CITIES, ENERGY AND CLIMATE: SEVEN REASONS TO QUESTION THE DENSE HIGH-RISE CITY

Chris Butters,[1] Ali Cheshmehzangi[2] and Paola Sassi[3]*

ABSTRACT

Dense high-rise cities offer some advantages in terms of sustainability but have considerable downsides. Low-dense and medium-rise typologies have been shown to offer good social qualities; their potential energy and carbon advantages have received less attention. As the energy consumption, emissions of cities and heat island effects increase; we question whether dense, high-rise cities offer optimal sustainability. We discuss seven areas where medium density and lower rise typologies offer advantages in terms of energy and climate including: land use/density; microclimate/green space; energy supply; transports; operational energy/carbon; embodied energy/carbon; and resilience.

The aim is to discuss the cumulative importance of these areas in the context of sustainable energy use and climate emissions. These areas are subject to ongoing research and are only discussed briefly, since the overarching synthesis perspective for urban planning is our focus. The picture that emerges when these points are seen together, suggests that medium density and lower rise options—like traditional European typologies—may offer, in addition to social qualities, very significant advantages in terms of energy, carbon and climate emissions.

KEYWORDS

sustainable cities, low rise cities, urban planning, climate emissions, energy planning

HIGHLIGHTS

- *Low-carbon typologies for sustainable cities are discussed*
- *Cities with moderate densities and heights offer advantages in terms of energy and climate emissions*
- *Problematic environmental aspects of dense and high-rise urban development are discussed*
- *Compact high-rise cities are especially problematic in hot climate developing countries*
- *Energy and carbon considerations require us to rethink sustainable urban form*

1. Centre for Development and the Environment (SUM), Sognsveien 68, 0855 Oslo, Norway
2. University of Nottingham Ningbo, 199 Taikang E Rd, Yinzhou Qu, Ningbo, 315000 China
3. School of Architecture, Faculty of Technology, Design and Environment, Oxford Brookes University, Gipsy Lane, Oxford OX3 0BP United Kingdom (*Corresponding author: psassi@brookes.ac.uk)

1. INTRODUCTION

According to the IPCC the urban population is expected to reach 67% of the global population by 2050; cities will then be accounting for around 75% of global primary energy use and 50–60% of climate emissions (Revi et al., 2014; UN Habitat, 2012). What kinds of cities can be most sustainable? There are always trade-offs between environment, economy and community; the

ultimate goal is a good balance between the three. Whilst acknowledging the many social and economic aspects, this paper highlights the environmental consequences of different urban forms. We focus on seven areas where urban form has implications for energy use and climate emissions. Some may appear minor, when seen individually, accounting for only a few per cent of the energy or climate impacts, and their relative importance will vary, but when seen cumulatively, they are of considerable weight in the quest for low carbon or low emission cities.

Alongside the global implications of urban energy and carbon, public health impacts can be of serious concern and are now receiving much attention. Cities are experiencing increasing heat events, including in temperate climates, with nearly 70,000 excess deaths in the European heat wave of 2003 alone (Robine et al., 2008)—in what are far from the hottest or least well-prepared countries. The urban heat island (UHI) effect may render hot climate cities virtually unliveable periodically (Lauwaet et al., 2005) and air pollution aggravates this further (Kovats and Hajat, 2018).

Our focus is on which city typologies are most conducive to low climate emissions and low energy solutions. With rapid urbanization, especially in developing countries, a worldwide tradition of low-rise settlements is giving way to life in urban apartments, with huge socio-cultural changes. Both the design of new cities and the adaptation of existing ones influence transport, energy needs, emissions, and many environmental qualities. Paradigms of urban form include European city typologies, modernist zoning, dense high-rise, garden cities, and suburban sprawl, with widely differing economic, social and ecological characteristics. Whilst movements such as New Urbanism champion the human and community qualities of traditional, dense but fairly low-rise cities, others argue for small, "human scale" towns; others praise the dynamic qualities of megacities. Do some typologies render it inherently easier to achieve low carbon, low emission solutions? (noting that the terms low energy and low carbon are largely interchangeable as long as energy systems are largely fossil fuel based).

The "compact city" concept, often cited as the "sustainable" answer, offers concentrated public transport networks and hence low carbon mobility, but it is seldom pointed out that "compact" also means a concentration of negatives: congestion, heat island effect, air pollution, noise—and very high land prices. Problematic social aspects can include insecurity, loss of identity and lack of green leisure spaces. Developing country cities should consider the "compact city" model with a particularly critical eye. Overcrowding and lack of energy amenities may, in a warming world, lead to very poor living conditions, as the following quite early study illustrated: "Hong Kong's first large-scale sustainability research initiative (Barron and Steinbrecher, 1999) has revealed the astonishing deterioration of the environment. The main environmental problems are associated with over-concentration due to high-rise and high-density development, and include poor air quality, water depletion, noise, and excessive waste production" (Zhang, 2000: 247).

There is also considerable research which queries the environmental "efficiency" of dense city centres (Vringer and Blok, 1995, Bjelle et al., 2018). Living in cities implies, and indeed partly compels, a certain lifestyle and consumption. A study of Helsinki found that "carbon dioxide equivalent (CO2e) emissions are substantially higher in the dense downtown area than in the surrounding suburbs" (Heinonen et al., 2011:1). Sustainable building and urban design alone can facilitate, but not ensure, sustainable lifestyles. City living is *situational* and often implies high consumption patterns, including city dwellers' higher use of holiday homes and leisure flights, which may outweigh the apparent advantages of compact cities such as transport efficiency. These are sociocultural factors, not addressed here but important to mention since they must be included to achieve a holistic perspective on the impacts of urban form.

The trend towards dense, high-rise urban environments is problematic not least in developing countries where solutions may be of poor quality both socially and technically. Large high-rise developments are now a common model in emerging economies; not only for business districts but also for residential areas. Common features are high density, increasing heights, extensive underground parking and a general lack of focus on energy efficiency or climate impacts. By contrast, traditional European type cities consist largely of dense but low- to medium-rise urban fabric. At the other extreme lies the very low-density suburban "sprawl" model, widespread not only in North America, and still an ideal for many people.

