# TALL BUILDINGS AND SUSTAINABILITY

Philip Francis Oldfield B.Arch (Hons), Dip.Arch (Hons)

Thesis Submitted to the University of Nottingham for the Degree of Doctor of Philosophy

April 2012

***"Up to our time...strict economy in the use of natural resources has not been practiced, but it must be henceforth unless we are immoral enough to impair conditions in which our children are to live"***

Daniel Burnham, early 20$^{th}$ Century [from Larson, 2003]

## Acknowledgements

It is difficult for me to thank each and every person who has supported this work, as so many have offered guidance and assistance over the past few years. However, I feel indebted to all those that have.

Firstly, my thanks to my supervisor, Antony Wood, who has provided constant and vital guidance, not only during this research, but also throughout my academic career. My particular thanks to Antony for inviting me out to Chicago to join the CTBUH team as Research Coordinator between the years of 2007 - 2009, a time which greatly helped shape my research, ideas and teaching, and was personally a truly fantastic experience. My thanks also to Brian Ford, whose guidance has been invaluable.

This research would not have been possible without the support of Arup, and in particular the numerous people who offered advice and opinions during several short secondments to the company including Rupert Blackstone, Peter Bressington, Fiona Cousins, Anthony Ferguson, Suzanne Freed, Alastair Guthrie, David Hadden, John Haddon, Richard Matthews, Steve McKechnie, Julian Olley, David Scott and Kate Wheadon. My appreciation to Ian Maddocks and Peter Thomson of Buro Happold, Anil Patel and Brian Quinn of Hilson Moran, Alex Lifschutz of Lifschutz Davidson Sandilands, Ken Shuttleworth of Make Architects and Karl-Otto Schollkopf of ThyssenKrupp who all gave up their time to talk to me during the early stages of this research.

My thanks to my colleagues at the University of Nottingham, Department of Architecture and Built Environment, in particular Sergio Altomonte, David Nicholson-Cole, Tim Heath, Chantelle Niblock, Peter Rutherford, Michael Stacey and Robin Wilson who have all offered fantastic advice during my time here.

The past few years would not have been half as enjoyable without the moral support of friends and family. My thanks to everyone at ‘Mid-Week-Spoons’ for good food and good company every Wednesday, and to my brothers and sisters – Richard, Katie, Edward and Emma. Massive thanks to my parents who provided the encouragement for me to follow this path in the first place. And finally thank you to Amanda, for her support, kindness and love.

## Contents

## 1.0 Overview of Submission

| | |
|---|---|
| Candidate: | Philip Oldfield |
| Position: | Lecturer in Architecture, Department of Architecture & Built Environment, University of Nottingham |
| PhD Submission: | By Published Works |
| Academic Supervisors: | Antony Wood (CTBUH Executive Director, Associate Professor, Illinois Institute of Technology, Chicago), |
| | Brian Ford (Professor, University of Nottingham, Department of Architecture and Built Environment) |

**Submitted Published Works**

The submission consists of the five published papers outlined below (in the order they appear in the work) in conjunction with an extended abstract and statements of joint authorship from collaborating authors.

Papers 1, 2, 3 & 5 have been published in academic peer-review journals, whilst paper 4 has been published in a peer-review conference proceedings.

1. WOOD, A. & OLDFIELD, P. (2008). **Global Trends in High-Rise Design**. *Urbanism and Architecture*, No. 49, October 2008, Heilongjiang Science and Technology Press, Ha'erbin, China, pp. 14 – 16, ISSN: 1673-0232. (Text in Chinese – English language version also included in submission).

2. WOOD, A. & OLDFIELD, P. (2007). **Bridging the Gap: An Analysis of Proposed Evacuation Links at Height in the World Trade Centre Design Competition Entries**. *Architectural Science Review*, Volume 50.2, June 2007, University of Sydney, Australia, pp.173 –180, ISSN: 0003 8628.

3. OLDFIELD, P., TRABUCCO, D. & WOOD, A. (2009). **Five Energy Generations of Tall Buildings: An Historical Analysis of Energy Consumption in High-Rise Buildings**, *Journal of Architecture*, Vol. 14, No. 5, pp.591 – 614, ISSN: 1360-2365.

4. KILAIRE, A. & OLDFIELD, P. (2010). **Aluminium and Double Skin Facades**. In KATGERMAN, L. & SOETENS, F. (eds.) (2010) *Proceedings of the 11th International Aluminium Conference 'INALCO': "New Frontiers in Light Metals"*, Eindhoven University of Technology, Holland, June 23 – 25, 2010, IOS Press, Amsterdam, pp.177 – 188, ISBN: 978-1-60750-585-3.

5. OLDFIELD, P. & WOOD, A. (2010). **From the Orthogonal to the Irregular: The Role of Innovation in Form of High-Rise Buildings**. *Urbanism and Architecture*, No. 73, October 2010, Heilongjiang Science and Technology Press, Ha'erbin, China, pp.27 – 31, ISSN: 1673-0232. (Text in Chinese – English language version also included in submission).

In some instances, additional research by the author is included in the extended abstract to provide context and supportive analysis to the submission. Where this occurs, it is clearly highlighted in the text.

**Support Material**

The author includes as part of the submission a 'Research Curriculum Vitae' document presenting an overview of his additional published materials, such as additional research output, media interviews, external presentations and published articles. See Appendix B.

## 2.0 Extended Abstract: Tall Buildings and Sustainability

### Background

The beginning of the 21st Century can easily be labelled the most active in the 125 year history of the tall building typology, with more, and taller, skyscrapers being constructed than at any other time[1]. This boom in construction has coincided with a global recognition for the need to reduce anthropogenic greenhouse gases with climate change becoming arguably the greatest challenge of the modern world. In light of this, attention has turned towards the environmental impact of tall buildings which are still seen by many as inherently unsustainable due to their typically high operating energy requirements, reliance on artificial lighting and conditioning, high embodied energies and lack of social / communal spaces (Roaf, Crichton & Nicol, 2005).

The year 2008 presented a unique standpoint in global history, as for the first time half the world's population – some 3.3 billion people – lived in urban areas. According to the United Nations, 193,107 new city dwellers are added to this figure every day, meaning urban populations will nearly double by 2050 (UNHABITAT, 2008). Where will these people live, work, play? It is clear the tall building could play a role in this, providing dense sustainable living and compact cities with reduced transportation emissions. However, despite this potential, the majority of tall buildings completed today continue to be designed with too little consideration of environment and sustainability. The importance of improving tall building sustainability then cannot be denied and frenzied research has – and continues to be – undertaken in order to improve their sustainable credentials[2].

### History of Research Programme

It is in this context that the author's research in the field of tall buildings and sustainability began. This work started initially by examining the opportunities for carbon neutrality in high-rise. A carbon neutral building is one that achieves zero-net-carbon operations, such that any energy it draws from a local supply grid – that is likely to use fossil fuels – for its day-to-day requirements is offset by energy generated from zero carbon sources on-site and sold back to the grid (Cousins, 2007).

---

[1] The year 2011 was by far the most active for tall building construction ever with some 88 buildings of 200 metres or taller in height completed. The previous two most active years, 2010 and 2009, saw 70 and 51 buildings of 200 metres or taller completed respectively. During the entire 20th Century, the highest tally in any one year stood at only 18 buildings completed in 1992 (Hollister & Wood, 2012).

[2] This rise in research focussing on tall building sustainability was reflected in the title of the CTBUH's 8th World Congress "Tall and Green: Typology for a Sustainable Urban Future", held in Dubai, March 3 – 5, 2008 (Wood, 2008).

The concept of carbon neutrality in high-rise builds on much of the current research in the field of tall buildings and sustainability, which has tended to focus on reducing the environmental impacts associated with their *operation*. This is reducing the energy required for (and emissions released from) activities such as space conditioning, lighting, equipment operation, water supply and water heating that occur on a day-to-day basis. Out of this research has emerged numerous tall building proposals and built projects that claim to have significantly reduced operating energy requirements (for example, see Frachette & Gilchrist, 2008; Fox, 2008). Significant legislation internationally also covers these issues of energy efficiency and renewable energy (Collins *et al.,* 2008).

However, whilst these advancements are vital for creating sustainable tall buildings, they are in themselves not enough. Sustainability, and the creation of sustainable tall buildings, goes far beyond just energy use and even broader environmental considerations. Perhaps the most famous definition of sustainable development is that of the Brundtland Report which defines it as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (United Nations General Assembly, 1987). This definition has evolved over the past decade to consider three 'dimensions' of sustainability namely, environmental, social and economic sustainability (Adams, 2006), also referred to as the triple bottom line, or the three P's of Planet, People and Profit (Collins *et al*., 2008).

The concept of carbon neutrality and the reduction of high-rise buildings' operating emissions then, only considers one small facet of the broader topic of tall building sustainability and excludes many additional and essential issues. Even considering just environmental issues, it is significantly incomplete. For example, whilst energy is required and emissions released through the day-to-day operation of tall buildings, there are also environmental impacts created through the production, transportation and assembly of materials and components into functioning buildings (known as embodied energy / carbon), which sit outside the definition of carbon neutrality. Little work has been undertaken to establish the importance of these environmental impacts in the high-rise typology, or their relation to operating emissions. A high-rise design that achieved carbon neutrality, could, at the same time, still have significant environmental impacts in terms of embodied carbon, exclude social considerations such as residential community, safety and security and economic issues such as staff efficiency and productivity.

It is with this in mind, and through extensive research, that the author's work evolved from an examination of carbon neutrality in high-rise alone, to the consideration of sustainability in tall buildings in the broader sense, encompassing environmental, social and economic issues, examining the links between these areas and how changes driven by the influence of one can impact the others. This need for a more holistic consideration of sustainability in high-rise is also recognised in the literature. Collins *et al*., (2008) note there is a need for "*a greater breadth of consideration in order that tall buildings may be assessed on their true range of impacts, good or bad*." They go onto say "*a new and more broadly dimensioned framework is therefore required, to correctly gauge the sustainable performance of tall buildings, including their social and commercial impact*".

**Overview of the Links between Papers**

The common theme that describes how the research presented here is tied together is *tall buildings and sustainability,* and the quest the author has undertaken to identify opportunities and challenges for more sustainable high-rise architecture. In considering the holistic sense of sustainability, including environmental, social and economic issues, the research is purposely broad and multi-dimensional, but in the author's opinion, such thinking is essential for the creation of more sustainable high-rise.

Paper 1 "*Global Trends in High-Rise Design*" starts the discussion by suggesting that tall buildings internationally are shaped primarily by economic forces alone, with too little consideration of environmental and social sustainability. However, it suggests this is beginning to change as a small but growing number of tall buildings are designed with a greater concern of the environment. It goes on to suggest that whilst carbon neutrality could be a future goal for high-rise, a better goal would be the full consideration and offsetting of environmental impacts across a tall building's entire life-cycle, including its embodied carbon.

Paper 1 goes on to discuss the importance of social sustainability in tall buildings, outlining the challenges in creating high-rise living suitable for families, with a particular emphasis on the UK context. These ideas are developed through Paper 2 "*Bridging the Gap: An Analysis of Proposed Evacuation Links at Height in the World Trade Center Design Competition Entries*" and Paper 5 "*From the Orthogonal to the Irregular: The Role of Innovation in Form of High-Rise Buildings*". In both, the author highlights the skybridge as a possible vehicle for improved social sustainability in tall buildings, creating large open spaces at height, but also providing opportunities for horizontal egress and multiple evacuation routes and thus improved safety and security.

Paper 3 *"Five Energy Generations of Tall Buildings: An Historical Analysis of Energy Consumption in High-Rise Buildings"* builds on the rising environmental consciousness in high-rise design outlined in Paper 1, but charts this back historically, examining factors that have influenced tall buildings' energy requirements since the late 19$^{th}$ Century.

