High-Rise Buildings: Energy and Density

Bristol High Rises Forum
5th March 2020

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Philip Steadman has a long history of involvement with the built environment. He studied Architecture at Cambridge in the early 1960s, was a visiting research fellow at Princeton University in the 70s and then became Director of the Centre for Configurational Studies for the Open University for over 20 years .

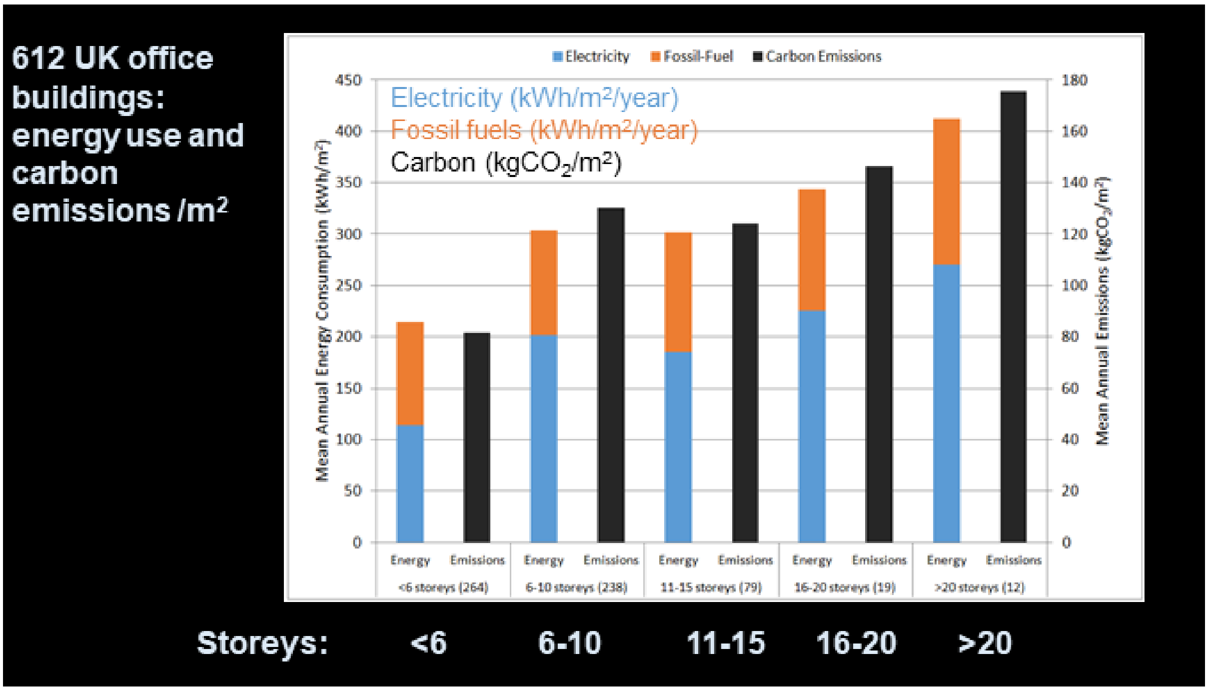
Philip developed a particular interest in the relationship of energy use both to the forms of buildings, and to land use patterns and transport networks in cities, and from the early '90s he worked for the UK government, with a large team, to build a model of energy use in the entire non-domestic building stock of England and Wales, testing policies for cutting CO_2 emissions.

Since 1999 Philip has been teaching at UCL and - coming right up to date - in 2019 he developed with colleagues the London Building Stock Model, a digital model of all buildings in the metropolis and their use of energy. He was also a partner in a European community funded project to compare European cities in terms of their sustainability. With such a broad and in-depth knowledge of his subject we are privileged to have him here with us today.

My talk is about two subjects: the use of energy in tall buildings, and the relationship of tall buildings to urban density. I'm from the Energy Institute at University College London, where my main collaborator on this work is Daniel Godoy. Two years ago, we carried out a research project on these subjects.

We looked first at offices, and assembled a sample of around 600 office buildings in the UK, ranging in height from 2 storeys to 30 storeys. Some were commercial, some government offices. Some were air-conditioned, others mechanically or naturally ventilated. They varied in age from the 19^{th} century to the present.

The sample came from three sources: public buildings with Display Energy Certificates; a consortium of large property owners, the Better Buildings Partnership; and buildings entered to an energy efficiency competition run by a previous Mayor of London. These sources provided figures for the actual annual energy consumption of all the buildings.



This graph shows energy use on the vertical axis, plotted against height on the horizontal axis. This is the *intensity* of energy use, per square metre of floor area.