Whilst existing cities face the huge task of restructuring for sustainability, new cities have the opportunity to "get it right" the first time. However, rapid growth combined with a lack of resources often leads to poor solutions. The fast pace of development in countries such as China can be illustrated by an example: "almost 80% of the residential construction projects in Xiamen Island were built after 1990, whereas only 6.7% of the construction was built before 1980 . . ." (Ye et al., 2011: 149). Such rapid growth is problematic, frequently occurring at the expense of

FIGURE 1. Medium-rise dense typology of historic European cities—here in south Germany (Photo: Butters).

local environment and of living quality. For instance, even in countries such as Thailand and China where adequate skills and planning systems exist, it has been seen as too early to impose strict requirements for energy efficiency, as this might hamper economic growth. To do so in poorer regions is even less realistic. Another "missed opportunity" is that favourable solutions such as district heating or cooling are not implemented. Many cities are thus locking themselves into huge future energy costs and climate emissions.

Research in specialised areas provides the pieces that must be fitted into an overall puzzle. This paper therefore offers a synthesis perspective combining established knowledge within urban studies and newer research related specifically to the energy/carbon and climate emissions of cities. When social and economic considerations are also taken into account, it is posited that a "middle ground" of compact and medium-rise urban solutions may be optimal.

2. SUSTAINABLE URBAN FORM

Principles for sustainable building and city planning are broadly recognised, but seldom applied due to reasons such as a rush for economic development, uncritical adoption of high-rise concepts, and the outdated zoning paradigm of the modernist era. Furthermore, the private car still dominates, with its impacts on the environmental and social characteristics of cities.

Whilst social, economic and environmental sustainability are equally important in urban design, the *environmental* parameters might be very briefly summarised as follows:

- Location: urban development ideally to be sited in compact and climatically favourable areas, minimising both building-related and transport energy needs and pollution;
- Zoning: mixed use, as opposed to modernist segregated zoning, co-locating housing, services and workplaces to reduce transport needs and ensure varied activity;
- Green-blue infrastructures: climatically favourable parks, water bodies and open spaces;
- Urban plan: street layouts, orientation, heights and setbacks enabling all buildings to avoid solar radiation and maximise urban ventilation (in hot climates), or to maximise solar gain and protect from wind (in cold climates);
- Building design: the individual buildings to be climate-responsive and energy efficient (plus efficient water use, waste management, noise and pollutant control, etc.);
- Energy supply: renewable energy sources, plus location and zoning optimising available local sources of energy and waste heat;
- Integration: coordinated design of the three levels of buildings, urban plan and energy system, to achieve optimal efficiency, including district-scale energy systems;
- User orientation: consumer-friendly technology, management and information to facilitate sustainable mobility and efficient resource consumption.

The environmental design goal is cities with minimal resource needs and impacts including carbon emissions, urban heat, pollution and wastes. It is broadly accepted that extremes of suburban sprawl and excessive high density are both unfavourable for sustainability. In between lie a range of medium-rise and medium-density options which can be favourable in terms of energy efficiency and climate emissions (LSECities/EIFER, 2014)—whilst enabling quite high population densities. This study addresses two key variables of urban form, density and height, and their implications on energy use and carbon emissions. The trend of high-density high-rise cities is questioned.

FIGURE 2. Medium-rise typologies with high energy efficiency: Distrikt Vauban, Freiburg (Photo: Butters).

The many other considerations in urban planning include biodiversity, human health, and social aspects. Whilst bearing them in mind, the "newer" issues of energy, climate emissions and urban heat island demand a rethinking of urban planning. Discussion of the seven points below is based on studies from both developed and developing countries. Each point merits an entire paper, but the aim here is to shed light on connections that are less often perceived, and on an important cumulative picture. We invite readers with in-depth knowledge in these areas to accept the broad-brush approach below, our express focus being how these pieces, when seen together, influence energy/climate considerations for sustainable cities.

3. SEVEN REASONS TO REVISIT MEDIUM-DENSITY AND MEDIUM-RISE OPTIONS

3.1 Land Use

Development density can be measured in Floor Area Ratio (FAR), which describes the amount of building on a given site; for example, a FAR of 1.0 indicates 100 m^2 of floor space on a site of 100 m^2; FAR 3.0 meaning a building of three floors totalling 300 m^2 on the same site. Surface Coverage (SC) describes what proportion of the land is built on; for example, SC 1.0 indicates a building covering an entire site of 100 m^2 even if many floors high; SC 0.5 indicating a building of 50 m^2 floor area, hence occupying only half the site, however tall. In addition to FAR and SC, other measures include dwellings or persons per hectare (dph, pph). None of these alone reflect space use per person or built conditions, and the measures may apply to single sites (net density) or to larger urban areas including streets and open spaces (gross density). Typical FAR figures range from well below 1.0 in suburbs to above 4.0 in some European city areas. The FAR in quite dense medium-rise districts seldom exceeds 2.0.

A key reasoning behind dense high-rise development is said to be the need to house many people in a compact area. That argument is not really valid; high population densities are achievable with moderate heights (Cheng, 2010). Table 1 provides density comparisons showing typical figures of FAR and SC as well as building heights in number of floors. It is notable that some traditional European city districts, such as in Paris or Istanbul, have a FAR reaching up to 4.0—actually a higher FAR than the high-rise "superblocks" in Chinese and similar new cities. Whilst the FAR itself does not guarantee high population density, given very unequal space use per person, it does describe how much living (or other) space is available within a given built typology.

Both measures and perceptions of building height and densities vary widely. The study "Superdensity" (Derbyshire *et al* 2015) classifies low-rise as up to four storeys and medium-rise from five to around eight floors. Briefly stated, low- and medium-rise corresponds to typical traditional European and similar cities, and to quite a few recent eco-type urban developments. For the purposes of this paper we posit a FAR of above 3.0 as a simplified benchmark of *high-density*; the term *high-rise* will be used here for heights from around nine floors to very high-rise of 20 and more floors, now not uncommon in the world's megacities; and we apply the term medium-rise to include broadly between four and eight storey buildings.