Paper 4 *"Aluminium and Double Skin Facades"* expands this discussion on environmental sustainability to consider in more detail the impact of embodied carbon. It explores how double-skin facades can impact both operational and embodied carbon in tall buildings and is supported by additional research examining their relative importance over a tall building's life. This research notes how embodied emissions will play a greater role in the total environmental impact of tall buildings in the future, and as such, supports the notion of full life-cycle thinking first touched upon in Paper 1.

Paper 5 brings many of these ideas together, explored through the vehicle of tall building form. It suggests how innovation in form can benefit environmental, economic and social sustainability. It also highlights links between these areas, noting, for example, that high-rise forms that reduce wind loading would also reduce structural materials and as such benefit both building cost and embodied carbon emissions.

Together this research provides an extensive agenda for improving sustainability in tall buildings. In doing so, it answers a number of research questions;

1. What major challenges need to be overcome in order to develop the tall building typology in terms of its sustainability?
2. What opportunities exist to improve the sustainable performance of tall buildings?
3. What role does embodied carbon play in the sustainable design of tall buildings? Is the tall building community justified in focussing the majority of its efforts on improving energy efficiency, or should more efforts be given to reducing embodied carbon?

## 2.1 Paper 1: Global Trends in High-Rise Design

Reference: WOOD, A. & OLDFIELD, P. (2008). **Global Trends in High-Rise Design**. *Urbanism and Architecture*, No. 49, October 2008, Heilongjiang Science and Technology Press, Ha'erbin, China, pp. 14 – 16, ISSN: 1673-0232.

This paper very much sets the scene for the submission as a whole, firstly by providing context in the form of trends and drivers, identifying what is happening in the field of tall building construction and why? Secondly, the paper goes onto to discuss why sustainability in tall buildings is important, and identifies a series of challenges for the typology to overcome in order to improve its sustainable credentials in the future. Whilst much research in this field focuses solely on the environmental performance of high-rise, this paper makes a contribution to the knowledge by also critically examining the social sustainability of tall buildings.

The paper starts by presenting four main drivers behind the current boom in tall building construction, namely the desire for maximum financial return from a piece of land, the desire to create global icons, the creation of dense concentrated cities for more sustainable ways of life, and the improved design of tall buildings following the collapse of the World Trade Center, New York. The paper continues by discussing sustainability trends, suggesting that most tall buildings completed today fail to respond to the local characteristics of climate, culture and context and instead are built to what is termed the 'standard model' – the rectilinear, air-conditioned, fully glazed box, a clearly unsustainable approach when such examples spring up in desert and tropical regions.

However, this is being challenged by a small, but growing number of architects and designers who are using appropriate environmental responses as the main design generators for tall buildings[3]. Whilst this increasing environmental awareness is clearly a positive move, the typology still has a number of challenges to face in the coming years and these are outlined in the paper as;

1. Improved environmental performance through greater consideration of the environmental impacts that occur across tall buildings' entire life cycle, including embodied energy / carbon.
2. Respond better to the unique qualities and challenges of urban locations, including local climate, culture and context.
3. Provide greater levels of mixed-use accommodation, including new functions at height.
4. Improve social sustainability through communal / recreational spaces at height.

It is perhaps the last of these that is examined in most depth in the paper. One of the primary arguments for the construction of high-rise buildings from a sustainability standpoint is they facilitate the creation of dense compact cities. The potential advantages of density are widely published – the reduction of suburban sprawl and loss of greenbelt, reduced infrastructure requirements, reduced gasoline use for private transportation, etc (for example, see Steemers, 2003). However, for these advantages to be truly realised, it is clear that inner-city residential provision is key, rather than the city centre being merely the realm of high-rise commerce. In the UK context, recent years have seen an influx of tall residential buildings in city centre areas, such as the Beetham Tower Manchester (2006), Strata Tower, London (2010), St Pauls Tower, Sheffield (2010) and Unity, Liverpool (2007), as cities strive to increase their urban residential population.

However, whilst this is clearly a positive development, it seems only young singles or couples and 'empty nesters' – older retired people who have no need for a suburban home – are residing in tall buildings and repopulating our urban centres. This statement is clearly supported by the statistics outlined in *table 1*, which shows in the UK only 13% of small families and 8% of large families live in flats.  In the author's opinion, it is pointless creating "environmental" tall buildings if only a small percentage of the many socio-economic groups will ever live in them.

[3] This paradigm shift towards more sustainable high-rise design is further examined in paper 3 where it is described by the author as a move from 'Fourth Energy Generation' to 'Fifth Energy Generation' tall buildings (see page 13).

**Table 1:** UK housing by typology (Source: Office for National Statistics, 1999)

| Household type | | Type of accommodation* | | | | | | | Base = 100% |
|---|---|---|---|---|---|---|---|---|---|
| | | Detached house | Semi-detached house | Terraced house | All houses | Purpose-built flat or maisonette | Converted flat or maisonette/ rooms | All flats/ rooms | |
| One adult aged 16-59 | % | 10 | 21 | 26 | 57 | 30 | 13 | 43 | *1107* |
| Two adults aged 16-59 | % | 27 | 32 | 25 | 84 | 12 | 4 | 16 | *1400* |
| Small family | % | 21 | 35 | 30 | 87 | 11 | 2 | 13 | *1716* |
| Large family | % | 22 | 40 | 31 | 92 | 7 | 1 | 8 | *511* |
| Large adult household | % | 28 | 37 | 28 | 94 | 5 | 1 | 6 | *1078* |
| Two adults, one or both aged 60 or over | % | 32 | 37 | 21 | 90 | 9 | 2 | 10 | *1447* |
| One adult aged 60 or over | % | 18 | 29 | 24 | 70 | 27 | 3 | 30 | *1345* |
| Total | % | 23 | 33 | 26 | 82 | 15 | 4 | 18 | *8604* |

The challenge to architects, designers and developers then, is to create tall residential towers that are appealing to a wider demographic, and in particular families. The main reason tall buildings are viewed as not suitable for families and children is the lack of open, recreational, communal spaces such as streets, plazas and gardens[4]. But why not create these spaces within tall buildings at height, with the added benefit of security, shelter and view?

Despite its office function, the paper puts forward the Commerzbank, Frankfurt, designed by Foster & Partners and completed in 1996, as a possible solution. It suggests the principles behind its design – stepped, multi-storey skygardens, airy open atria promoting natural ventilation and communal green spaces at height above the city – can be reinterpreted to produce a model for the socially-sustainable residential tower. However, the author would also highlight the case study of Singapore as pointing the way forward in terms of tall building social sustainability. In a city-state where 86% of people live in social housing, the majority of which is high-rise (Yuen, *et. al*., 2003), Singaporean towers have embraced the idea of skygardens, with many incorporating some form of social spaces (see *figure 1*). These include children's play areas, fitness centres for the elderly, jogging tracks and more, all at height above the city. Many of these buildings also have greater rents and increased apartment prices, providing a financial incentive to developers to incorporate such spaces[5]. This is a theme that is common throughout the submission, with these ideas developed through papers 2 and 5.

[4] This statement is supported by research undertaken to outline the failures of tall buildings in terms of their social sustainability. For example, Fowler (2008), suggests children living in tall buildings are less free to explore their neighbourhoods and have fewer friends than those who lived in townhouses, whilst a survey of residents living in towers in Atlanta and Chicago showed over 60% missed the greenery associated with low-rise living (Conway, 1977).

[5] For example, the apartments in the Pinnacle @ Duxton, which is illustrated in *figures 1a, 1b, 1c and 1d*, were some of the most expensive ever sold in Singapore, with five-room units selling for $646,000 SGD. Despite being social housing, the building includes top-end features such as large communal skybridges offering panoramic city and sea views and community space at height which increased the units' value significantly (Teo, 2009).


**Figure 1:** A selection of the many social / communal spaces at height in tall buildings in Singapore. (a) The Pinnacle @ Duxton consists of seven 50-storey residential towers connected by skybridges housing social and recreational spaces; (b) The Pinnacle @ Duxton, jogging track for residents on the 26th storey; (c) The Pinnacle @ Duxton, 50th floor skygarden seating area; (d) The Pinnacle @ Duxton, 50th floor skygarden and gathering area; (e) Multi-storey skygarden at the National Library Singapore; (f) The Icon Loft, a 46 storey residential tower with residents' gardens on the 30th floor; (g) The Icon Loft, internal view of residents' gardens (Source: all by author)

## 2.2 Paper 2: Bridging the Gap: An Analysis of Proposed Evacuation Links at Height in the World Trade Center Design Competition Entries

Reference: WOOD, A. & OLDFIELD, P. (2007). **Bridging the Gap: An Analysis of Proposed Evacuation Links at Height in the World Trade Centre Design Competition Entries**. *Architectural Science Review*, Volume 50.2, June 2007, University of Sydney, Australia, pp.173-180, ISSN: 0003 8628.

This paper follows on from the social sustainability research presented in paper 1, although here with a particular emphasis on safety and security in tall buildings post 9/11. Whilst issues surrounding community, neighbourhoods and social interaction are central to the development of social sustainability, it is clear that safety and security are also key components of tall building sustainability, especially after the collapse of the World Trade Center Towers. Colantonio & Dixon (2007), for example, define a socially sustainable community as one which is safe and inclusive, well planned, built and run, and that offers equal opportunity and good services for all.

The collapse of the World Trade Center Towers some ten years ago sparked a huge flurry of research into the typology[6], with evacuation and occupant safety at the forefront of this. Whilst some research has examined improving existing evacuation systems such as stairs, and using elevators for evacuation, significant research has also examined 'alternative' evacuation concepts such as the horizontal egress of occupants at height through skybridges. Paper 2 and its content thus evolved out of an acknowledgement by the authors that five of the seven official proposals for the World Trade Centre re-design competition included some form of skybridge or connectivity at height, as did numerous unofficial proposals. This led the authors to investigate if this could be a new direction for the improved safety and performance of tall buildings.

The case for the skybridge is made throughout the paper, with particular emphasis on evacuation. The linking of a number of towers provides occupants with multiple horizontal and vertical evacuation routes, a system which would be of great benefit in extreme events such as those of 9/11. This advantage is especially apparent in the scheme by Team Peter Eisenmann, Charles Gwathmey, Steven Holl and Richard Meier, and the proposal by United Architects. However, the paper also adds to the knowledge by undertaking a systematic and detailed review of all five proposals that incorporate skybridges including considerations of the horizontal connections technically, structurally, in terms of planning, circulation, quality of life, etc.

[6] For example, the CIB – CTBUH conference in 2003 was entitled "Strategies for Performance in the Aftermath of the World Trade Center", and presented nearly 100 papers and presentations on this theme (Shafii *et al.*, 2003).

The paper concludes that it is in large-scale urban schemes such as the World Trade Center re-design where the skybridge becomes most plausible. In these scenarios a multitude of towers are simultaneously conceived, designed and constructed and the development of any horizontal connectivity between them would be integral to the design in terms of structure, construction and aesthetics. Since the paper's development there have been many examples of urban-scale schemes constructed including skybridges such as the Pinnacle @ Duxton, Singapore (see also page 11), Marina Bay Sands, Singapore and Linked Hybrid, Beijing thus supporting this conclusion.

The paper acknowledges there are significantly greater challenges in the retrospective / incremental incorporation of skybridges, but presents the case study of the existing low-level skybridge network in Hong Kong as a possible solution. This network has evolved over 40 years and conjoins approximately 40 buildings over many kilometres. Its analysis in the paper highlights several additional social and environmental advantages of the skybridge such as the creation of a shaded pedestrian environment above the automobile-dominant ground level, greater security, redundancy and sharing of services between buildings, etc.