Blue shows electricity, and orange shows fossil fuels – gas and oil. Building height, on the horizontal axis, is grouped in five intervals: 2-5 storeys, 6-10 storeys, 11-15, 16-20, and 21 storeys and above.

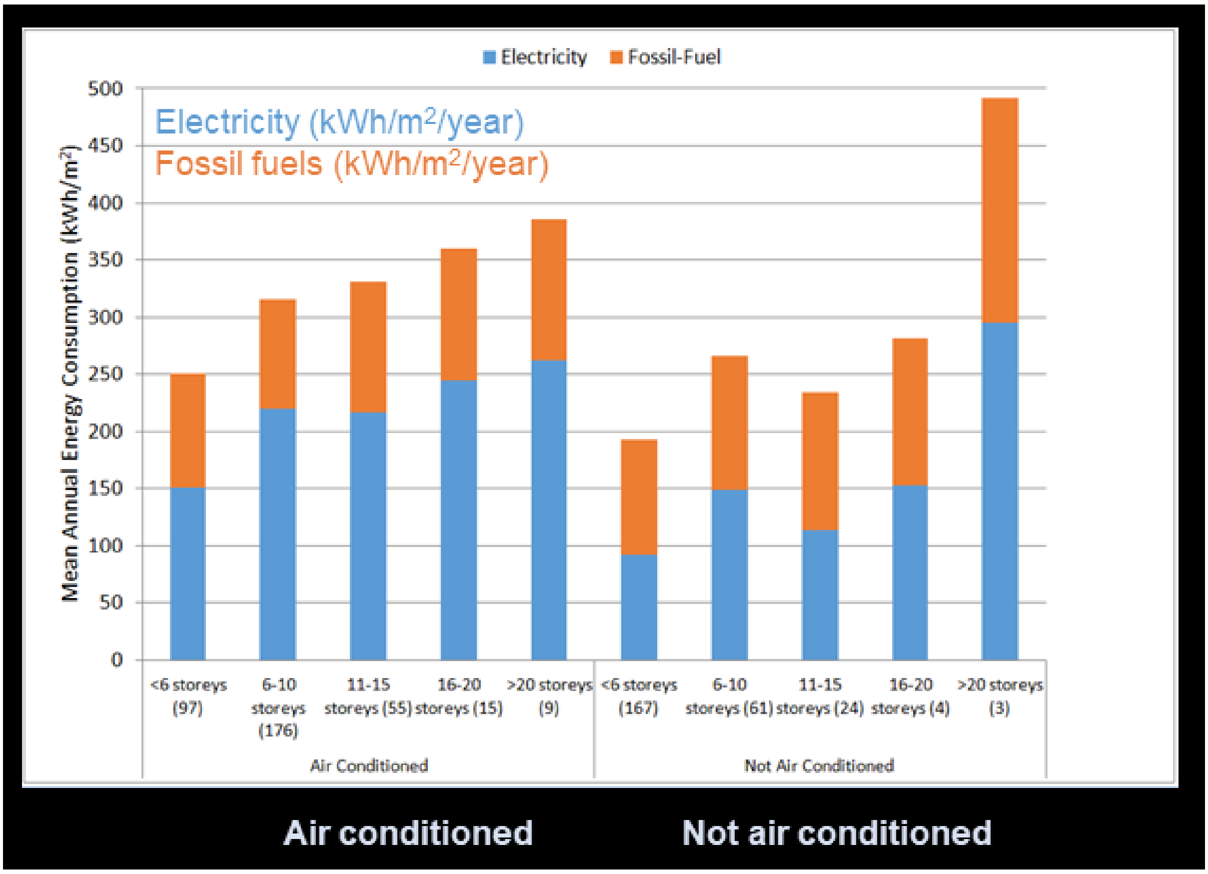
Over this whole range, the intensity of fossil fuel use increases by 40%. The intensity of electricity use increases by 135%. Total energy intensity is doubled. The black bars show carbon emissions per square metre: these are more than doubled.

These results were a big surprise. (I think some people didn't quite believe them, or didn't want to believe them.) This kind of analysis, strangely, had never been made before, using actual consumption figures for large numbers of real buildings in use. Previously, people in the construction industry and the design professions would have told you that, yes, tall buildings might be somewhat more energy-intensive, but the increases were modest. I'll come back to this point.

What might be the explanation? We've shown the effect, but not the cause.

The main uses of energy in office buildings are for heating, cooling and air conditioning; for lighting; for electrical equipment including computers and IT; and for lifts and escalators. Lifts account typically for around 3% of the total, so they're not responsible. There seems to be no reason why electricity use for office equipment should vary with the height of a building. Office work is office work, whatever level above ground it's done on. One might imagine that the use of electricity for lighting could vary with building height, on the argument that taller buildings are less over-shadowed by their neighbours, and can see more of the sky. But this should mean a *reduction* in the demand for artificial lighting in taller buildings, not an increase.