Another common argument in favour of "compact cities" *is economies of scale*. But this has been questioned. O'Toole (1996) noted that empirical studies consistently found that lower operating costs in the suburbs more than offset the higher initial capital costs of infrastructure. Similarly, "The cost increase from the low to the medium-density scenario is nearly 100%, while the cost increase from the medium- to the high-density scenario is just over 50%" (Biermann, 2000: 304). This applies especially in low-income contexts: "High demographic growth, low

TABLE 1. Urban Density Comparisons.

Urban Typology	SC—Surface Coverage	FAR—Floor Area Ratio	Average height
1. Europe, detached housing	0.10–0.30	0.2–0.7	1.5–2.5
2. Europe, row/terrace housing	0.15–0.35	0.5–1.0	2.0–3.0
3. Ningbo low-rise traditional	0.50	1.4	2.4
4. Ningbo 6 storey block 1990s	0.23	1.2	5.0
5. Jinan medium blocks 1980s	0.34	1.8	5.3
6. Europe modernist high-rise	0.10–0.25	1.0–2.5	8.0–14.0
7. Jinan superblock 1990s	0.22	2.0	10.1
8. Ningbo high-rise block	0.17	2.6	15.5
9. Europe compact city block	0.35–0.55	2.0–4.0	4.0–6.0

Notes:
1. Average height (number of floors) is less than the high-rises themselves due to some low-rise commercial and other buildings on most sites. For example, the high-rises themselves in example 8 are around 30 floors.
2. Sources: Ningbo the authors (Cheshmehzangi and Butters, 2015), Jinan cases (Yang, 2010), Europe cases (LSECities/EIFER, 2014).

levels of economic development, high income inequalities, small urban budgets and shortages of environmental infrastructure, shelter and basic services have a critical effect on densification policies and the effectiveness of policy instruments. The merits of densification at a high level of development may disappear at a lower level and be counterproductive without significant improvement to this level" (Burgess, 2000:15). Hence, high-density solutions (whether medium- or high-rise) do not necessarily provide economies of scale.

Traditional settlements in many cultures are low-rise but quite dense, from Mediterranean towns to North African *medinas* or Chinese *hutong*. They were often located and laid out in climatically favourable ways. By contrast, highly pressured megacities often have to expand into suboptimal areas such as flood plains, north facing slopes or poorly ventilated valleys—necessitating added costs and energy—or into agricultural land and green areas. By contrast, small-scale regional cities can better adapt to local landscape and environmental conditions. Regardless of the quality of the developments, what Table 1 illustrates is that to achieve quite high population density, the high-rise solutions offer no inherent advantage.

3.2 Microclimate and Blue-Green Space

Achieving a good urban microclimate is a significant factor for reducing energy needs and climate emissions. Green spaces and water bodies have many functions including microclimatic amelioration, urban ventilation, socialising and recreation. As is widely discussed today in the biodiversity hypothesis in medical research, access to nature is also a key to robust immune systems, health and wellbeing (Hahtela et al., 2013; Hanski et al., 2012).

Energy savings attributable to blue-green spaces can be very significant. An empirical study of Beijing's green spaces concluded that the cooling effect ranged from 0.65–0.85kWh/m^2 of green space which "amounts to a 60% reduction in net cooling energy usage in Beijing" (Zhang et al., 2014: 247). The cooling effect of trees, vegetation and water bodies is also very widely documented: "An increase in the green area of 10% decreases the average surface temperatures by 1.3C" (Klok et al., 2012:27). UHI adds several degrees to city temperatures, and each degree corresponds to around 5% increased energy demand for cooling (Santamouris, 2007).

A key difference between typical modern high-rise areas and traditional European cities is that where the former may have considerable green space between the high-rises, European type cities often have only small green spaces locally, but large urban parks nearby. In addition to being truly public and accessible to all, these are larger, giving more microclimatic effect, higher biodiversity, and more activities or socialising than the often privatised or gated spaces between high-rise blocks—which often have very limited functionality.

High-rise developments can have considerable green space that offers a cooling effect of air movement; but high-rise buildings cannot be shaded by trees, and they often cause problematic turbulence effects. Traditional low- and medium-dense towns in both hot and cold regions provided good microclimates through favourable layouts, trees, design and location (Shanthi Priya et al., 2012; Givoni, 2011; Santamouris, 2006). Furthermore, the denser the city is, the greater the urban heat island problem. Overall city population densities in European type cities are not dissimilar to those in modern Chinese high-rise cities. Both can offer considerable green space although as noted, of significantly different character. Large urban parks in the European medium-rise typology are climatically more effective than scattered green areas between high-rises. Increasingly, high-rise and high-density solutions imply a progressive loss of blue-green space, negative both socially and for urban microclimate and resulting in increased energy needs and emissions.

3.3 Sustainable Energy Supply

Next, we consider the consequences of city form for energy supply options. The almost universal solution of small-scale air conditioning in hot cities adds huge amounts of waste heat to the urban environment, is far less efficient than large-scale cooling systems, and can be both noisy and unhealthy. An advantage of high-density is that it is favourable for district energy systems. District heating (DH) systems are well known; district cooling (DC) is little known but is receiving increasing attention (Butters, 2018). Much of the world's population will be in hot climate cities and district cooling has the unique advantage of removing heat from the city; it is as good as the only way to reduce UHI in the hot climate megacities. There are limitations however. District energy systems are very costly to install in existing cities; and as individual buildings become much more energy efficient, the economic feasibility of district energy systems decreases.

In addition, an important goal is for sustainable energy generation to be provided by on-site renewable energy technology. Of the main renewables—solar, wind, hydro, wave and bioenergy—only solar can be significantly located within cities. Building-integrated solar energy seems likely to become a standard feature in all climates; but solar systems integrated into roofs and facades can only cover a significant amount of the energy demand of low- to medium-rise buildings (Lee et al, 2016; Byrd et al, 2013; Rodríguez et al, 2017). A photovoltaic (PV) roof on a skyscraper might be enough to power the lifts and little more.