## 2.3 Paper 3: Five Energy Generations of Tall Buildings: An Historical Analysis of Energy Consumption in High-Rise Buildings

Reference: OLDFIELD, P., TRABUCCO, D. & WOOD, A. (2009). **Five Energy Generations of Tall Buildings: An Historical Analysis of Energy Consumption in High-Rise Buildings**. *Journal of Architecture*, Vol. 14, No. 5, pp. 591 – 614, ISSN: 1360-2365.

There have been many attempts to categorise tall buildings based on factors that influence their design. It is common, for example, to categorise tall buildings based on their structural material (steel; concrete; composite), or function (mixed use; office; residential; hotel) or even aesthetics (functional; eclectic; modern; post modern – for more on this see Huxtable, 1982). It seems strange then, considering the importance of sustainability that no attempts have been made to categorise tall buildings based on their environmental performance. This paper fills this research gap by examining the history of energy use in tall buildings, from their origins in North America in the late nineteenth century to the present day. In doing so, it categorises tall buildings into five chronological 'generations' based on factors affecting their energy performance. The main factors considered include the building's shape and form (particularly the surface area to volume ratio), artificial lighting requirements, facade thermal performance, facade transparency, ventilation strategies and general attitudes towards sustainability.

The role of the paper is to provide an historical 'stock take' of the typology, to examine what has influenced the environmental performance of tall buildings over the past 125 years, and how? Through this, the paper provides context for the current challenge of designing sustainable tall buildings and also highlights potential lessons for the future. A short overview of each of the five energy generations as determined by the authors is outlined below.

**First Energy Generation: From the Birth of Tall Buildings in 1885 to the 1916 Zoning Law**

Energy in first-generation tall buildings was predominantly consumed in the heating of occupied spaces and providing vertical transportation, as technologies such as fluorescent lighting and air-conditioning were not yet commercially developed. Artificial lighting levels were typically very low, between 22 and 43 lux in office buildings, due to inefficiencies of lighting technologies of the time (Osterhaus, 1993). The quality of internal space thus depended on natural light through large bay windows and high ceilings that allowed penetration deep into office spaces. Many tall buildings of the time, such as the Chicago Quarter Block Buildings[7], also utilised large central atria spaces to further flood interiors with natural light. Despite the use of large windows, envelopes of the time remained heavily influenced by load-bearing technology, were often quite thick and of masonry construction. Although lacking in thermal insulation and air-tightness, such build-ups did provide a degree of thermal mass to maintain warmth in the winter and absorb excess heat gains in the summer months. The form of first-generation buildings was typically compact and bulky, the result of repetitive stacking of large floor plates for the return of maximum rentable floor area. The resultant low surface area to volume ratios of such towers was inherently energy efficient in terms of heating, as it provided a smaller area of building envelope per unit floor area, thus facilitating less heat loss.

**Second Energy Generation: From the 1916 Zoning Law to the Development of the Glazed Curtain Wall, 1951**

The 1916 New York Zoning Law was brought in as a response to the proliferation of increasingly bulky and massive first-generation tall buildings, which were blocking sunlight from streets and neighbourhoods across New York. The Zoning Law required tall buildings to incorporate set-backs within their form, to allow light to penetrate onto streets below, and thus created the familiar 'wedding cake' skyscraper style of the era. Research by the authors has demonstrated that this change in regulation, not only influenced building form, but also how energy was consumed in towers at the time. As shown in *figure 2*, the stipulation of more slender buildings significantly increased surface area to volume ratios, and thus, facilitated greater heat loss through increased quantities of building envelope[8]. However, like first-generation towers, these buildings also benefited from high thermal mass within the envelope construction.

[7] Chicago Quarter Block Buildings, as the name suggests, took up a quarter of a city block and were typified by a bulky form with an O-shaped plan housing a central 'light court'. Forty such examples existed in Chicago in 1909 (Willis, 1995).

[8] To support this argument, the paper refers to research undertaken by Depecker *et al.* (2001) which demonstrates that in a climate with cold winters, such as New York, energy requirements for space heating are proportional to a building's surface area to volume ratio. For more on this see the 'supporting research' on page 18.

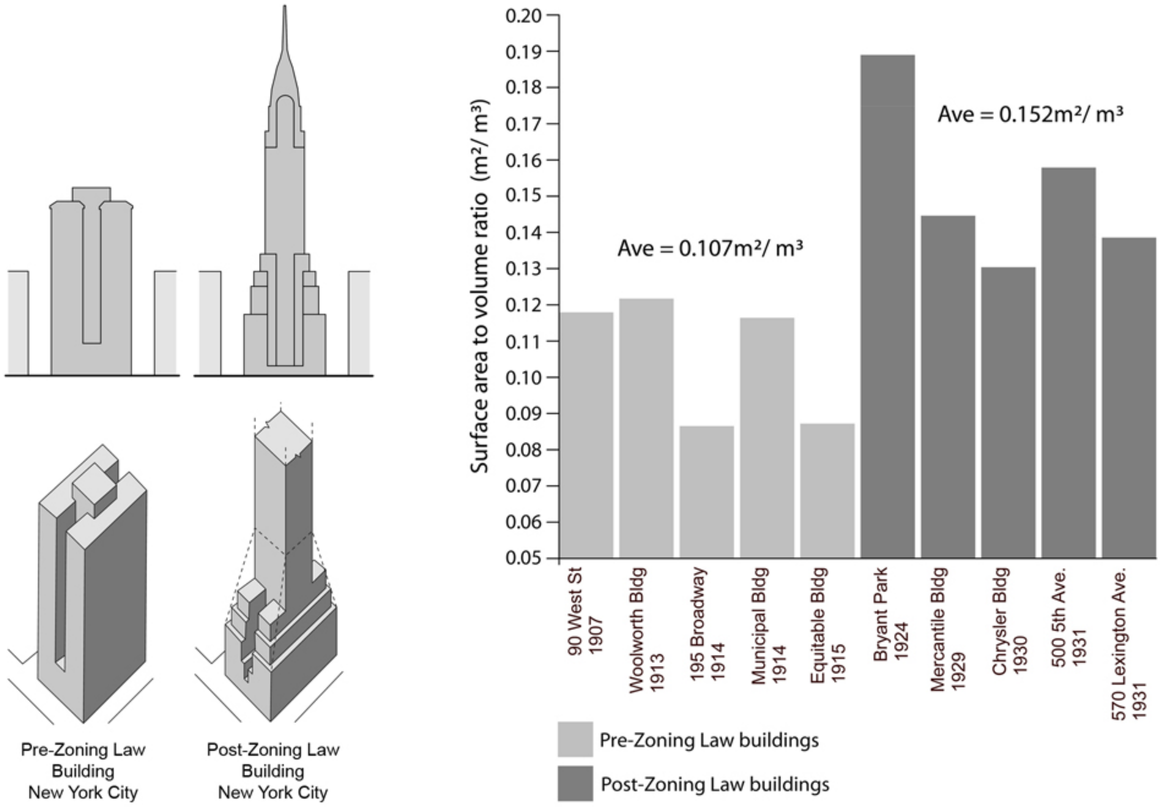


**Figure 2:** Impact of the 1916 New York Zoning Law on tall building form (left) and surface area to volume ratios (right) (Source: authors)

**Third Energy Generation: From the Development of the Glazed Curtain Wall, 1951, to the 1973 Energy Crisis**

The energy performance of tall buildings of this era was primarily influenced by a dramatic shift in building envelope style and technology – the development of the fully-glazed, curtain wall facade. Whereas tall buildings of the first and second generations had facade transparencies of typically between 20% and 40%, this new era heralded buildings with much greater quantities of single glazing, typically between 50% and 75% of facade area. The impact of this change on envelope thermal performance was both dramatic and detrimental, with U-values increasing from around 2.5W/m²K to 3.0 – 4.2W/m²K, promoting greater heat losses and gains through the building fabric. In addition, the fashionable use of tinted glass perversely meant that despite high quantities of glazing in the facade, little natural light would actually penetrate into the office spaces. It is not surprising then that artificial lighting requirements rose significantly in this period. Due to changes in zoning laws and the corporate need for larger floor plates, tall buildings also reverted away from the slender towers of the second generation to more bulky rectilinear forms. All in all, tall buildings of this generation were hermetically sealed boxes, totally reliant on mechanical conditioning[9] and artificial lighting to compensate for poor facade performance and deeper floor plans.

[9] It is worth noting that although air conditioning was commercially available during the second energy generation, with the 1928 Milam Tower in San Antonio the first high-rise office building to be completely air-conditioned (Pauken, 1999), it is not until the third generation that such technologies became standard.

**The Fourth Energy Generation: From the Energy Crisis of 1973 to the Present Day**

The energy crises of 1973 and 1979 brought about a new attitude towards energy efficiency, with many developed nations bringing in building energy performance codes. This triggered the development of better insulating and solar-control glass, and forced a widespread switch to double-glazing in high-rise facades (Johnson, 1991). Curtain wall performance improved dramatically, with U-values falling from 3.0 – 4.2W/m²K to 1.0 – 1.5W/m²K, whilst improved building management systems and efficiencies in plant equipment further benefitted energy consumption. Further research by the authors also identified that this new era of energy efficiency also resulted in a significantly reduced quantity of black skyscrapers being constructed. Influenced by the fashion of the 'International Style', and popular during the third energy generation, these buildings suffered from increased solar absorbance due to their black cladding, leading to greater heat gains through the building fabric.

**The Fifth Energy Generation: From the Rise of an Environmental Consciousness (1997), to the Present Day**

Recent years have seen an even greater environmental awakening, as the world comes to grips with the challenge of climate change and the need for more sustainable ways of life. As also outlined in paper 1, in response a growing number of tall buildings are developing with environmental performance as the main design generator. This is typified by the Commerzbank, Frankfurt[10], which displays many of the characteristics of fifth generation buildings. These include a central atrium allowing for natural lighting and ventilation, spiralling skygardens to further increase daylight penetration and provide areas for social gathering at height, a facade facilitating natural ventilation for over half the year, a water-based cooling system of chilled ceilings and more (Fischer *et al.*, 1996). The authors also acknowledge that a further common characteristic of this generation is the exploitation of on-site energy generation from low-and-zero carbon sources.

The paper concludes by acknowledging that a growing number of tall buildings constructed today meet fifth energy generation criteria, which is clearly a positive direction for the typology. However, the vast majority of tall buildings are still built to fourth energy generation characteristics – meeting regulatory energy requirements, but not focussing on environmental performance as a primary design driver. Greater efforts are therefore needed to promote fifth energy generation characteristics in future high-rise.

[10] Completed in 1997, the authors argue that this is first significant tall building designed with sustainability as the primary design generator, although one could look at the works of Ken Yeang, SOM or Frank Lloyd Wright as earlier examples (Wood, 2007).

The author here would also note the parallels between first and fifth energy generations. In both eras tall building design is influenced by the desire to condition internal spaces by passive means through natural lighting and ventilation – in the first generation due to lack of mechanical means, and in the fifth generation due to the desire to improve environmental performance. This can be clearly seen through the common use of atria and light courts in both generations as shown in *figure 3*. Perhaps future tall buildings may also benefit from additional first and second generation characteristics such as increased opacity and thermal mass in the building facade, and a move away from the fully-glazed curtain wall?