The biggest uses of energy are heating and cooling. We know that air-conditioned buildings, other things being equal, are more energy-intensive than buildings without air conditioning. So perhaps, you might think, the high-rise buildings in our sample are all air-conditioned, and the low-rise are not, and that's the explanation.



Well, not so. In this graph we've split the sample into 350 buildings with air conditioning, on the left, and 250 buildings without air conditioning, on the right. Each group is broken into the same five height bands as before. The air-conditioned buildings are more energy-intensive in every height band, except the very tallest. But there's a similar pattern of increasing energy intensity with height in both groups. (One should be slightly careful about attaching too much significance to the tallest group of non-air-conditioned buildings, since there are only three of them. They do nevertheless stand out.)

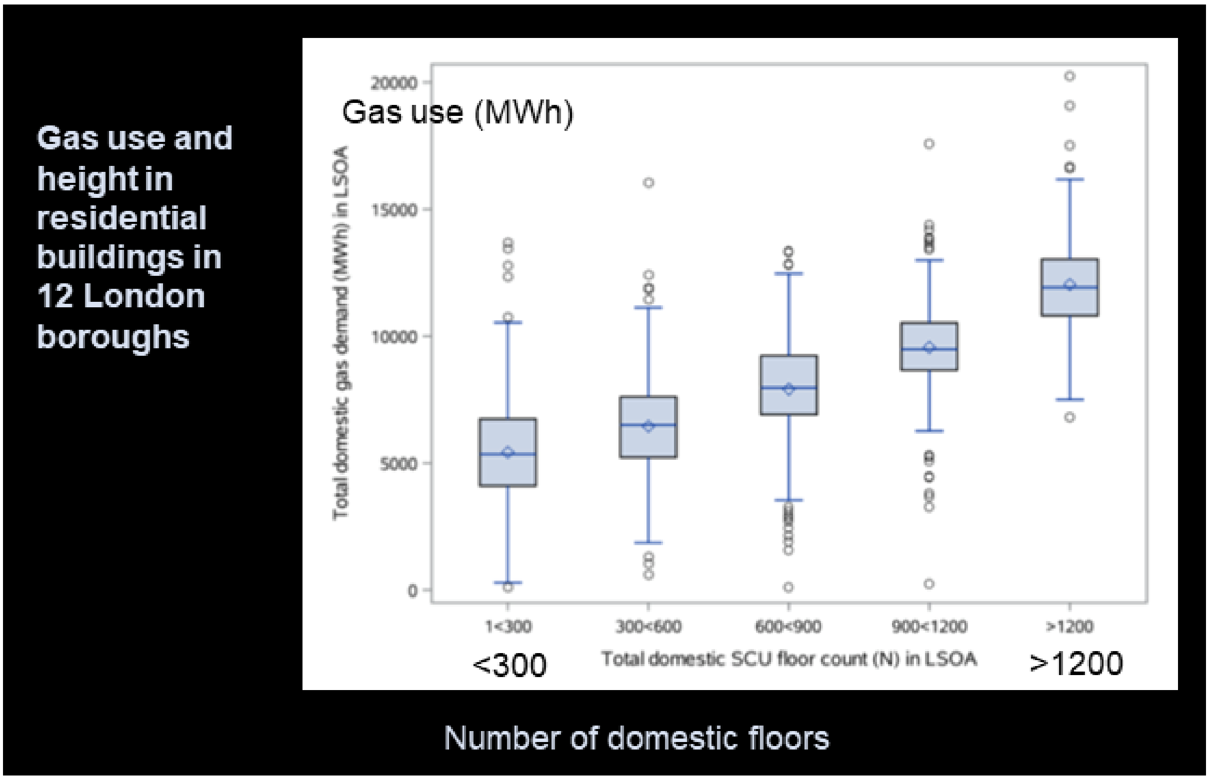
I was surprised to find so many tall buildings in Britain without air conditioning. It seems to be the accepted wisdom in the construction industry today that air conditioning is essential in tall buildings. But all skyscrapers built before the 1940s were naturally ventilated. The Empire State Building still has openable windows. One trend in the construction of tall buildings that we observed, and that won't surprise you, was an increasing use of glass curtain walls as buildings get higher.