A Netherlands study showed that the potential electricity generation from photovoltaic cells in a typical two-storey neighbourhood with a FAR of 0.3 would exceed the electricity demand by 18%. Between 35–55% of the heating requirement could also be provided through solar collectors on roofs and integrated in the road, and higher coverage would be expected in

FIGURE 3. Plus-energy area in Freiburg, Germany, by Rolf Disch. Only in fairly low-rise can solar energy provide all the energy required. (Photo: Butters)

new low-energy developments (Agudelo-Vera et al, 2012). The Solarsiedlung area in Freiburg completed in 2004 (Figure 2) with a FAR of around 1.0 also produces more electricity than it consumes (Disch, n.d.). Hence, increasing density does facilitate district energy solutions regardless of heights but less so given future low energy buildings; and medium-rise options, whilst still enabling fairly high population densities, offer definite advantages in terms of renewable energy.

3.4 Urban Transports

Mobility is a key issue for energy, economy and society. Megacities require extensive and extremely costly multi-level transport solutions (underground, surface and elevated). Despite these, vehicle speed is often little above walking speed; congestion entails large productivity losses and multiplies emissions and pollution (Baker and Steemers, 2000). Furthermore, gasoline efficiency in city driving is much lower, thus partly negating the "compact city" advantage (Heinonen et al., 2013). Car parking in inner cities becomes extremely onerous requiring underground or multi-level parking—which as noted in section 3.6 is also extremely carbon intensive.

This point is relevant for urban density and not heights. That urban density impacts heavily on energy use for transport was shown by Newman and Kenworthy (1989) 30 years ago and this has been refined since by including other variables such as socio-economic mix, road design, destination and transit distance (Ewing and Cervero, 2010; Cervero 2002; Ewing at al 2017). According to Steemers (2003) the lack of public transport can counteract the benefits of dense cities: "historic European cities, such as Paris, lie at a national 'optimum'—achieving moderate energy use for modest densities—whilst sustaining a rich urban life. It is not evident that moving towards increasing urban density will lead to reduced car traffic—in fact, in the short-term the opposite is likely to be the case. In the absence of extra capacity in the form of effective integrated public transport, increasing the density will inevitably increase traffic".

A car-oriented city may have somewhat lower overall population density due to broad streets and high vehicle density—at a high cost of land, pollution, noise, congestion, lost time and fuel use. A more "car-free" city can achieve higher population densities. This also offers an economic benefit: in a car-free district a higher proportion of the extremely valuable urban land can be capitalised instead of devoted to vehicles. But there are stringent conditions to achieve lower vehicle use: cities must have mixed use zoning (homes, work, services and leisure not separated by long distances), they must be fairly small (walkable distances) and have exceptionally good public transport. The challenge is to render private car use largely unnecessary; notably, in cities such as Freiburg or Oslo, most people possess cars, but do not need them for most activities (Nielsen, 2007).

Hence, the perception that high city density offers sustainable mobility since it enables efficient and public transport systems, is largely invalid, *unless* private car use is radically reduced, Vehicle use accounts for around one-third of total climate emissions (and waste heat production) in cities—over 45% in Los Angeles (Gurney et al., 2018). But even with emission free vehicles, high traffic density still implies congestion, huge costs of road infrastructures, and a large proportion of the urban land occupied by vehicles. In the absence of radical changes in "car culture," however, high density will not, as is often suggested, be favourable for transport-related energy use and emissions.

3.5 Operational Energy

The largest energy requirement in buildings is normally operational energy (OE), mainly for space heating or cooling in cold and hot climates respectively. In hot climates, high overall density aggravates UHI, thus increasing the need for cooling, particularly in high-rise buildings. As shown in Table 1, high-rise areas do not necessarily house more people than quite low-rise ones; High-rises are often deep buildings, leading to apartments with one-sided ventilation and poor daylighting, hence poor comfort as well as increased energy use for lighting and mechanical ventilation. If given more glazing for daylighting, the result is summer overheating and/or excessive heat loss in winter. Many high-rise apartments or offices are also unfavourably oriented, facing only towards troublesome east or west sun. Mechanical ventilation is expensive, cumbersome and resource consuming, whereas in lower density areas there is often sufficient natural ventilation.

Further, high-rise typologies hinder the implementation of many well-recognised passive solutions to reducing operational energy:

- one can often not choose climatically favourable sites, building orientation or solar access,
- one cannot use courtyards and similar vernacular solutions to create improved microclimate,
- solar protection, a key to energy efficient design in hot climates, is difficult since much more of high-rise facades are exposed (Niu, 2004),
- high-rise buildings cannot be shaded by trees, as low- and medium-rise buildings can.

Many factors thus make it challenging or costly to design low energy buildings of high-rise type. It is notable that many recent eco-efficient districts in Europe such as in Freiburg and Malmø are low- to medium-rise (Butters et al., 2011). Studies such as LSECities/EIFER

FIGURE 4. High-rise, one-sided and heavily glazed apartments, Ningbo, China: climatically inappropriate and energy demanding design (Photo: Butters).

(2014) and Jabareen (2006) show that high-rise urban areas are, in terms of thermal energy performance, not optimal; and many high-rise buildings have extreme energy needs. This point, operational energy, relates mainly to individual buildings not to the density of urban fabric; operational energy efficiency can be better in low- and medium-rise than in high-rise buildings. But as noted above, increasing urban density does increase urban heat island effects; hence, in hot climates high density also increases operational energy demand.

3.6 Embodied Energy/Carbon (EE/EC)

This point merits somewhat longer discussion since it is still less widely recognised. Embodied energy (EE) comprises the sum of all energy (and/or carbon) inputs through a building's life cycle: extraction of raw materials, processing into construction materials, on-site energy use, recurrent energy for maintenance and replacement, and finally post-use recycling or disposal. We discuss each of these below. Of these, the materials production is normally the major item. But as the building operational energy is reduced in today's low energy solutions, the part played by the EE, in particular the materials, increases dramatically—as has been show for some years now (Ibn-Mohammed et al., 2013; Sartori and Hestnes, 2007) and can be as large as the OE, such as in a recent sustainable office building in Norway where EE and OE are 69 and 75 tons CO_2/year respectively (Future Built Program, 2014).