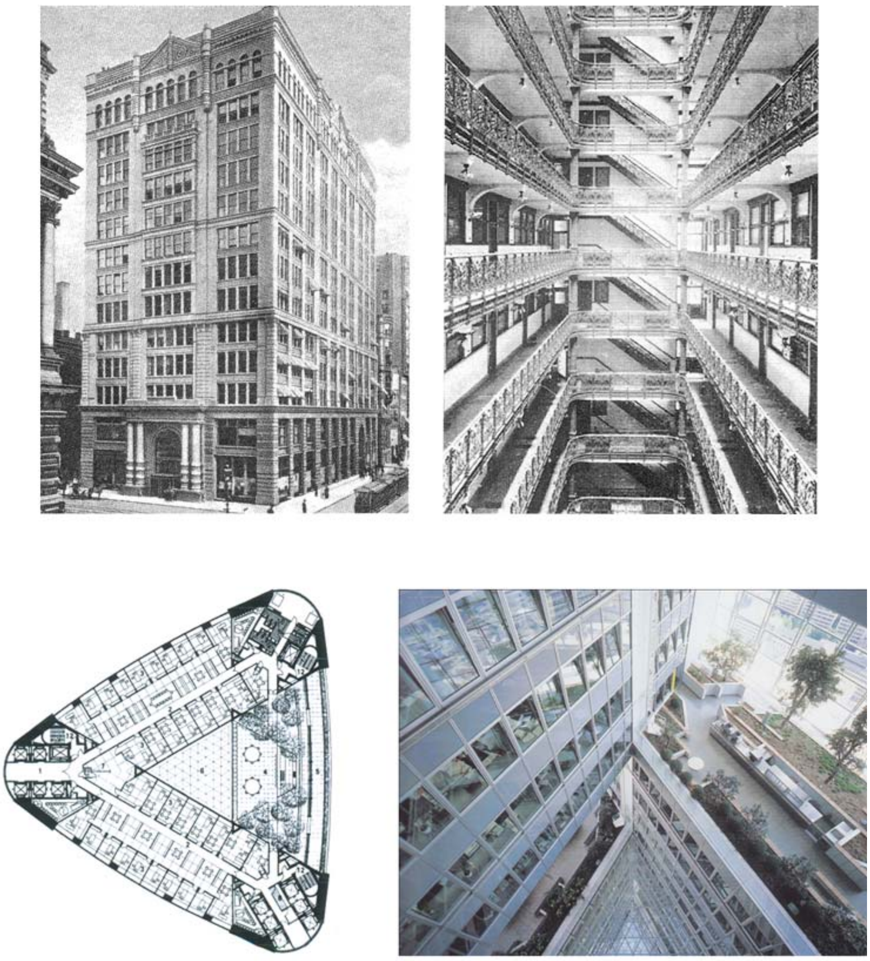

**Figure 3:** Comparison between first energy generation and fifth energy generation tall buildings showing similarities in use of central atria to facilitate natural light and ventilation. Top: Chamber of Commerce Building, Chicago, 1889, exterior view and internal light court (Source: Willis, 1995) Bottom: Commerzbank, Frankfurt, 1996, plan and central atrium (Source: Fischer *et al.*, 1996)

## Supporting Research: The Importance of Compactness and Surface Area to Volume Ratios in Tall Buildings[11]

One of the factors identified in paper 3 as impacting tall building energy performance is compactness of form, or surface area to volume ratio. The author is undertaking additional research into the importance of this variable as part of a larger ongoing study investigating the opportunities and challenges for 'Passivhaus' thinking in tall buildings[12].

Passivhaus itself is a building concept where thermal comfort is achieved to a maximum extent through passive measures such as super-insulation, heat recovery, passive use of solar energy and internal heat gains. To be considered Passivhaus compliant buildings need to achieve less than 15kWh/m²/annum for heating or cooling and less than 120kWh/m²/annum for primary energy requirements (Passipedia, 2011). Typically, Passivhaus buildings can be characterised by six factors;

1. The use of super-insulation and triple-glazing in a high-performance building envelope - typical building fabric U-values of less than 0.15W/m²K for opaque elements and 0.85W/m²K for transparent elements (McLeod *et al.,* 2011)
2. The use of mechanical ventilation with heat recovery (MVHR)
3. Careful exploitation of solar gain
4. A high degree of airtightness with a limit of 0.6 air changes per hour at 50 Pascals pressure (McLeod *et al.,* 2011)
5. Minimisation of thermal bridges
6. Compactness of form

The primary advantages of Passivhaus buildings are significantly reduced energy demands for space conditioning as compared to 'typical' buildings and high levels of interior comfort for occupants. It seems strange then that despite many thousands of Passivhaus compliant buildings being constructed globally over the past twenty years, very little exists, or has even been proposed in terms of Passivhaus high-rise[13].

[11] Although unpublished in text form, this research was published by the author as part of a conference presentation in: OLDFIELD, P. (2011). The Passivhaus Skyscraper - Opportunities and Challenges for 'Passivhaus' Thinking in Tall Buildings. *CTBUH 2011 World Conference "Why Tall? Green, Safety and Humanity"*, Seoul, South Korea, October 10 – 12, 2011. This presentation along with descriptive text is included in Appendix A, pages 162 – 202.

[12] This research evolved out of a 6-month studio design research project the author ran with 27 students in 2010 as part of his role as Lecturer in Architecture at the University of Nottingham, Department of Architecture and Built Environment. The studio, entitled 'The Passivhaus Skyscraper', challenged students to design tall buildings that met Passivhaus performance criteria, and is now run annually by the author. A selection of studio output is presented in Appendix A, pages 176 – 202.

[13] The one notable exception to this is the Power Tower, Linz, completed in 2008. The building, designed by Kaufmann Partner Architektbűro is described as the world's first Passivhaus office tower (SAUTER, 2008). More detail on the Power Tower is outlined in Appendix A, pages 168 – 170.

This ongoing research then, examines if there are any characteristics inherent in high-rise that lends the typology to Passivhaus performance, or which restricts the use of Passivhaus thinking in tall buildings. One particular quality of high-rise identified by the author as a potential opportunity in this respect is that of surface area to volume ratio. As discussed in paper 3, surface area to volume ratio is a key characteristic influencing building energy performance; a high surface area to volume ratio means the building has greater quantities of envelope facilitating heat loss, and as such requires increased energy for heating in temperate climates (Depecker *et al*., 2001). A low surface area to volume ratio means reduced envelope facilitating heat loss and thus reduced heating requirements[14]. The quality identified by the author is that tall buildings, by nature of their compact form and density of apartments, have significantly reduced surface area to volume ratios as compared to other residential typologies. This is illustrated in *figure 4*.

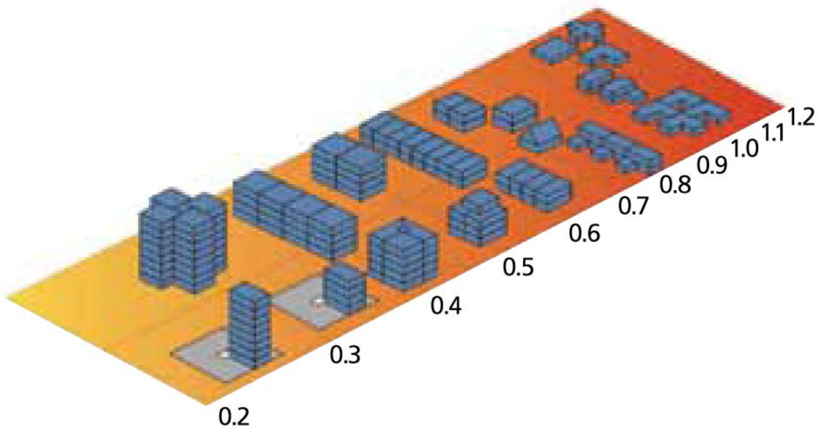


**Figure 4:** Surface area to volume ratios of different residential typologies, (Source: McLeod *et al.,* 2011)

To examine the impact residential typology and surface area to volume ratio has on Passivhaus performance, preliminary research has been undertaken by the author in conjunction with Masters in Architecture student Chuyu Qiu. Four buildings representing different residential typologies – detached house, terrace house, low-rise apartments and high-rise apartments – have been studied, and their annual heat demand determined by the Passive House Planning Package 2007 (Feist, 2007). This is essentially a series of linked spreadsheets that can determine Passivhaus performance based on the input of key building characteristics (U-values, floor and wall areas, windows, ventilation system, etc).

[14] It is important to note the difference here between surface area to volume ratio and 'wall to floor' ratio. The former can be used – as in this instance – to examine building energy performance by comparing external surface area with internal volume. The latter is a comparison between external surface area and floor area often used to examine building economics by cost consultants as envelope, along with structure, are the most expensive elements in modern high-rise buildings (Watts & Kalita, 2007). The two are inter-related with building shape, plan form and height impacting both ratios. For example, slender towers have higher surface area to volume ratios, impacting energy required for heating, but also higher wall to floor ratios, increasing building cost per unit floor area (Watts & Kalita, 2007).

The three low-rise typologies are based on as-built Passivhaus buildings, but due to a lack of completed Passivhaus towers, the high-rise residential example is based on a non-Passivhaus building with its envelope and mechanical performance upgraded to Passivhaus specification. As the study is an examination on the impact of typology and surface area to volume ratio, all other characteristics of the four scenarios – location, orientation, thermal performance of facade, glazing, shading, etc – are kept the same. A full list of building characteristics and assumptions are outlined in *table 2* below. An illustration of each of the four buildings, along with their surface area to volume ratios is outlined in *figure 5.*

**Table 2:** Building characteristics and data sources

| **Characteristics** | **Detached House** | **Terraced House** | **Low-Rise Apartments** | **High-Rise Apartments** |
|---|---|---|---|---|
| **Building** | Camden Passivhaus, London UK | Hannover-Kronsberg Passivhaus | Lodenareal Passivhaus | Beetham Tower, Manchester (upgraded to Passivhaus performance) |
| **Architect** | bere:architects | Rasch & Partner | Architekturwerkstatt din-a4 | Ian Simpson Architects |
| **Data on building form and dimensions** | Lewis, 2011 | Feist *et al*., 2005 | din-a4, 2009 | Courtesy of the Beetham Organisation |
| **Floors** | 2 | 2 | 6 | 47 |
| **Surface area to volume ratio** | 1.091m²/m³ | 0.639m²/m³ | 0.302m²/m³ | 0.163m²/m³ |
| **Location** | London | Hannover | Innsbruck | Manchester |
| | All modelled in Manchester, England | | | |
| **Orientation** | All modelled as north / south orientated | | | |
| **Envelope U-Values** | All buildings modelled with the same envelope U-values. Wall U-Value = 0.138W/m²K, Floor U-Value = 0.131W/m²K, Roof U-Value = 0.108W/m²K, Glazing U-Value = 0.78W/m²K. These are taken from the example Passivhaus building outlined in the 2007 Passivhaus Planning Package (Feist, 2007). | | | |
| **Glazing** | All buildings modelled with the same glazing ratios. South Facade = 42% glazing, North Facade = 21% glazing, West Facade = 2% glazing, East Facade = 2% glazing. These are taken from the example Passivhaus building outlined in the 2007 Passivhaus Planning Package (Feist, 2007). | | | |
| **Shading** | No shading from surrounding buildings is considered. | | | |
| **Ventilation** | All buildings modelled with the same ventilation system with a heat recovery efficiency of 83% and an electrical efficiency of 0.4Wh/m³. This is taken from the example Passivhaus building outlined in the 2007 Passivhaus Planning Package (Feist, 2007). | | | |

Detached Typology
Camden PassivHaus, London
**SA / V = 1.091$m^2/m^3$**

Terraced Typology
Hannover-Kronsberg PassivHaus, Germany
**SA / V = 0.639$m^2/m^3$**

Low-RiseTypology
Lodenareal PassivHaus, Innsbruck
**SA / V = 0.302$m^2/m^3$**

High-Rise Typology
Beetham Tower, Manchester
**SA / V = 0.163$m^2/m^3$**

**Figure 5:** Surface area to volume ratios of the four different typologies (Source: author)

*Figure 5* clearly shows the impact form and typology has on building surface area to volume ratio, with the tall building having almost seven times less surface area per unit volume as compared to the detached typology. The effect of this on annual heat demand, as determined using the Passive House Planning Package, is outlined in *figure 6*. These results show a linear relationship between surface area to volume ratio and annual heat demand – the greater the surface area to volume ratio, the greater the energy required to heat the building. In this case, the high-rise typology has the lowest heat demand, followed by the low-rise apartments, terraced house and detached house. In fact, in this instance, the detached house would not meet Passivhaus heating requirements of being below 15kWh/m²/annum and would require additional insulation, or a change in shape, orientation or glazing to reduce heating demands. All the other typologies had heating demands well below Passivhaus requirements.