To me and my colleagues these facts suggest that the explanation of our findings has to do with the external environments of tall buildings, and how the weather affects the buildings’ demands for heating and cooling. In summer, tall buildings that rise above their neighbours are exposed to more direct sun than lower buildings, which are shaded. So they need cooling. And in winter, tall buildings are exposed to lower temperatures and stronger winds. We all know how cold and windy it can be on the tops of hills or tall towers. Air temperature drops with height above ground. And wind speed increases with height, in particular it gets stronger above the general level of roofs in cities. Glass isn’t as good an insulator as masonry, and so buildings clad in glass can lose and gain more heat through the walls. All of this explanation I should say is hypothetical at this stage: we’re planning new research to investigate these ideas.

Embodied energy: the energy use while constructing tall buildings
I’ve been talking so far about energy used in the operation of *buildings*. But energy is also used in the materials and the construction of buildings, before they’re ever occupied – so-called *embodied* energy. This isn’t my field: but a group in Australia led by Graham Treloar have looked at embodied energy and height in office buildings. They studied two low-rise offices on 3 and 7 storeys, and two high-rises on 42 and 52 storeys. Embodied energy per square metre of floor areas was 60% greater in the high-rise: mainly due to the steel frames, which have to be stronger, and the foundations, which have to be deeper.

Embodied energy per square metre of floor area in 42 and 52-storey office buildings is 60% greater than in 3 and 7-storey buildings

What about tall blocks of flats? We weren’t able to assemble comparable data on actual energy use in operation for large numbers of individual residential buildings. Instead we compared *total* energy use in residential areas, with the *total* height of all buildings in those areas; and we found a sharp increase in the intensity of gas use with height.



This contrasts with the offices, where the greater increase was in electricity. But it makes sense, because the biggest use of energy in houses and flats is for heating, and in Britain the main heating fuel is gas. We're just about to start on some new work on tall residential buildings, of which we now have a very big sample in London, with actual meter data in every case.

In passing, why has there been such a large programme in Britain of re-cladding high-rise council blocks of flats to add extra insulation? I read recently that residents of other buildings next to Grenfell Tower, whose cladding has been removed, have seen their heating bills shoot up. Local councils ought to know how energy intensity compares between high and low-rise flats. But I've not seen this discussed in public

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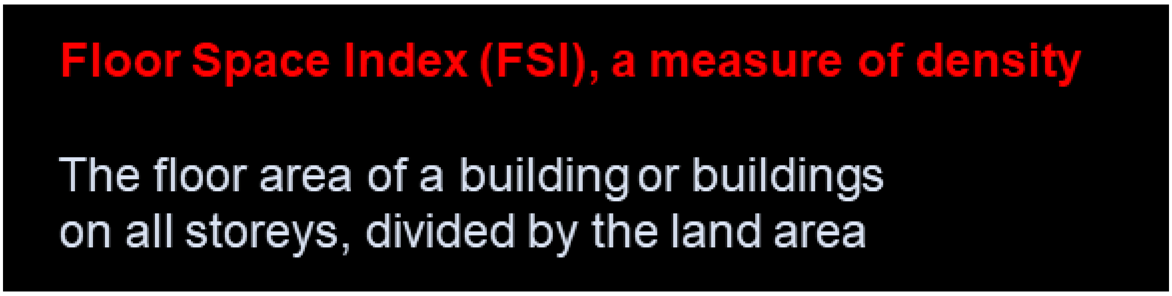
Why haven't people done this kind of research before, and why haven't these effects been well known? The key to our research was to use actual electricity and gas meter data, and they're difficult to get hold of. The data tend to be confidential and sensitive, and property owners are reluctant to give access to their utility bills. Instead the industry and the professions rely on computer simulations of energy performance. At this point I have to be rather careful what I say. But I've increasingly come to suspect that these computer models are either not capable of predicting energy use in high-rise buildings correctly; or that they *are* capable, but aren't being rigorously or correctly used in practice.

Anecdotally, I've seen studies by architectural consultants using computer models that predict an increase in energy intensity in office buildings of around 15% over 20 storeys. One recently published American study of a proposed skyscraper in New York, using computer simulation, even suggested that factors in the external environment would act to *decrease* energy demand. At the same time one sees books and articles on the design of high-rise buildings a talking about ‘green skyscrapers’, perhaps betraying a kind of nervous intuition that tall buildings might *not* be green or efficient, but could be made so by various technical means. I should reiterate, however, that this is all speculation and anecdote, and we need some serious investigation into the energy modelling of tall buildings by computer before we can know exactly what’s been going on.

So tall buildings are much more energy-intensive than low-rise.

What about the argument, as often made, that tall buildings are essential to achieving high densities in cities? It’s sometimes argued that by building at high densities around transport hubs, residents can be encouraged to travel by public transport rather than by car, so reducing energy use in travel. This is a good argument. But notice that it’s a case for high *densities*, not for high buildings as such.