Firstly, *materials*: EE will almost inevitably be greater in high-rise building solutions, due to extra materials required for services, shafts, lifts and stairs and especially due to the energy-intensive materials such as concrete, steel, glass, etc. Cement products and steel often contribute the majority of EE. (Table 2). In medium-rise buildings, simpler materials with lower EE can be used.

Low carbon concretes reduce the embodied energy/carbon, but it still remains high. One can also argue that steel as main structural material is recyclable. Tall buildings have also been constructed in materials such as timber. though this seems likely to remain an exception. Even so, the embodied energy/carbon of tall buildings remains high due to their technical complexity as well as fire and safety requirements. Fireproofing coatings,on steel in particular,are environmentally problematic.

But it is not only the buildings that must be accounted. The infrastructures and site works in dense inner-city contexts are very carbon-intensive, involving mainly concrete and steel. These include roads, drainage, culverts, retaining works, water supply and other services, many of them underground. "Green" areas between tall buildings often consist of no more than a thin green layer over extensive engineering works such as underground parking and services. In a study of one Chinese high-rise area, the embodied carbon of these infrastructures was found to comprise

TABLE 2. Embodied carbon of typical modern buildings.

EMBODIED CARBON IN MATERIALS		
Concrete and steel often comprise by far the major part of the total carbon footprint:		
Sweden, 4-storey offices	81%	source: (Wallhagen et al., 2011)
Italy, 6-storey apartment block	76%	source: authors' analysis, from (Blenghini, 2009)
China, high-rise office building	>70%	source: (Zhang and Wang, 2015)

around 20% of the total carbon footprint of the development (Butters et al., 2016). This mainly residential block (Figure 5) has tower blocks of 23–30 floors set around landscaped areas—but an overall density no higher than that in traditional European city blocks of four to eight floors. Given future low carbon buildings above ground, these hidden infrastructures could come to comprise well over one-third of the total carbon footprint. The site works and infrastructures required for less dense and low- to medium-rise urban areas offer very significant advantages in terms of embodied carbon. This perspective—the carbon impact of urban infrastructures and site works—is we suggest new, and needs research.

Secondly, the shares of EE attributable to *transport of materials*, and *on-site energy* use during construction, are typically in the range of 2% to 6% each (Chang et al., 2012; Dixit et al., 2010) and will also generally be greater in complex high-rise buildings as well as city centres. Albeit “minor” today, it can be noted that the part played by these items will increase in future as OE and EE are reduced.

Thirdly, building *lifetime* plays an important role in such calculations. Current practice often sets this at just 50 or 60 years (Eurocodes, 1990), in our view too short for “sustainable” buildings. Building components with high EE are only justifiable if they have a long and maintenance-free lifetime. In reality, in situations of rapid urban change, many structures are demolished within well under 50 years; a much shorter time than their technical lifespan.

Fourthly, buildings and urban infrastructures require ongoing maintenance, repair and replacement of parts: These *recurrent* inputs add a large fraction to the whole life embodied energy/carbon. Roof and façade claddings, climatization systems and interiors are often changed several times during a building lifetime. The technical complexity of typical inner-city areas and high-rise buildings that require harnessed access or scaffolding for all cleaning and maintenance of the exterior, of lifts, etc., (Au-Yong, 2018; Chua, 2018; Pomponi, 2018) renders this more energy-demanding than in low-rise areas. Hence as regards recurrent energy and carbon, high urban density as well as high-rise buildings in particular have definite disadvantages.

Finally, the *post-use* energy to dismantle and dispose of or recycle both urban infrastructures and buildings is often considered to be minor, although that view is questionable. Recycling steel saves over 50% of the energy needed for producing virgin steel; but recycling concrete can require 5% *more* energy than new concrete, and recycling plasterboard has been estimated as using over 40% more energy than producing virgin material (Gao et al., 2001). Hence, even recycling is not always a carbon-positive or sustainable policy. Post-use impacts are often little considered, perhaps because demolition materials have little or no economic value—and little or no disposal penalty either. This phase requires more research. Life cycle analysis (LCA) often covers only up to the stage of building completion (“cradle to gate”). But a large steel building for example represents a valuable “stock” of future savings of energy or carbon that is not accounted in the “cradle to gate” LCA perspective. This methodological issue is important for correct carbon accounting but beyond the scope of this discussion. The post-use or demolition phase of urban buildings and infrastructures may lie far in the future; but our choices of urban form today will have significant energy and carbon consequences. Modern high-rise constructions are often very complex. It is notable that traditional cities have buildings comprised of very few materials, allowing for easy modification, disassembly and recycling. The post-use impacts of dense cities and high-rise buildings are almost inevitably greater than for medium-rise ones, due to complicated demolition and recycling or disposal of more complex and polluting construction materials and technical components.

FIGURE 5. High-rise urban block, Ningbo. far = 2.6. apparent "green space," but almost the entire site is in fact covering underground parking in reinforced concrete; extreme embodied carbon. (photo: Butters).

This point—the embodied energy/carbon—is a major component, and multifaceted. It concerns both individual building typology and the urban planning dimension. High-rise is definitely problematic as a building typology, and high density as a city typology implies very complex infrastructures with higher embodied requirements than lower density typologies.

3.7 Resilience

Resilience, adaptability for change and modification over time, is a key to ecological, economic and social sustainability. Energy self-sufficiency in cities is one key aspect of resilience as discussed in 3.3. Complex large-scale urban infrastructures and buildings are generally difficult to modify, adapt or replace. Although not explored in detail here, it can be posited that medium-rise, smaller scale solutions tend to be more adaptable and resilient, accommodating change more easily. Transport networks and arteries are often the most demanding to change substantially—as many cities are experiencing—since that involves major structural changes. It is, similarly, much easier to upgrade or replace an energy-inefficient building than to alter a whole street layout that channels cold winds.