These results sit well with other research in the field; research by Depecker *et al.* (2001), shows a similar relationship with a study on 14 buildings[15] located in Paris, France (see *figure 7*).

[15] The thermal performance of the building envelopes in the Depecker study is far inferior to Passivhaus criteria, hence the greater heating loads identified, albeit with the same linear relationship between heating requirements and surface area to volume ratio.

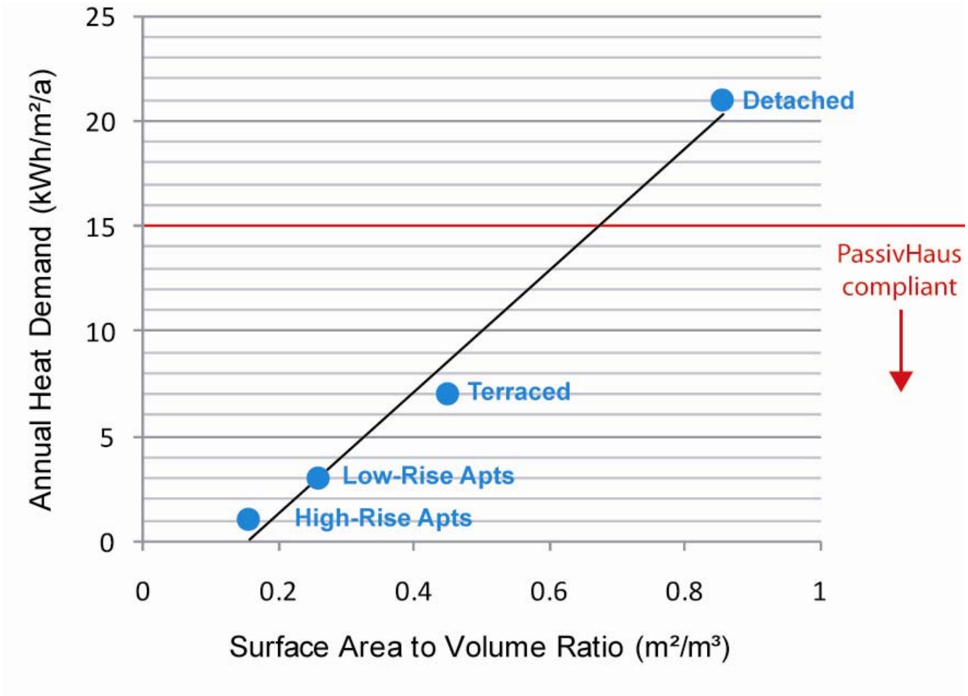


**Figure 6**: Relationship between compactness (surface area to volume ratio) and the annual heat demand of four Passivhaus buildings in Manchester, UK (Source: author)

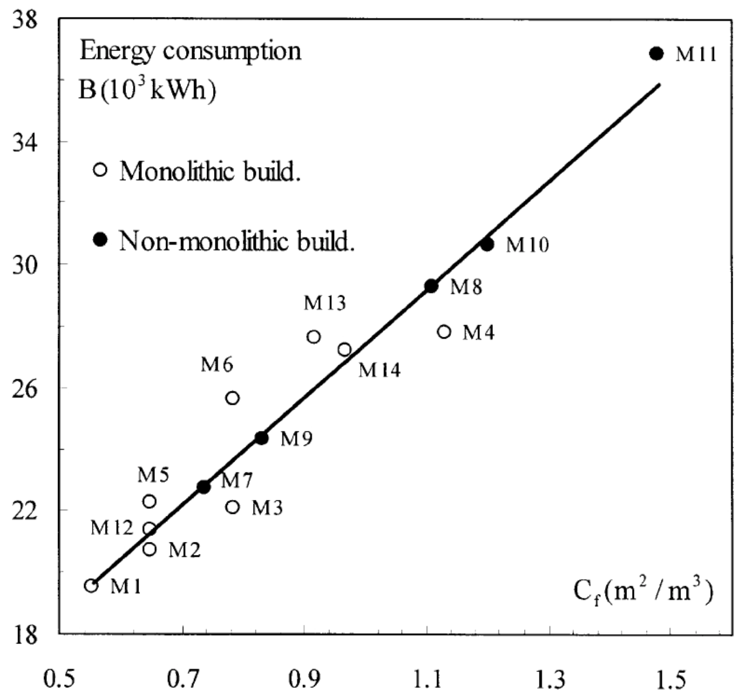


**Figure 7**: Relationship between compactness (surface area to volume ratio) and the annual heat demand of residential buildings in Paris, France (Source: Depecker *et al.*, 2001)

The impact this has on high-rise Passivhaus design is significant. Tall buildings, by nature of their inherent compactness, could meet Passivhaus heating criteria much easier than other typologies, and benefit from significantly reduced heating demands. This would give architects more freedom to explore different high-rise forms, shapes and geometries and still achieve Passivhaus performance. On the flip side, designers of low-rise Passivhaus buildings are far more restricted to maintaining compact building forms in order to reduce heat losses (McLeod *et al.*, 2011).

**Future research**

As previously mentioned, the above is preliminary research. The author is currently undertaking additional research in this field, including the examination of the following points;

- McLeod *et al.* (2011) note that buildings with high surface area to volume ratios will likely require a better envelope performance – beyond the recommended 0.15W/m²K – to achieve Passivhaus standards (within the range of 0.08 – 0.10W/m²K). By the same logic, could tall buildings, with their significantly reduced surface area to volume ratios, achieve Passivhaus performance with lower performance envelopes, perhaps with much less insulation and maybe even double-glazing, instead of the usual triple-glazing? This could significantly reduce cost (and embodied carbon) making high-rise Passivhaus more economically feasible.
- Are there any disadvantages to reduced surface area to volume ratios in high-rise buildings? Does the lack of building envelope also restrict the dispersal of unwanted internal heat gains from sources such as hot water pipes, people and equipment through the building fabric, which could cause overheating in summer months?
- The above research focused only on residential typologies in a temperate climate. Does surface area to volume ratio impact the performance of office buildings or Passivhaus performance in warmer climates?

## 2.4 Paper 4: Aluminium and Double Skin Facades

Reference: KILAIRE, A. & OLDFIELD, P. (2010). **Aluminium and Double Skin Facades.** In KATGERMAN, L. & SOETENS, F. (Eds.) (2010) *Proceedings of the 11th International Aluminium Conference 'INALCO': "New Frontiers in Light Metals"*, Eindhoven University of Technology, Holland, June 23 – 25, 2010, IOS Press, Amsterdam, pp.177 – 188, ISBN: 978-1-60750-585-3.

Whilst the previous paper examined factors that impact tall building operational energy performance, this paper examines a topic of increasing importance in the built environment and construction industry, and one which the author feels is particularly relevant in the quest for tall buildings with reduced environmental impacts – that of *embodied energy / carbon*. Throughout a building's lifecycle, environmental impacts occur at a variety of stages, from the extraction of the raw materials needed to construct the building, to the disposal and recycling of materials after its demolition. This complete boundary, encompassing all the activities related to a building's creation, use and removal is known as cradle-to-grave (see *figure 8*).

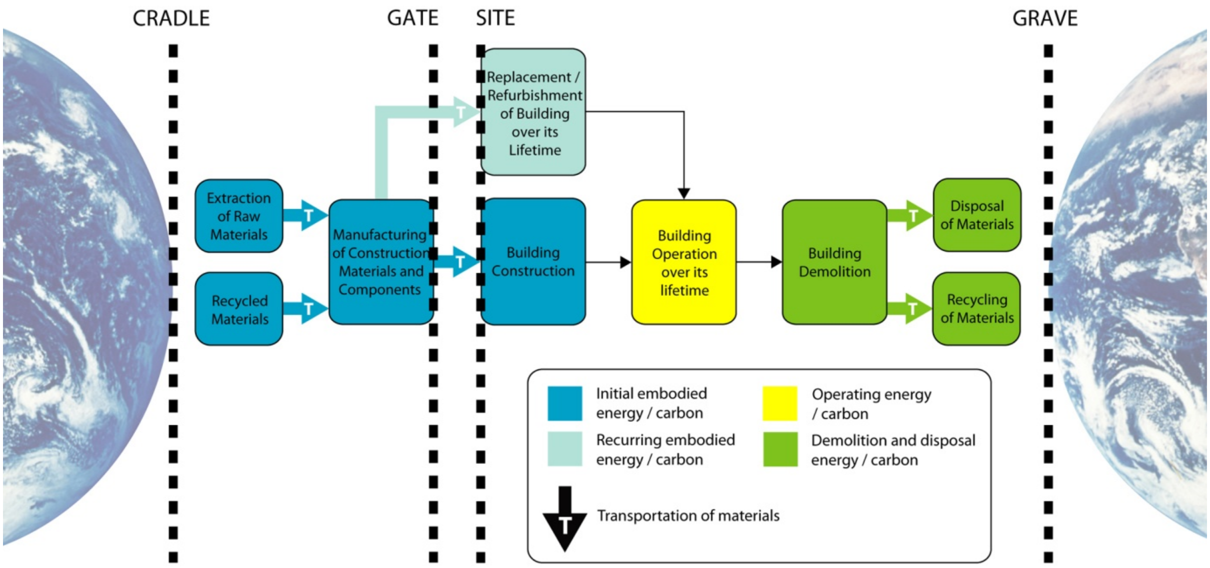


**Figure 8:** Building life-cycle environmental impacts (Source: author)

As outlined in the image above, the embodied energy of a building comprises the energy required to extract, transport and refine the raw materials (e.g. mining iron ore), manufacture the building components (e.g. creating steel beams) and construct, renovate and maintain the building[16] (Fay *et al*., 2000). The total embodied energy of a building can be considered the sum of its initial embodied energy and its recurring embodied energy. The former is the energy required in initially creating the building, whilst the latter is the energy required in maintaining, repairing and refurbishing the building over its effective life (Chen *et al*., 2001).

[16] It is worth noting that some definitions of building embodied energy include the energy associated with the building's demolition and disposal. For example, Rawlinson & Weight (2007), define a building's embodied carbon as the $CO_2$ produced during the manufacture of materials, their transport and assembly on site, maintenance and replacement, disassembly and decomposition. However, within the scope of this submission, building embodied energy / carbon does not include the energy / carbon associated with demolition and disposal, which is categorised separately. This approach is consistent with the majority of published embodied energy / carbon studies and definitions.

Whilst it is well known that the energy required to operate buildings throughout their life makes a considerable contribution to global anthropogenic greenhouse gas emissions, embodied energy also has a significant impact upon the environment. The construction and maintenance of buildings requires vast quantities of raw materials – some three billion tonnes globally each year, which equates to 40 – 50% of the total flow in the global economy (UNEP, 2007; Roodman & Lenssen, 1995). The global production of concrete, a key component in the construction of the built environment, has increased from 40 million cubic metres in 1900 to 6.4 billion cubic metres in 1997, making it the most widely used construction material in the world, with only fresh water utilised in larger quantities (Aïtcin, 2000). The extraction, processing and transportation of these materials depletes natural resources, pollutes water and the air, requires large quantities of energy and releases $CO_2$ and other greenhouse gases into the environment. Every tonne of cement, for example, requires about 1.5 tonnes of raw materials, and about 4,000 to 7,500MJ of energy for production (Swamy, 2001), with the cement industry estimated to contribute 5% of all global anthropogenic $CO_2$ emissions (Worrell *et al*., 2001).