The density of development can be measured in different ways, but one measure widely used by architects and planners is the floor space index or FSI. This is calculated by summing the floor area in a building or buildings, on all levels, and dividing by the area of the land on which they stand. I’m going to show you a series of aerial photos of locations in London, for which we’ve calculated the overall density of the buildings on the site or city block in question. In every case, the density, the value of the floor space index, is the same. It’s 3 in all cases. What varies is the average height of the buildings.

St James's Square SW1

5.8 storeys

Density, FSI = 3

Filbert Village, Leicester

7.1 storeys

Density, FSI = 3

Farringdon Street EC4

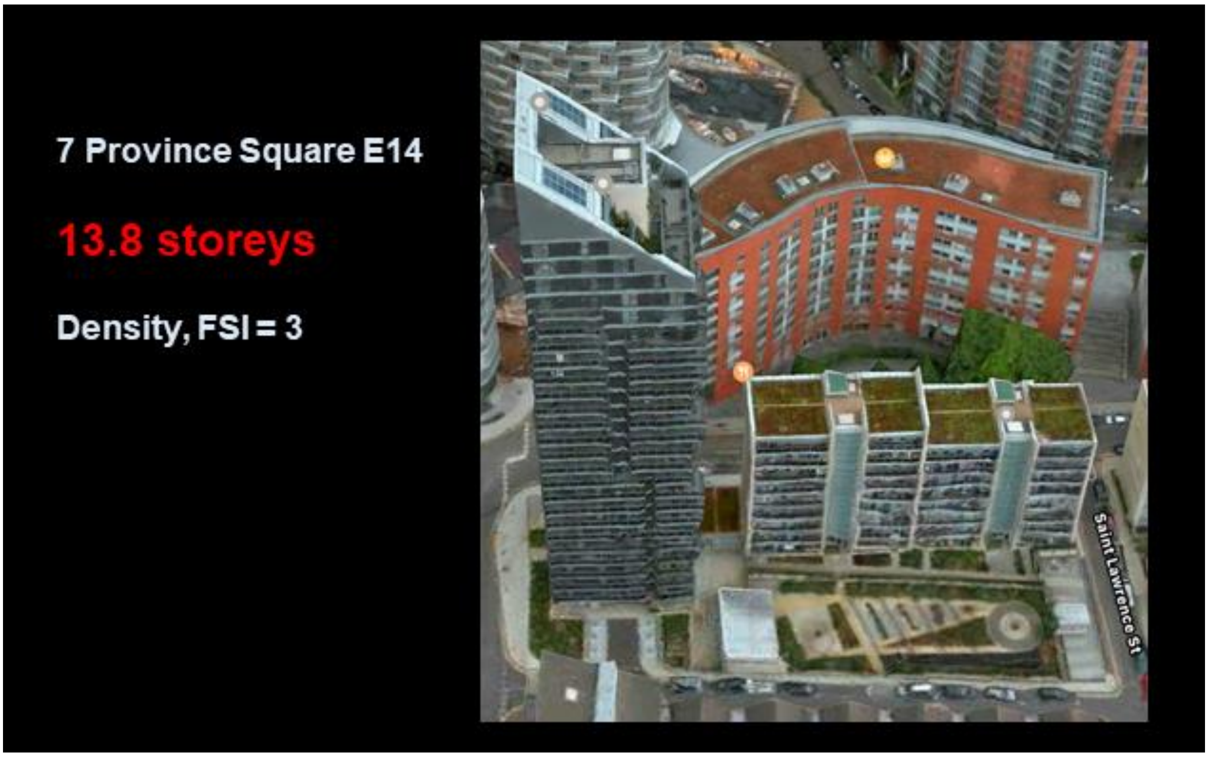