Amongst examples of urban resilience is the Vauban district in Freiburg, Germany, one of the leading examples of medium-rise urban sustainability in Europe (Butters et al., 2011). Now some 20 years old, it provides an example of economic and social as well as ecological resilience. The typology is mainly three to five storey structures with a population density of 135 people per hectare, high compared to Freiburg city as a whole with 50 people per hectare (Sommer and Wiechert, 2014). Vauban was transformed from a military area into a mixed use urban district, with new workplaces, excellent public transport and a vibrant community. Many buildings were converted to new uses. Building types typical of our older cities have shown themselves to be easily transformed to low, even zero energy standards (Figure 6) and are being successfully "greened" whereas more recent buildings are being demolished.

One may query to what extent large modern urban buildings will be amenable over time to adaptation and change—as debated in the classic study "How Buildings Learn" by Stewart Brand (1994). As recent "passivhaus" discussions have shown, there are many arguments in favour of *simplicity* in design and construction—what has been termed Ecominimalism (Liddell, 2013). Risks relate to technical vulnerability, everyday operation and behaviour as well as health (Harrysson, 2015). Simpler solutions such as traditional cities and modern eco-neighbourhood types, both of moderate height and density offer, not the only but certainly favourable options.

FIGURE 6. Resilience: typical old urban buildings in Zurich renovated to extremely low energy use. Karl Viriden Architects. (Photo: Butters).

4. DEVELOPING COUNTRY CITIES

Much of the world's population will soon be in hot climate megacities. These are where pollution and heat-related mortality, as well as climate emissions, are increasing rapidly. But the waste heat produced by urban energy use, especially by vehicles and air-conditioning, mostly impacts the poor. Whilst business districts can at least afford to pay for cooling, UHI is most harmful for low-income contexts with overcrowding and no air-conditioning. It is the poor who most often must work and move around outdoors, or else in poorly climatised buildings. In low-income contexts, construction quality is frequently poor too, which also argues against dense high-rise typologies as an appropriate model. For, whereas *high quality* compact cities may provide satisfactory conditions, *low cost* high-rise can often lead to little better than "vertical slums."

The choice of urban form is thus also a question of equity (Thomas and Butters, 2018) and especially relevant to urban policy in developing countries. When discussing the energy use and carbon emissions of various urban solutions, we must note that negative impacts are most often borne by the poor. This in itself may argue for avoiding high-density and high-rise type cities.

5. CONCLUSION

Considerations of energy, carbon and climate are relatively new and require a rethinking of our paradigms of urban form. We have focused on the energy and climate impacts of cities related in particular to density and height. On the one hand, whilst extreme urban density is clearly problematic for many reasons, quite high density can be achieved in several ways, including well tried medium-rise solutions—also offering a minimal energy/climate footprint. On the other hand, high-rise buildings do not easily offer good solutions for sustainability.

To summarise: medium-density and medium-rise developments can offer advantages in comparison to dense high-rise developments in relation to:

- Microclimate and Blue-Green Space;
- Renewable Energy
- Operational Energy
- Embodied Energy
- Resilience.

We note that the above apply, with room for exceptions, to both density and height. Further, when compared to medium-density and medium-rise options, typical high-rise urban areas do not bring advantages in relation to:

- Population Density—unless *extremely* dense
- Transport/Mobility—unless genuinely car-free

The appropriateness of both density and height will naturally depend on context, and on avoiding extremes. Scale and density are questions of degree; but high population densities can be achieved without high-rise, and environmental disadvantages increase as urban development becomes extremely high and dense.

Whilst the above seven areas are all recognised, embodied carbon, post-use and resilience are aspects that have been less explored in particular as they impact on low carbon city planning. Further research is required to quantify the impact of the seven points and perhaps provide new metrics that accounts for the interrelated nature of the points as well as their socio-economic impacts. Naturally, some of the above points are not applicable in all contexts. Some may appear to be minor, seen individually, but their *cumulative* significance appears to be very considerable. Many will be of increasing significance.

Choice both of building typology and of urban typology has a large influence on the energy and climate footprint of cities. With a strong word of caution as to simplifications inherent in this necessarily brief discussion, the above seven points offer a new synthesis perspective, and indicate that quite compact, medium-density and medium-rise city typologies appear particularly favourable in terms of energy and climate.

REFERENCES

Agudelo-Vera, C.M., Leduc, W.R.W.A., Mels, A.R., and Rijnaarts, H.H.M. (2012) *Resources, Conservation and Recycling*, 64: 3–12.

Au-Yong C.P, Ali A.S and Chua S.J.L (2018) "A Literature Review of Routine Maintenance in High-Rise Residential Buildings: A Theoretical Framework and Directions for Future Research," *Journal of Facilities Management*, 17 (1): 2–17.

Baker, N. and Steemers, K. (2000) *Energy and Environment in Architecture: A Technical Design Guide*. Spon Press, London.

Barron, W. and Steinbrecher, N. (1999) *Heading Towards Sustainability?* Centre of Urban Planning and Environmental Management, University of Hong Kong, Hong Kong.

Biermann, S. (2000) "Bulk Engineering Services: Costs and Densities," in: Jenks, M. and Burgess R. (Eds.), *Compact Cities, Sustainable Urban Form for Developing Countries*. Spon Press, London and New York, p. 304.

Bjelle, E.L., Steen-Olsen, K., and Wood, R. (2018) "Climate change mitigation potential of Norwegian households and the rebound effect." *Journal of Cleaner Production* 172 pp. 208–217.

Blenghini, G. (2009) "Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy." *Building and Environment* 44:319–330.

Brand, S., (1994) *How Buildings Learn: What Happens to them after they are built*. Viking Penguin, London.

Burgess, R. (2000) "The Compact City Debate: A Global Perspective," in: Jenks, M. and Burgess, R. (Eds.), *Compact Cities, Sustainable Urban Form for Developing Countries*. Spon Press, London and New York, p. 15.