Most current sustainability thinking is informed by the fact that roughly 20% of a building's total environmental impacts are embodied in the materials with the remaining 80% due to operations (Kestner, 2009), although figures for embodied energy in office buildings have been found to range from equivalent to 3.1 years (Scheuer *et al.*, 2003) to 40 years (Treloar *et al.*, 2001) of operating energy. It is clear, however, that there is a growing acknowledgement in the construction industry that reducing buildings' embodied energy is of significant importance in improving the sustainability of the built environment.

Paper 4 then builds upon this research by establishing the carbon impact of double-skin facades in office buildings in the UK context. Double-skin facades are a design strategy increasingly used in medium and high-rise buildings in temperate climates to facilitate natural ventilation, and thus, potentially reduce operational energy requirements[17]. However, despite many successful applications, the addition of ventilated cavities with opening slots and an additional layer of glazing have led some to criticise these systems as expensive, complicated and suffering from increased embodied energy and carbon requirements (Shuttleworth, 2008). The paper investigates if this is actually the case, by determining the initial carbon cost of double-skin facades through increased material requirements, and examines whether, and in what time frame, any reduction in operating carbon emissions through natural ventilation offsets this.

[17] For a full discussion on the role of double-skin facades, including their advantages see pp.177 – 178 of paper 4.

The paper examines a 12-storey, 7,000m² GFA office building, the characteristics of which are designed to represent those commonly under construction in the UK. In terms of facade make-up, three scenarios are investigated[18];

Scenario 1: Single-skin facade, fully air-conditioned
Scenario 2: Double-skin facade, mixed-mode conditioning[19]
Scenario 3: Double-skin facade, naturally ventilated

The results demonstrate that there is indeed an initial embodied carbon cost to double-skin facades as compared to a single-skin amounting to an extra 31.4kg$CO_2$/m²GFA. Over the whole building, this equates to an extra 208 tonnes of carbon dioxide, or 4% of the total initial embodied carbon. However, at the same time, the naturally ventilated / mixed-mode scenarios benefit from reduced energy demands due to lesser requirements for fans and pumps from reduced cooling and mechanical ventilation needs. Scenario 3 (double-skin facade, natural ventilation) has the least emissions, 5% below scenario 2 (double-skin facade, mixed-mode conditioning) and 22% below scenario 1 (single-skin facade, air-conditioned). As shown in *figure 9*, examining the life-cycle carbon emissions of all three scenarios over the first ten years of their life demonstrates that any additional embodied carbon in double-skin facades is offset by reduced operational requirements in 6.8 years when using mixed-mode conditioning (scenario 2) or 5.1 years when using natural ventilation (scenario 3).

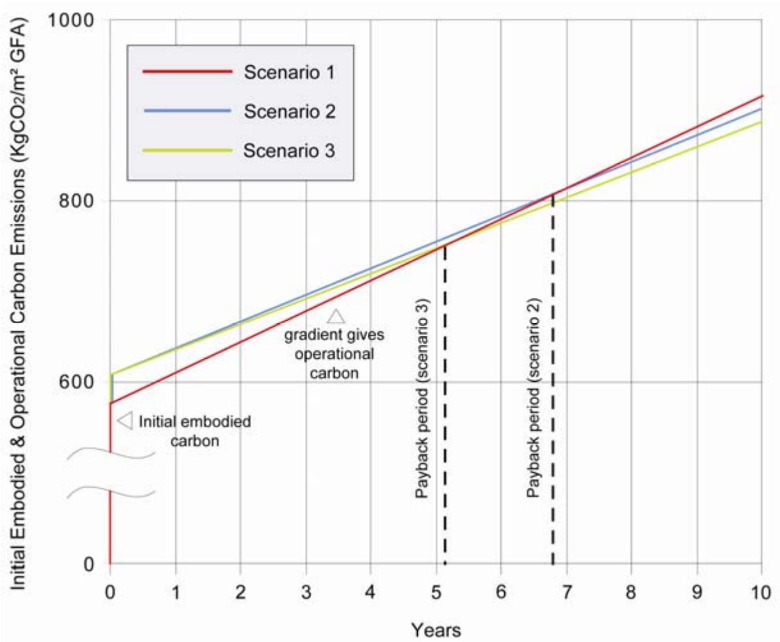


**Figure 9:** Initial embodied and operational carbon emissions of scenarios 1 – 3 over the first ten years of their lifetime. Carbon payback periods are identified for scenarios 2 and 3 as compared to scenario 1 (Source: authors)

18 A full description of the study parameters and methodology is outlined on page 178 of paper 4.

19 'Mixed mode' refers to a system that utilises natural ventilation where possible, but also includes some form of mechanical conditioning to be used when natural ventilation is not possible (e.g. during extreme temperatures).

The paper argues then that as these carbon payback periods are relatively short, embodied carbon should not be a barrier to the implementation of double-skin facades and natural ventilation in the UK context. In fact, research has shown that the adoption of passive energy measures can actually reduce embodied carbon emissions. A study undertaken by Davis Langdon, for example demonstrates that incorporating passive chilled beams with reduced glazing, improved lighting, advanced plant efficiencies and biomass not only reduced annual operating emissions of an office building, but also reduced embodied carbon (Davis Langdon LLP, 2009).

Paper 4 further explores this idea through the case study of the Deutsche Post Tower, Bonn. Here the use of a double-skin facade with internal atria allows for the building to be naturally ventilated without a central mechanical system (see *figure 10*). Whilst there is quite clearly an embodied carbon and economic cost for creating an additional layer of skin over 7,000m² of building facade, there are also environmental and economic advantages. These include the elimination of all vertical air distribution shafts[20] (reduction in building materials and improved net-to-gross efficiency) and the removal of an entire mechanical floor saving materials required for technical building equipment, and 1,000m² of rentable floor space[21] (Jahn *et al*., 2004).

**Figure 10:** Deutsche Post Tower, Bonn. Left: The building in context. Right: The double-skin facade allowing for natural ventilation (Source: Jahn *et al*., 2004).

[20] It is interesting to note that the adoption of natural ventilation in tall buildings could lead to reduced floor-to-floor heights through the elimination of horizontal ductwork also. Tall office buildings typically have a floor-to-floor height of 3.5m – 4.2m, much of which is necessary to accommodate significant air-conditioning distribution systems. If these could be eliminated, or reduced, through using natural ventilation systems, the resultant implications on building embodied energy / carbon and building cost would be significant. A meagre 200mm saving per floor over a 50 storey building would save 10 metres in height, or the equivalent of approximately two and a half storeys. This would reduce materials and construction needed for building structure, facade, services and many other elements.

[21] It is worth noting that saving rentable floor area and improved net-to-gross efficiencies can impact building embodied carbon in a favourable manner. In the case of the Deutsche Post, the saving of 1,000m² not only meant a reduction in building materials from eliminating plant, but also meant an additional 1,000m² of floor space did not have to be built elsewhere at an additional embodied carbon cost.

In conclusion then, the paper demonstrates that the implementation of passive technologies in tall buildings, such as natural ventilation, can have reasonable carbon payback periods, and may, in some instances actually reduce embodied carbon. The paper suggests it is financial barriers (e.g. initial capital costs), rather than embodied carbon, that restrict the adoption of such systems.

### Supporting Research: The Carbon Impact of Tall – Embodied Energy and High-Rise[22]

One of the many criticisms levelled at tall buildings is the high quantities of structure and materials required to support, clad and service them, coupled with energy intensive construction at height.

> *"Currently we permit the development of tall buildings even when we know that the materials from which they are built, that their methods of construction and the waste material from their construction are expensive in energy terms...In sum the greenhouse gas equivalence of the energy embodied in tall buildings constitutes a significant proportion of the annual release of $CO_2$."* [Troy, 2001]

A well referred to study by Treloar *et al.* (2001a) examining the initial embodied energy in five office buildings in Melbourne, Australia – 3, 7, 15, 42 and 52 storeys in height – shows the two high-rise buildings have approximately 60% more embodied energy per unit gross floor area than the two low-rise buildings. Furthermore, the same study identifies the embodied energy in the structural building elements (columns, walls, etc) and energy from the construction process as increasing with height, whilst other building elements (such as substructure, windows and finishes) did not appear to be influenced by the building height (see *figure 11*).

[22] This research was published by the author as part of a conference presentation in: OLDFIELD, P. (2010). The Carbon Impact of Tall – Embodied Energy and High-Rise, *CTBUH 2010 World Conference, "Remaking Sustainable Cities in the Vertical Age"*, Mumbai, India, 3-5 February, 2010.

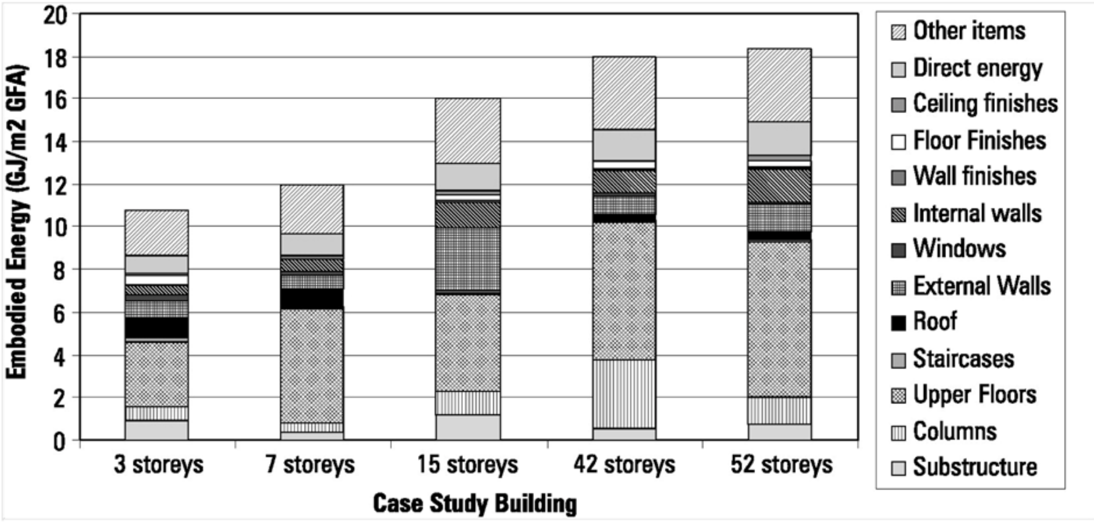


**Figure 11:** Embodied energy of five buildings in Melbourne, Australia. Embodied energy per unit floor area increases with storey height (Source: Treloar *et al.*, 2001a)

The work of Treloar *et al.* and the idea that embodied energy increases with building height has been expanded upon by the author as part of this research. A thorough literature review of published embodied energy studies has been undertaken with values of initial embodied energy compared against building storey count. The results of this analysis are outlined in *figure 12* below.

