparability of these buildings in several respects, there are differences that could be complicating the picture. One building has a large data centre with a very heavy use of power. Some of the tallest buildings in the sample are curtain-walled, and have deeper plans than the lower-rise buildings.

The Energy Follow Up Survey (EFUS) of the English Housing Survey provides some evidence of the relationship of energy use to height in tall residential buildings.[8] A preliminary analysis of data on low-rise and high-rise purpose-built flats in EFUS shows that the high-rise flats use on average more than *twice* the amount of electricity annually, while the levels of gas consumption are about the same. (It is likely that many of the blocks in question are all-electric.) The sample of high-rise flats is however small.

There have on the other hand been studies that have shown little or no difference in energy use with height. For example Aedas Architects analysed theoretical designs for tall office buildings, using simulation models, and found only small increases in energy intensity with height.[9] Philippe Rodes and colleagues at the London School of Economics carried out a major study of energy use for heating in residential buildings of many different types in four European cities, and found that this actually *decreased* with height.[10] Energy use was again estimated using simulation. However the LSE sample included buildings only in the range 7 to 11 storeys. The increase in height over this range was at the same time a transition from detached houses, to terraces, to flats; and we would expect these types to be progressively more energy-efficient because of their geometries. The ratio of surface to volume in detached houses is generally greater than in terraced houses, and greater again than in flats.

In terms of basic building physics, why might we expect energy use to increase with height, as shown by Lam and colleagues' data? The outstanding and obvious characteristic of tall buildings is that they stick up above their neighbours. They are therefore exposed to higher winds. Wind speeds increase regularly with height above ground.

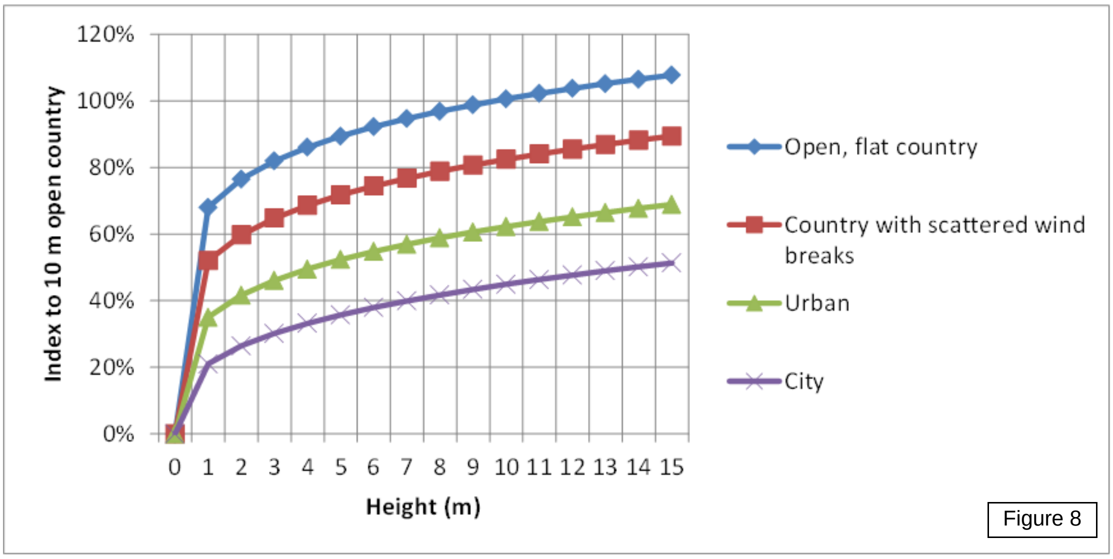

Figure 8: Variation in wind speed (vertical axis) with height above ground in metres (horizontal axis) plotted by Mark Barrett, UCL Energy Institute from data given in CIBSE Guide A, Environmental Design, Chartered Institution of Building Services Engineers (2015). Wind speeds are expressed as percentages of a notional speed of 10 metres per second at a height of 10 metres in open country.

Figure 8 is plotted from figures published by the Chartered Institution of Building Services Engineers and shows this relationship. The horizontal axis gives height above ground in metres. The vertical axis gives wind speeds as percentages of a notional speed of 10 metres per second, 10 metres above ground, in open country. Speeds in built-up areas and cities would be lower than in the country. The relationships are shown only up to 15 metres, but wind speeds would continue to rise with height, especially in cities above the roofs of the majority of buildings.