Butters, C. et al. (Eds.) (2011) *Signals: Local action—success stories in Sustainability*, Stiftelsen Idebanken (The Ideas Bank Foundation), Oslo, Norway.

Butters, C. (2012) "A holistic method of evaluating sustainability," in: Haas, T. (Ed.), *Sustainable Urbanism and Beyond*, Rizzoli, New York.

Butters, C. and Thomas, T.H. (2016) *Comparing the Carbon Impact of Buildings to that of the Site Works*. ELITH program, Warwick University, UK, Available at https://warwick.ac.uk/fac/sci/eng/elith/publications/all_publications/elith-w07.pdf

Butters, C. (2018) "District Cooling: a Key Solution for Hot Climate Cities," in: Cheshmehzangi, A. and Butters, C. (Eds.), *Designing Cooler Cities, The Asian Perspective*. Palgrave Macmillan, Singapore.

Byrd, H., Ho, A., Sharp, B., and Kumar-Nair, N. (2013) "Measuring the solar potential of a city and its implications for energy policy" *Energy Policy* 61(2013)944–952.

Cervero, R. (2002) "Induced Travel Demand: Research Design, Empirical Evidence, and Normative Policies." *Journal of Planning Literature*, Vol. 17, No. 1.

Chang, Y., Ries, R.J., and Lei, S. (2012) "The embodied energy and emissions of a high-rise education building: A quantification using process-based hybrid life cycle inventory model." *Energy and Buildings* 55:790–798.

Cheng, V. (2010) "Understanding density and high density." In: Ng, E. ed. *Designing High-Density Cities for Social and Environmental Sustainability*. Earthscan, London; Sterling, VA, pp. 3–17.

Cheshmehzangi, A. and Butters, C. (2015) "Refining the Complex Urban: The Study of Urban Residential Typologies for Reduced Future Energy and Climate Impacts," in: *Proceedings of 8th Conference of the International Forum on Urbanism*. Incheon, South Korea, 2015.

Chua, S.J.L, Zubbir, N.B., Ali, A.S, and Au-Yong, C.P. (2018) "Maintenance of high-rise residential buildings," *International Journal of Building Pathology and Adaptation*, Vol. 36 Issue: 2, pp. 137–151.

Derbyshire, B., Goulcher, M., Beharrell, A. and von Bradsky, A. (2015) *Superdensity the sequel*. London: HTA, Levitt Bernstein, PTE, PRP Architects.

Disch R., n.d. *Rolf Disch Architects Plusenergiehaus—das Wohnmodul*. Freiburg. Germany. Available at http://www.rolfdisch.de/index.php?p=home&pid=78&L=0&host=2#a285.

Dixit, M.K., Fernández-Solís, J.L., Lavy, S., and Culp, C.H. (2010) "Identification of parameters for embodied energy measurement: A literature review." *Energy and Buildings* 42:1238–1247.

Eurocodes, 1990. EN 1999:2002. *Basis of Structural Design*. Available at: http://eurocodes.jrc.ec.europa.eu/showpage.php?id=130.

Ewing, R. and Cervero, R. (2010) "Travel and the Built Environment. A Meta-Analysis." *Journal of the American Planning Association*, Vol. 76, No. 3.

Ewing, R., Hamidi, S., Tian, G., Proffitt, D., Tonin, S., and Fregolent, L. (2017) "Testing Newman and Kenworthy's Theory of Density and Automobile Dependence," *Journal of Planning Education and Research*, 1–16. https://nls.ldls.org.uk/welcome.html?lsidyva30a779b

Future Built Program (2014) Ostensjoveien 27, Hovedresultater og Sammenligning av Alternativer. Oslo, Norway. Available at: www.futurebuilt.no/prosjektvisning?projectID=207426. Accessed 23.10.2017.

Gao, W., Ariyama, T., Ojima, T., and Meier, A. (2001) "Energy Impacts of Recycling Disassembly Material in Residential Buildings." *Energy and Buildings* 33:553–562.

Givoni, B. (2011) "Indoor temperature reduction by passive cooling systems." *Solar Energy* 85 (2011) 1692–1726.

Grandclément, C., Karvonen, A., and Guy, S. (2015) "Negotiating comfort in low energy housing: The politics of intermediation." *Energy Policy* 84:213–222.

Gurney KR, Romero-Lankao P, Seto KC, Hutyra LR, Duren R, Kennedy C, Grimm NB, et al. (2015) "Climate Change: Track Urban Emissions on a Human Scale." *Nature* 525 (7568): 179–81.

Hahtela, T., Wolgate, S. et al. and WAO Special Committee on Climate Change and Biodiversity, (2013) "The biodiversity hypothesis and allergic disease: world allergy organization position statement." *World Allergy Organisation Journal*. 2013 Jan 31;6(1):3.

Hanski, I., von Hertzen, L., Fyhrquist, N., et al. (2012) "Environmental biodiversity, human microbiota, and allergy are interrelated." *Proceedings of the National Academy of Sciences*, May 22;109(21):8334–9, USA.

Harrysson, C. (2015) *Energianvändning och innemiljö i småhus byggda på 2000-talet eller tidigare*. Bygg & Teknik 5/15:20–31, Stockholm. (Energy use and indoor environment in dwellings built in the 2000s and earlier).

Heinonen, J., Kyrö, R., and Junnila, S. (2011) "Dense downtown living more carbon intense due to higher consumption: a case study of Helsinki." *Environmental Research Letters*, 6:3. doi:10.1088/1748-9326/6/3/034034.

Heinonen, J., Jalas, M., Juntunen, J.K., Ala-Mantila, S., and Junnila, S. (2013) "Situated lifestyles: I. How lifestyles change along with the level of urbanization and what the greenhouse gas implications are—a study of Finland." *Environmental Research Letters*, 8 025003. doi:10.1088/1748-9326/8/2/025003.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., and Acquaye, A. (2013) "Operational vs. embodied emissions in buildings—A review of current trends." *Energy and Buildings* 66:232–245.