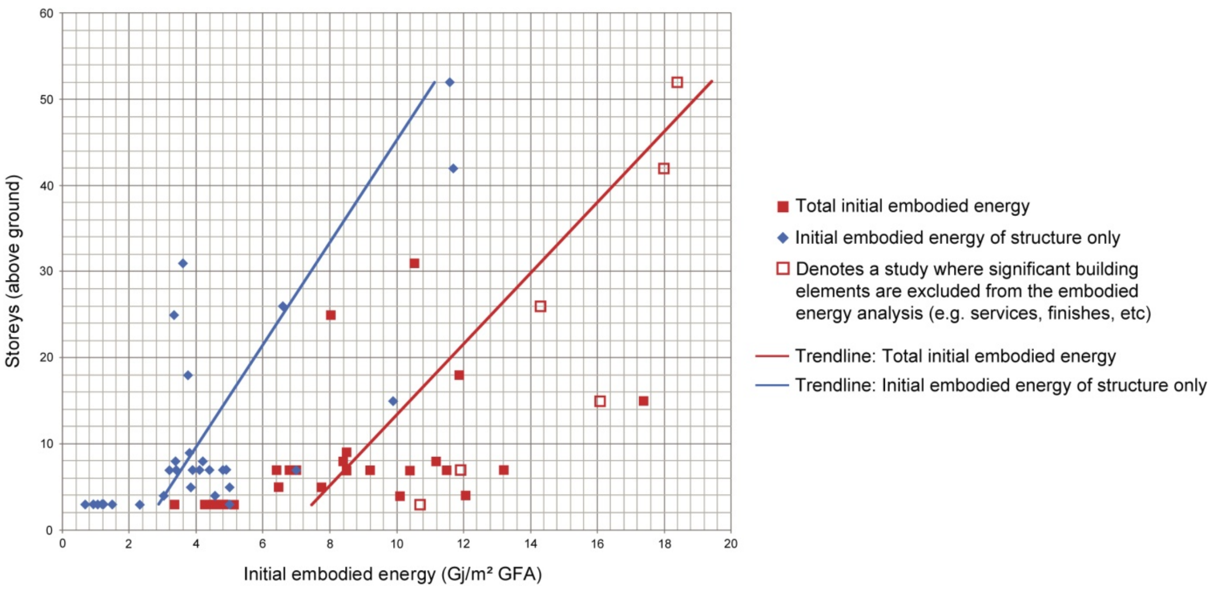


**Figure 12:** Graph showing relationship between initial embodied energy and building height, as taken from published studies (Sources: graph by author, data from Cole & Kernan, 1996; Honey & Buchanan, 1992; Kernan, 1996; Kofoworola & Gheewala, 2009; Oka *et al*., 1993; Richards, 2001; Scheuer *et al*., 2003; Suzuki & Oka, 1998; Treloar *et al.,* 2001a; Treloar *et al.,* 2001b)

This research compares favourably with that undertaken by Treloar *et al.* suggesting tall buildings do require greater quantities of initial embodied energy per unit gross floor area as compared to low-rise buildings, although, with some scattered results[23]. The embodied energy of the 'structural elements' from the literature review also increases with building height. This can be attributed to the greater quantities of structural material per unit floor area that are required in tall buildings to resist the lateral loads created by increased wind, and occasionally seismic forces, at height. For buildings over ten storeys, the additional material required for wind resistance increases non-linearly with height (Stafford-Smith & Coull, 1991). This apparent link between building height and increased embodied energy has led Treloar (and many others in the architectural community) to suggest alternatives to tall buildings should be sought where possible (Treloar *et al.,* 2001a). However, the author disputes this point of view, and suggests that it presents a simplistic and at times inaccurate portrayal of the issues surrounding embodied energy and tall buildings. For example, changes to the functional unit[24] used to compare the embodied energy of high-rise and low-rise buildings can significantly influence the results. A study by Norman *et al.* (2006) compares the embodied energy of detached suburban dwellings with that of 15 storey condominiums in Toronto, Canada. The findings, as shown in *figure 13*, show that when compared per unit floor area, the high-rise condominiums do indeed have greater embodied energy, but when compared per person the condominiums have 33% less embodied energy than the low-rise dwellings. This fact is due to high-rise apartments accommodating more residents per unit floor area than single, low-rise dwellings.

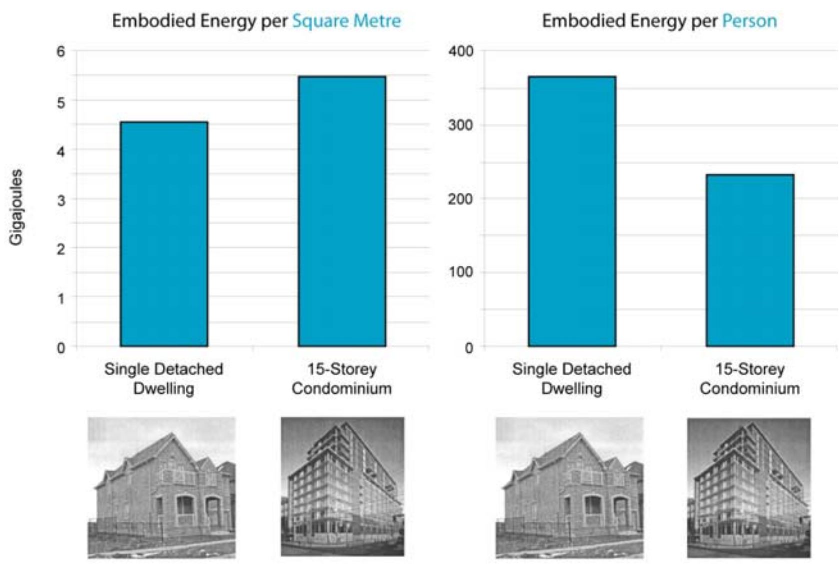


**Figure 13:** Embodied energy comparison of detached suburban dwellings and 15-storey condominiums, in Toronto, Canada (Source: by author, data from Normal *et al.,* 2006)

[23] The scattering of results demonstrates how a number of factors can impact embodied energy studies. These factors include building design characteristics, age of study, local material embodied energies and differing methodological approaches. For more on this see Ortiz *et al*., 2009 and Treloar *et al.*, 2001b.

[24] The purpose of a 'functional unit' within a life cycle or embodied energy / carbon analysis is to present a reference to which the inputs and outputs can be related (ISO, 1997). This allows for two, or more, completely different products, services or buildings, to be compared on equal footing. For example, when assessing the environmental performance of a building frame, it would be misleading to compare a tonne of structural steel with a tonne of concrete, as very different quantities of each material would be required to construct a building frame with the same structural capability (Roaf, 2004).

In the author's opinion, the comparison per person is a far more valid approach, as we build predominantly to accommodate people (workers, residents, etc), and the fact that tall buildings house more occupants per unit floor area can be considered a significant benefit in terms of sustainability. However, the issue of embodied energy and high-rise is not simply a case of being better or worse than low-rise construction, and there are a variety of advantages and disadvantages to building tall in terms of embodied energy. These are outlined by the author in *table 3* below.

**Table 3:** Environmental advantages and disadvantages of tall buildings from an embodied energy / carbon standpoint (Source: author)

| **Tall Buildings and Embodied Energy / Carbon: Advantages** | **Tall Buildings and Embodied Energy / Carbon: Disadvantages** |
|---|---|
| Residential high-rise typically accommodates more occupants per unit area than single-detached housing, which can result in reduced embodied energy per resident | Increased height means increased structural material requirements to provide resistance to wind and lateral loads |
| Increased density of cities can reduce infrastructure requirements, thus saving materials for road construction, water and waste supplies, etc | Construction at height requires lifting materials often hundreds of metres into the sky (energy requirements for craning, pumping concrete, etc) |
| Repetition of floor plates, facade and other elements allows for prefabrication, re-use of formwork, etc | Tall building construction often requires specialist materials / components which may not be available locally (e.g. transportation implications) |
| Tall buildings are generally refurbished or renovated rather than demolished and replaced with entirely new constructions (see also page 40) | Reduced net-to-gross efficiencies as compared to low-rise (e.g. more materials needed for less usable space) |
| | Due to greater wind speeds at height, natural ventilation strategies often require additional materials such as double-skin facades (see paper 4) |
| | Limited opportunities[25] for timber frame construction which has reduced embodied energy as compared to steel or concrete systems - see Cole & Kernan (1996) |

[25] The Stadthaus in London, designed by Waugh Thistleton Architects, is thought to be among the tallest timber framed buildings in the world at a mere nine storeys (Wells, 2011). However proposals have been put forward for much taller timber structures to be built in the future, up to some 30 storeys in height (Wells, 2011; Green & Karsh, 2012)

**The Importance of Embodied Carbon in Tall Buildings: A Case Study**

Whilst there has been significant research investigating the relative importance of embodied energy as part of low-rise buildings' life cycle environmental impacts (Cole & Kernan, 1996; Fay *et al.,* 2000; Langston & Langston, 2008), little work has focussed on this importance in the high-rise typology. To make an original contribution to the knowledge in this area, the author has undertaken a life-cycle analysis of the 180 metre-tall 30 St Mary Axe Tower[26] in London, UK, which was completed in 2004. The scope of this analysis is *cradle-to-end of life*, encompassing all $CO_2$ emissions until the end of the building's effective life, but excluding demolition / disposal of materials[27]. The analysis boundary includes all major architectural elements such as structural frame, substructure, upper floors, envelope, internal walls, partitions, stairs, finishes and building services. Elements outside this boundary include fit-out and furniture and embodied carbon of local infrastructure and landscaping. A full list of case study building characteristics and data sources is outlined in *table 4.*

The results of this analysis, outlined in *figure 14*, show that the building has an initial embodied carbon of 61,715 tonnes of $CO_2$, or 957kg$CO_2$/m²GFA. This is equivalent to 12.5 years of operating emissions. Corresponding with previous research, it is the structural elements (structural frame, substructure and upper floors) which make the largest contribution being responsible for 55% of the building's initial embodied carbon. The building's recurring embodied carbon – the emissions related to its repair, refurbishment and maintenance – have also been determined over a 50 year lifespan. In this instance, the annualised recurring embodied $CO_2$ emissions are taken from Davis Langdon, 2009, with the results outlined in *figure 15*. The building has a recurring embodied carbon of 12,249 tonnes of $CO_2$, or 190kg$CO_2$/m²GFA, with recurring emissions contributing 17% of total embodied carbon. It can also be seen that whilst the structural elements are the greatest contributor to initial embodied carbon, building services and finishes also have a significant environmental impact due to their regular refurbishment and maintenance.

[26] The building is more commonly known as the 'Swiss Re Tower' or the 'Gherkin'.

[27] Demolition and disposal of building materials are excluded from this study for two main reasons. Firstly, research has suggested that this phase of a building's life cycle is often negligible – for example, Scheuer *et al.* (2003) showed on a 6 storey building demolition and disposal only accounted for 0.2% of total life cycle energy. Secondly, determining what happens to building materials many years in the future, in terms of waste and recyclability, requires multiple assumptions regarding recycling techniques, future markets and scrap value of materials, etc. Such assumptions can lead to inaccuracies, and as such, this element of the building's life-cycle is not considered in this study.