8.7 storeys

Density, FSI = 3

10 Bermondsey Square SE1

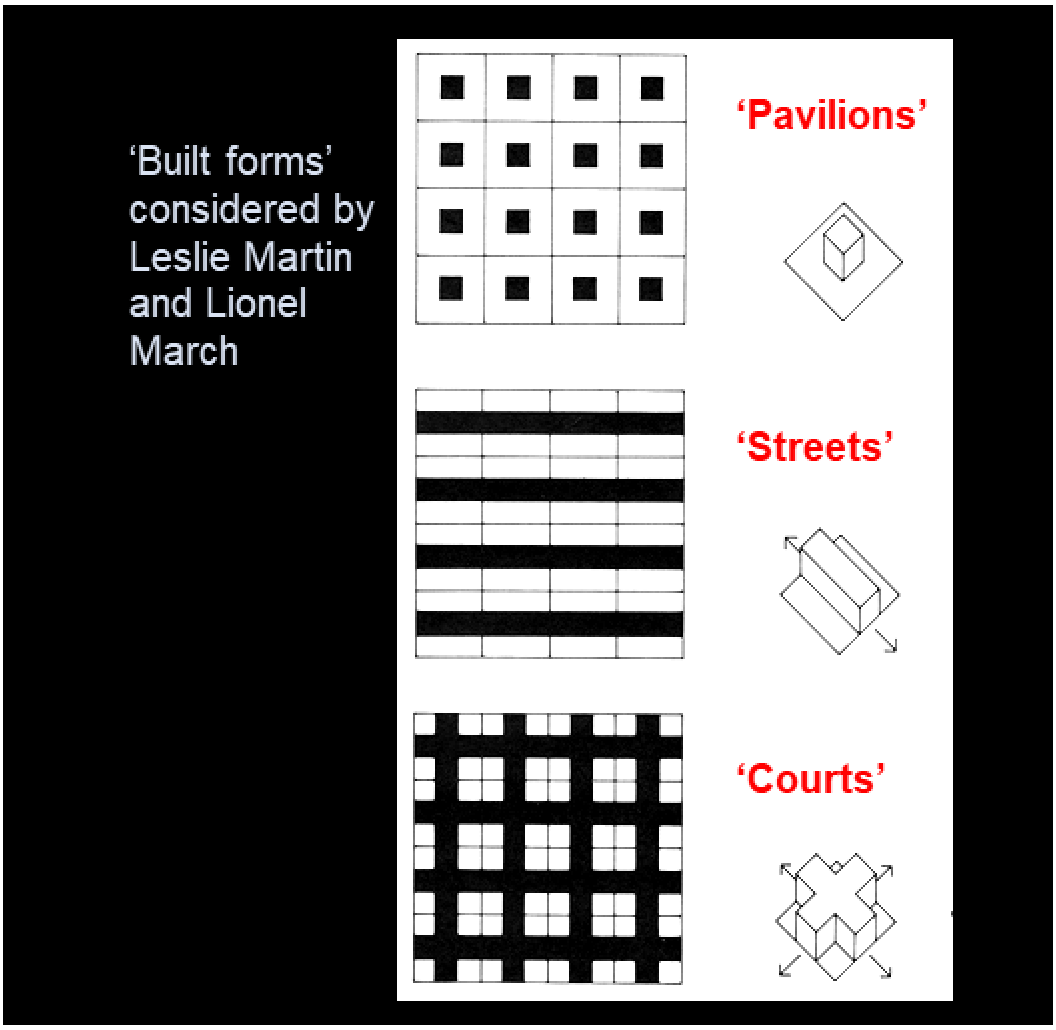
7.6 storeys

Density, FSI = 3



So this combination of tower and slab in the East End, whose average height is 14 storeys, achieves the same overall density as St James's Square on 6 storeys, less than half the height. Notice that the low-rise buildings are courts and squares, while the high-rise are freestanding slabs and towers.

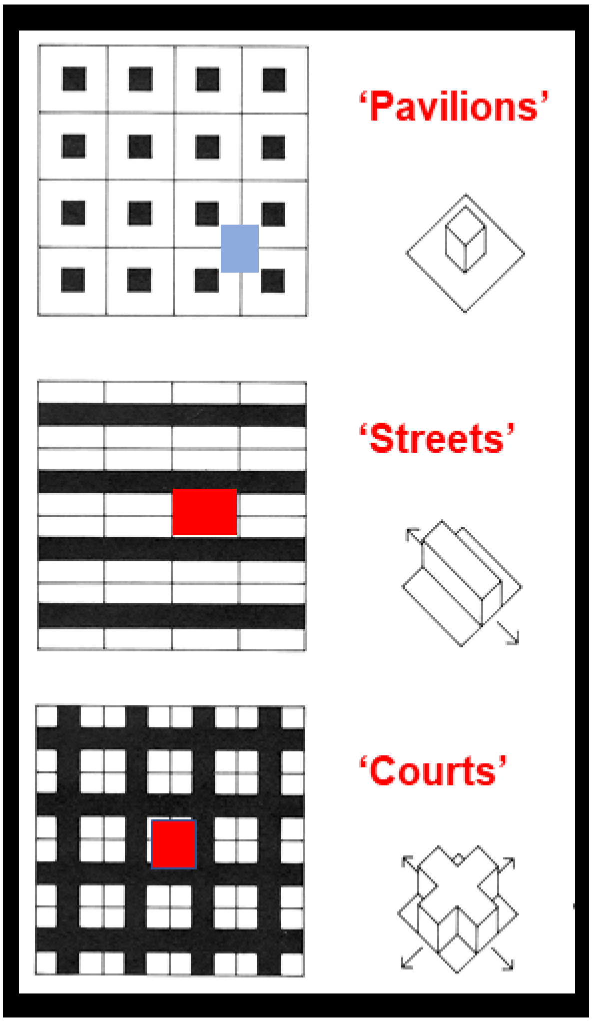
Leslie Martin and Lionel March studied the relationship between the forms of buildings and density in Cambridge, more than fifty years ago. They compared three generic forms of building: what they called 'pavilions', which if made tall would be towers; parallel 'streets'; and inward-facing 'courts'.