Jabareen, Y.R. (2006) "Sustainable Urban Forms, their Typologies, Models, and Concepts," *J. of Planning Education and Research* 26:38–52.

Karl Viriden Architects, Zurich, Switzerland, www.viriden-partner.ch.

Klok, L., Zwart, S., Verhagen, H., and Mauri, E. (2012) "The surface heat island of Rotterdam and its relationship with urban surface characteristics." *Resources, Conservation and Recycling* 64 (2012) 23–29, p.27.

Kovats, R.S. and Hajat, S. (2008) "Heat Stress and Public Health: A Critical Review." *Annual Review of Public Health Vol.* 29:41–55.

Lauwaet, D., Hooyberghs, H., Maiheu, B., Lefebvre, W., Driesen, G., Van Looy, S. and De Ridder, K. (2015) "Detailed Urban Heat Island Projections for Cities Worldwide: Dynamical Downscaling. CMIP5 Global Climate Models," *Climate* 2015:3, 391–415; doi:10.3390/cli3020391

Lee, K.S., Lee, J.W., and Lee, J.S. (2016) "Feasibility study on the relation between housing density and solar accessibility and potential uses." *Renewable Energy* 85 (2016) 749–758.

Liddell, H. (2013) *Ecominimalism*. RIBA Publishing, UK.

LSE Cities/EIFER (2014) *Cities and Energy. Urban Morphology and Heat Energy Demand*. Final Report. London. Available at: https://files.lsecities.net/files/2014/03/LSE-Cities-EIFER-2011-Morphology-and-Energy-Report1.pdf.

Newman, P. and Kenworthy, J.R. (1989) *Cities and automobile dependence: a sourcebook*. Aldershot: Gower.

Newman, P. and Kenworthy, J. (2006) "Urban Design to Reduce Automobile Dependence." *Opolis*, Vol. 2: No. 1, pp. 35–52.

Nielsen, G. (2007) *Miljøbyen Freiburg—noen lærdommer for norske byer*. Arbeidsdokument 31. juli 2007 OI/1929-2007. Transportøkonomisk Institutt, Oslo, Norway.

Niu, J. (2004) "Some significant environmental issues in high-rise residential building design in urban areas." *Energy and Buildings* 36:1259–1263.

O'Toole, R. (1996) *The vanishing automobile and other urban myths*. Different Drummer, The Thoreau Institute, USA.

Pomponi, F., De Wolf, C. and Moncaster, A. (eds) (2018) *Embodied carbon in buildings: measurement, management, and mitigation*. Cham: Springer.

Revi, A., Satterthwaite, D.E., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R.B.R., Pelling, M., Roberts, D.C. and Solecki, W. (2014) "Urban areas." in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E. et al., (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, pp. 535–612.

Robine, J-M., Cheung, S.L.K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J-P. et al. (2008) "Death toll exceeded 70,000 in Europe during the summer of 2003." *Comptes Rendus Biologies*. 2008 331 (2): 171–8.

Rodríguez, L.R., Duminil, E., Ramos, J.S., and Eicker,U. (2017) "Assessment of the photovoltaic potential at urban level based on 3D city models: A case study and new methodological approach." *Solar Energy* 146 (2017) 264–275.

Santamouris, M. (Ed.) (2006) *Environmental Design of Urban Buildings: An Integrated Approach*. Earthscan Publications, London.

Santamouris, M. (2007) "Heat Island Research in Europe, state of the art," *Advances in Building Energy Research* 1:123–150.

Sartori, I. and Hestnes A.G. (2007) "Energy use in the life cycle of conventional and low energy buildings: a review article." *Energy and Buildings* 39 (3):249–257.

Shanthi Priya, R., Sundarraja, M.C., Radhakrishnan, S., Vijayalakshmi., L. (2012) "Solar passive techniques in the vernacular buildings of coastal regions in Nagapattinam, Tamil Nadu-India—a qualitative and quantitative analysis." *Energy and Buildings* 49 pp. 50–61.

Sommer, U. and Wiechert, C., (2014) *Lernen von Vauban. Ein Studienprojekt und mehr*. RWTH Aachen University.

Steemers, K. (2003) "Energy and the city: density, buildings and transport." *Energy and Buildings* 35:1, pp. 3–14.

Thomas, T.H and Butters, C. (2018) "Thermal equity, public health and district cooling in hot climate cities." *Proceedings of the Institution of Civil Engineers—Municipal Engineer*. DOI: https://www.icevirtuallibrary.com/doi/10.1680/jmuen.17.0002

UN Habitat (2012) *Energy*. Available at: https://unhabitat.org/urban-themes/energy/

Vringer, K. and Blok, K. (1995) "The direct and indirect energy requirements of households in the Netherlands," *Energy Policy* 23:10, pp. 893–910.

Wallhagen, W., Glaumann, M.,and Malmqvist, T. (2011) "Basic building life cycle calculations to decrease contribution to climate change—Case study on an office building in Sweden." *Building and Environment* 46:1863–1871.

Yang, J. (2010) *Does Energy Follow Urban Form? An Examination of Neighborhoods and Transport Energy Use in Jinan, China*. MIT, USA.

Ye, H., Wang, K., Zhao, X., Chen, F., Li, X., and Pan, L. (2011) "Relationship between construction characteristics and carbon emissions from urban household operational energy usage." *Energy and Buildings* 43:147–152.

Zhang, X., and Wang, F. (2015) "Life-cycle assessment and control measures for carbon emissions of typical buildings in China." *Building and Environment* 86:89–97.

Zhang, X.Q. (2000) "High-rise and high-density compact urban form: the development of Hong Kong," in: Jenks, J. and Burgess, R. (Eds.), *Compact Cities, Sustainable Urban Form for Developing Countries*, Spon Press, London and New York.

Zhang, B., Xie, G., Gao, J., and Yang, Y. (2014) "The cooling effect of urban green spaces as a contribution to energy-saving and emission-reduction: A case study in Beijing, China." *Building and Environment* 76:37–43.