Higher winds can contribute to increased energy consumption in several ways. They remove heat from the surfaces of buildings. They increase rates of infiltration of outside air (drafts) meaning that the air inside requires more heating or cooling. And they can increase the rates of conduction of heat through the building's envelope, especially through glazing. Tall buildings tend also to be more exposed to the heat of the sun, and are less likely than low-rise to be overshadowed by trees or other buildings. This can lead to increased energy requirements for cooling in summer.

It seems at least possible that such effects are not fully represented in the simulation models used to estimate energy consumption during the process of design of tall buildings; or that the relevant facilities provided in the models are not always used. This could lead to underestimates of predicted energy consumption in practice. We will explore this possibility in our research with experiments using models. The bulk of the work in the project however will be to make comparisons where possible on the basis of actual consumption data, not computer simulations. We will collect real energy use data for as many tall buildings as possible, and use statistical tchniques to separate out the effects of pure height from all the other potentially confounding variables. What are *the consequences of height in itself* for energy consumption?

One topic that the project will not cover is *embodied energy*: that is the energy needed at all stages to produce the materials of construction and to erect a building. It is worth noting however that a study by G J Treloar and colleagues in 2001 showed that embodied energy per square metre of floor area in Australian office buildings was 60% greater in buildings of 42 and 52 storeys than in 3 and 7-storey buildings.[11] The differences were largely - as one might expect - due to structural components.

It is sometimes suggested that a concentration of tall buildings around public transport hubs can help shift travellers from cars to buses or trains and so reduce energy consumption in transport. This may be true, but it is an argument for *higher densities* rather than higher buildings as such.

Finally there has been much discussion in the architectural literature of the possibility of ‘green’ or ‘sustainable’ skyscrapers. Several such buildings have been erected, including notable pioneering examples such as Ken Yeang’s Menara Mesiniaga tower of 1992 and Norman Foster’s Commerzbank building in Frankfurt of 1997. Researchers such as Josie Close and C K Chau have looked at the potential for ‘green’ retrofitting of existing tall buildings.[12] Valuable as this work is, it seems possible that most if not all of the conservation measures and renewable technologies employed in ‘green’ or low-energy skyscrapers could equally be applied – perhaps with greater effectiveness and ease – in low-rise buildings. One could also imagine that the potential for adaptation, refurbishment and change of use would be greater in low buildings than in tall ones. Might the most sustainable form of skyscraper not be a skyscraper at all?

About the author

Philip Steadman is Professor of Urban and Built Form Studies at UCL. He works on the relationship of energy use both to the forms of buildings, and to land use patterns and transport networks in cities. From the early '90s he worked for the UK government, with a large team, to build a model of energy use in the entire non-domestic building stock of England and Wales, whose purpose was to test policies for cutting CO2 emissions. He has also carried out, with colleagues, a series of studies of fuel use in buildings and in transport in cities using integrated land-use and transport simulation models. He is currently directing the EPSRC-funded 'Energy and Buildings Data Frameworks' project, which is analysing gas and electricity consumption for 11 million dwellings in the UK. He has written books on energy and the built environment, American cities, the effects of nuclear attack on Britain, and the painting technique of Johannes Vermeer. He is presently working on a book about building types, considered from both historical and geometrical points of view, with the provisional title Building Types and Built Forms.

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1 New London Architecture, *London's Growing Up*, NLA, London 2014

2 A 12-month project, starting in November 2015, funded by the Engineering and Physical Sciences Research Council

3 Quoted in *London's Growing Up* p.18

4 M Berghauser Pont and P Haupt, *Spacemate*, PERMETA architecten, Amsterdam 2002

5 These are Martin and March's 'streets', or what Berghauser Pont and Haupt call 'strips'.

6 Berghauser Pont and Haupt refer to all these courts as 'blocks', either 'open' (with gaps between buildings) or 'closed'.

7 J C Lam et al, 'Electricity use characteristics of purpose-built office buildings in subtropical climates' *Energy Conservation and Management* Vol.45 2004 pp.829-844

8 Department of Energy and Climate Change, *Energy Follow Up Survey (EFUS): 2011*, at www.gov.uk/government/statistics/energy-follow-up-survey-efus-2011

9 J Kimpian, personal communication

10 P Rode et al, *Cities and Energy: Urban Morphology and Heat Energy Demand*, LSE Cities, London 2014

11 G J Treloar et al, 'An analysis of the embodied energy of office buildings by height', *Facilities* Vol.19 pp.204-214

12 J Close and C K Chau, *Every Building a Powerhouse*, BEC Climate Change Business Forum, Hong Kong 2010