They showed that, in theory, given a court form of a specified height, a street or slab form achieving the same density would have to be twice as tall, and a tower form would have to be three times as tall. There are many complications, but this was the essence of what they proved. Martin and March's demonstration was mathematical and counter-intuitive, which was perhaps why it wasn't more widely understood.

There are two effects at work. Taller buildings need to be more widely separated in order to gain the same access to light and air; so they use more land.

And there's a crucial difference between buildings whose facades face outwards like towers, and buildings whose facades face inwards like courts. Speaking very loosely, in the courtyard, the volume of space contained by the court is used four times to get light and air to the four facades; while in street forms, the space of the street is used twice, by the facades on opposite sides of the street. In towers, the spaces in front of the facades are used only once (sort of).

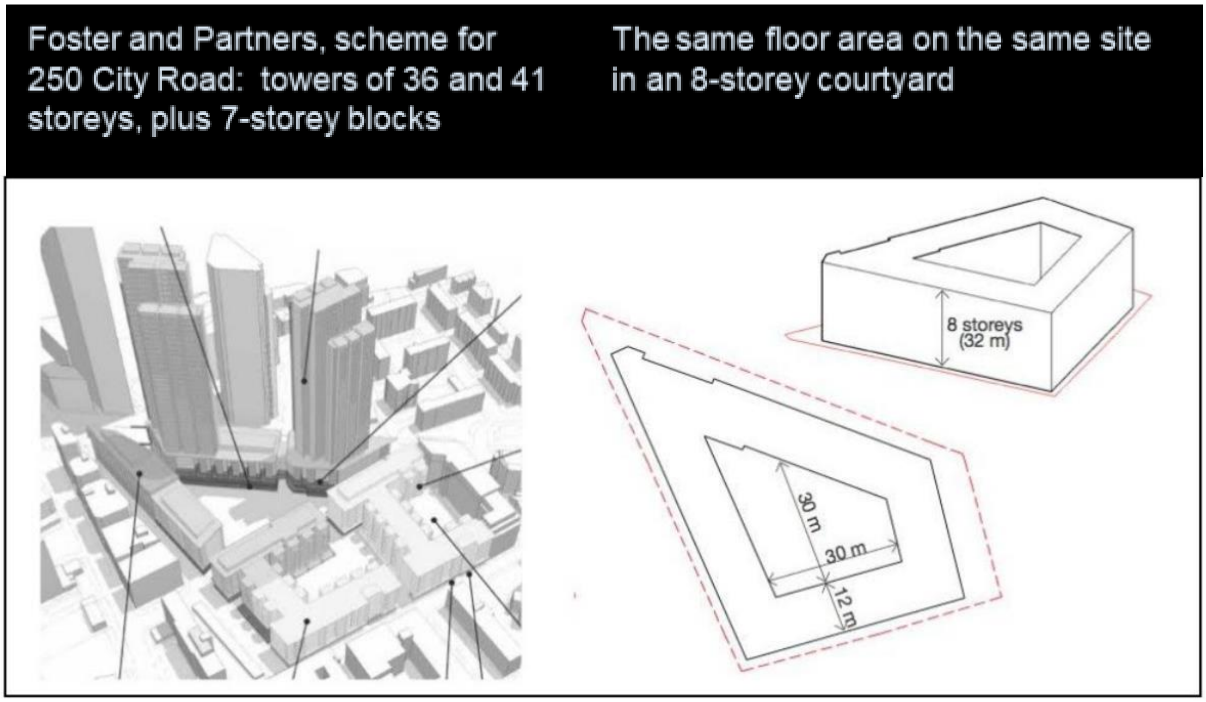


In the 18th and 19th centuries, before the invention of lifts, very high densities were achieved in walk-up buildings on six or seven storeys – as in London's squares or along Hausmann's boulevards in Paris.

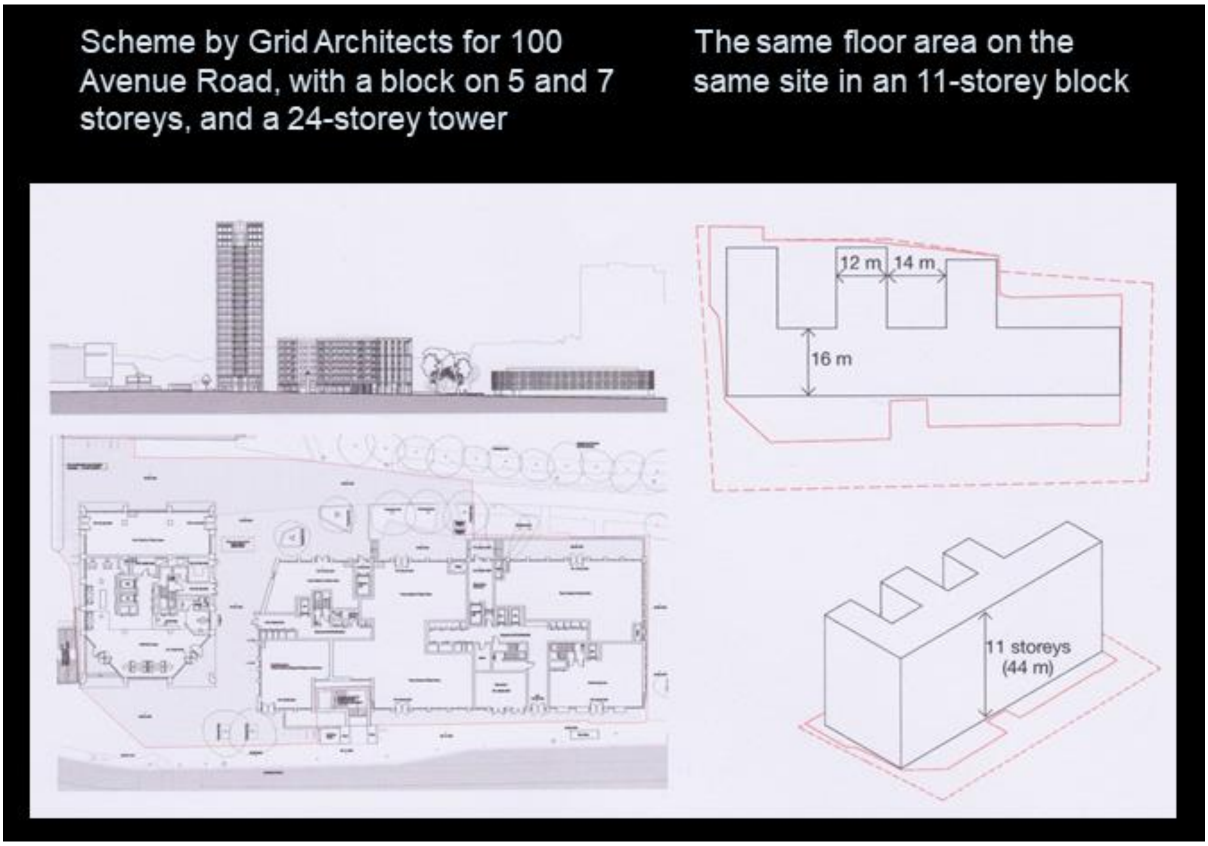
In some parts of central Paris the floor space index reaches values of 4 or 5 in seven-storey buildings. (In the examples in London I showed you, the FSI was 3.)

Of course, if a developer has a small site, and he wants to achieve the highest possible density, and he isn't forbidden by law, then he can only do this by building a tall tower. But in so doing, he prejudices what can be built on next-door sites, and casts a literal shadow over them. In order to achieve high densities in low-rise buildings, it's necessary to accumulate larger sites. If planning controls were to put general limits on building height, then developers would have incentives to find, or put together large sites.

Here's a couple of illustrations from our own work, showing alternative geometrical forms for two recent high-rise projects in London. Here on the left is Foster and Partners scheme for 250 City Road, which I think may now be complete. It consists of two towers of 36 and 41 storeys, plus some 7-storey slabs. On the right is an 8-storey courtyard building on the same site, which has exactly the same density. This isn't an architectural proposal, just a diagrammatic illustration of one option, out of a range of possible forms at the same density.



And here is a very controversial scheme now under construction at Swiss Cottage, with a 24-storey residential tower and an office block on 7 and 5 storeys. The same accommodation could be put on the same site in a branching slab like this one, on 11 storeys.



So in conclusion:

- Energy intensity in UK office buildings increases with height, and is doubled going from 5 storeys to 20 storeys and over.

- Energy intensity also increases with height in UK blocks of flats

- Embodied energy is 60% greater in 40 and 50-storey offices than in low-rise buildings

- Computer models of energy use do not appear to predict these effects

- The same densities achieved by tower buildings can generally be achieved in slabs or courtyard buildings of less than half the height, depending on the sizes of their sites.

- Much energy could thus be saved by building lower, without sacrificing density.