**Table 4:** Case study building characteristics and data sources

| **Case Study Building Characteristics** | | **Sources** |
|---|---|---|
| Building height | 180m | Powell, 2006 |
| Number of storeys | 41 | Powell, 2006 |
| Gross Floor Area | 64,469m² | Powell, 2006 |
| Net Floor Area | 41,806m² | Powell, 2006 |
| Treated Floor Area | 54,799m² | Assumed as 85% of GFA as per the guidelines in BRECSU (2000) |
| Structural system | Steel diagrid | Powell, 2006 |
| Facade | 24,000m² Double-skin glazed curtain walling | Powell, 2006 |
| Operational carbon emissions | 76.4kg$CO_2$/m²GFA/yr | Assumed to be 'Good practice prestige air-conditioned' office building as per ECON19. Figure is 24.5kgC/m²TFA/yr, with carbon converted into $CO_2$ by multiplying by 3.67 (BRECSU, 2000). |
| Building material quantities | Various | Weight of building structural steel, foundations and curtain wall data taken from Powell, 2006. Steel decking data taken from Richard Lees Steel Decking, 2009. Figures for internal walls, partitions, stairs, finishes and building services taken from a study in Davis Langdon, 2009. In some instances material quantities are estimated by the author from drawings. |
| Material wastage factors | Various | Chen *et al.,* 2001 |
| Embodied carbon of materials (cradle-to-gate) | Various | Hammond & Jones, 2008 |
| Material locations | Structural Steel - The Hague / Brussels; Facade - Aesch, Switzerland; Concrete – 50km | Locations as per the completed building, taken from Powell, 2006 |
| Emissions from freight transportation | 0.132Kg$CO_2$/tkm | DEFRA, 2008 |
| Construction emissions | Assumed as 7.5% of cradle-to-site embodied emissions | Scheuer *et al*., 2003 |

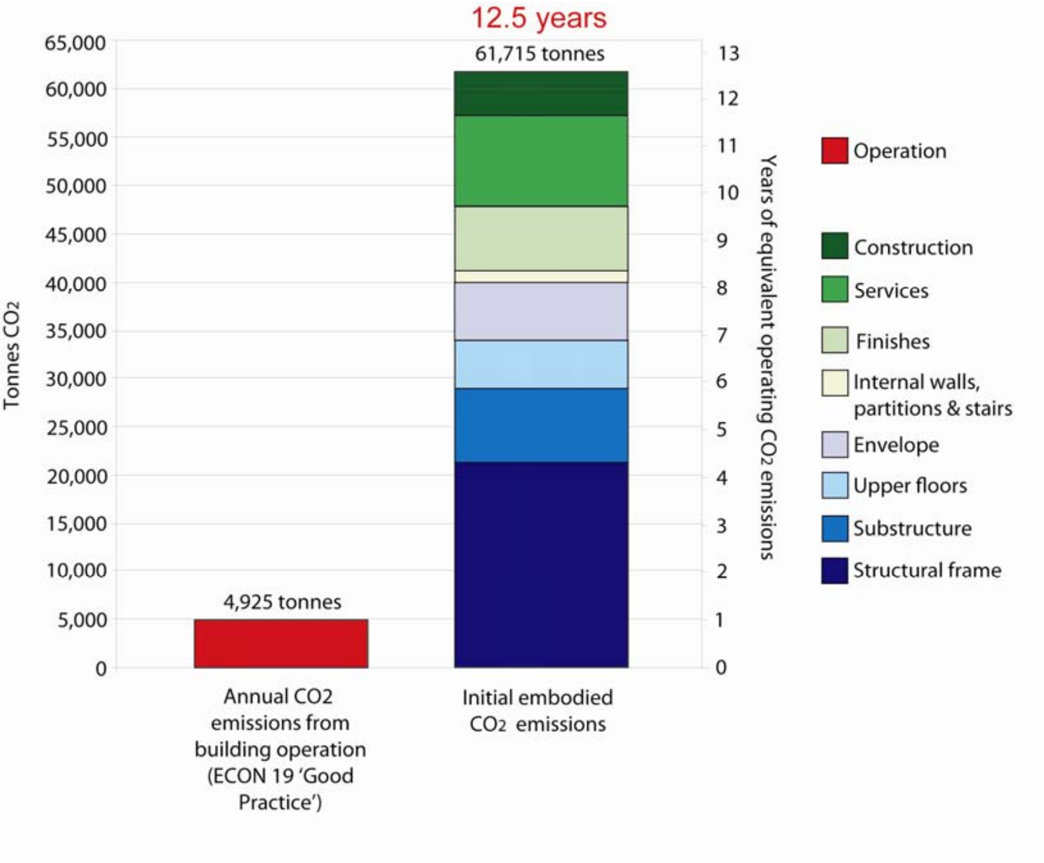


**Figure 14:** Comparison between case study building annual operating carbon emissions and initial embodied carbon by building element (Source: author)

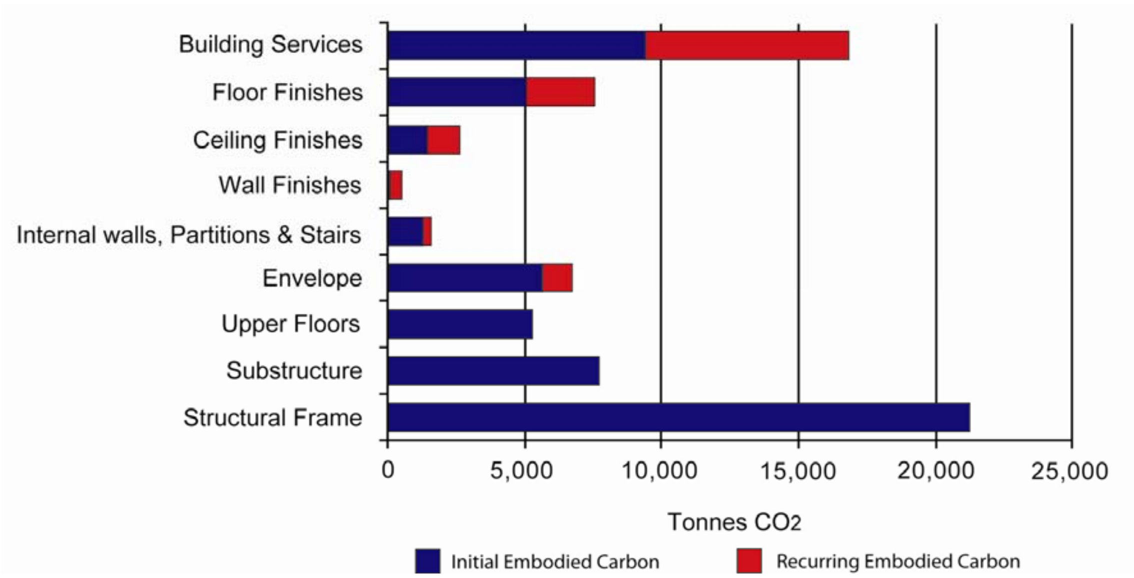


**Figure 15:** Case study building total embodied carbon by building element, including recurring embodied carbon over a 50 year life cycle (Source: author)

The total life-cycle carbon emissions of the building over a 50 year life span stands at 320,069 tonnes of $CO_2$, or approx 5 tonnes of $CO_2$ per metre gross floor area (see *figure 16*). Agreeing with current sustainability thinking, it is the operational emissions that are primarily responsible for this, contributing 77% of total emissions. This reinforces the general consensus, that reducing tall building operational emissions has the best potential for improving their environmental performance. The total embodied carbon of the building stands at 73,797 tonnes of $CO_2$, or 1,147kg$CO_2$/m²GFA – equivalent to 15 years of operating emissions. Whilst this is only 23% of the total carbon emissions, it is clear this is not an insignificant proportion, and strategies to reduce embodied carbon – particularly to structural elements, services and finishes – will have a positive impact on tall building sustainability.

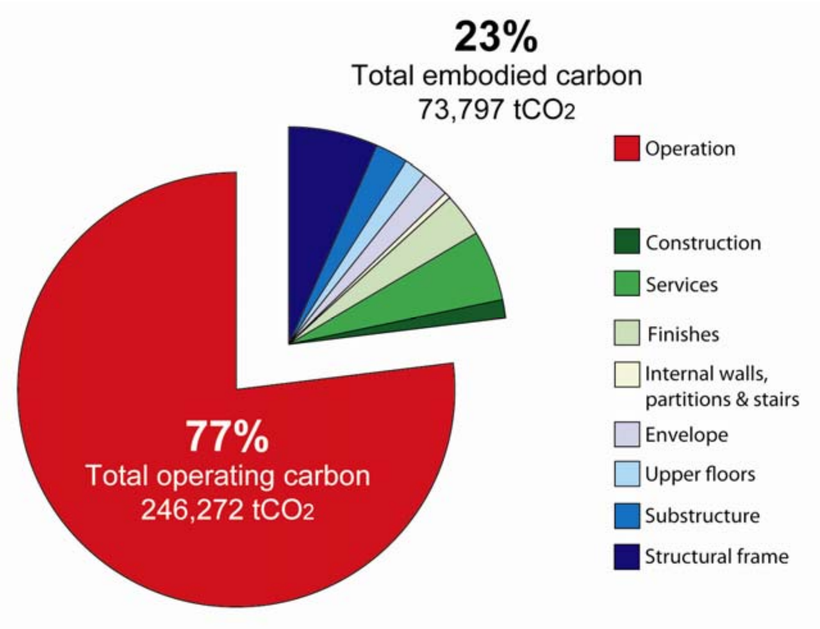


**Figure 16:** Case study building total life-cycle carbon emissions over a 50 year period (Source: author)

However, the author would suggest that embodied emissions actually have a more significant importance to tall building sustainability both in the short and longer term. Over the next decade, it is clear that vast anthropogenic green house gas emission reductions will have to occur globally in order to reduce the impacts of climate change. The Intergovernmental Panel on Climate Change (IPCC), for example, states that for low and medium $CO_2$ concentration stabilisation levels, developed countries as a group would need to reduce their emissions by 2020 on the order of 10% to 40% below 1990 levels (Levine *et al.*, 2007). Governments and regions have also set aggressive carbon reduction targets for this time frame, such as the UK 'Climate Change Act' of 2008 setting a target of a 26% reduction by 2020 against a 1990 baseline (UK Parliament, 2008). This urgency for global emissions reductions adds significance to savings that can be made in the *short-term* future. Any reduction to a tall building's initial embodied carbon would be made in this short-term future, long before the building is even occupied. Considering a tall building completed recently, in 2010, it is clear that within the 2020 timeframe, embodied emissions will play a more significant role than operational emissions. *Figure 17* shows that for the case study building, by 2020, 56% of its total carbon emissions will be due to the initial embodied carbon.

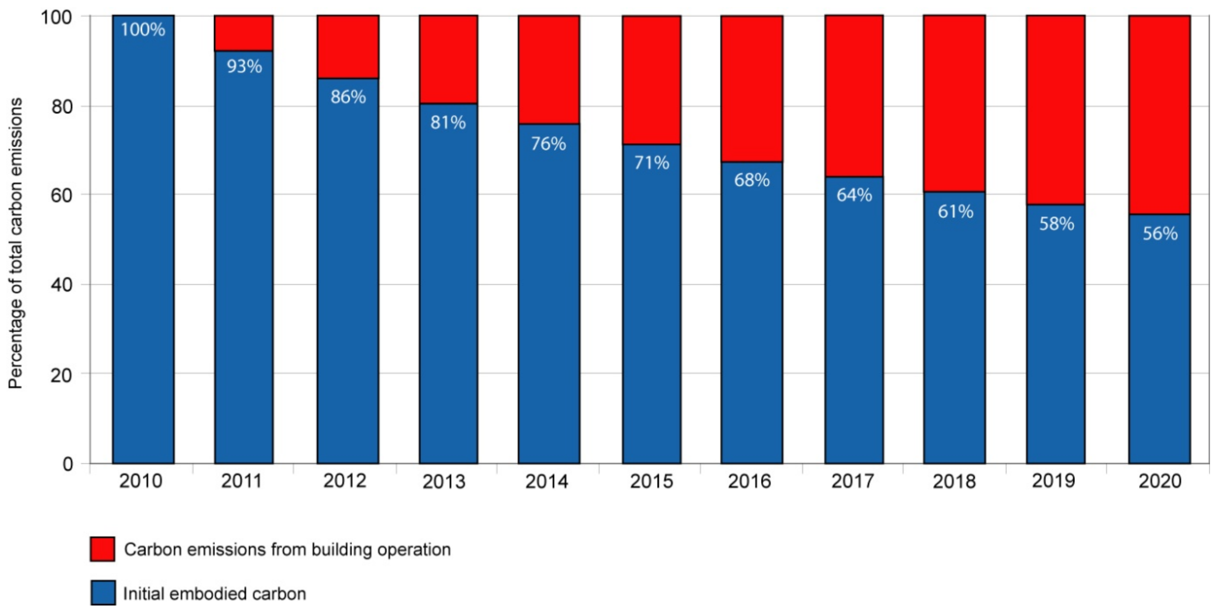


**Figure 17:** Case study building initial embodied carbon and operating carbon emissions 2010 – 2020 (Source: author)

In addition, the life-cycle carbon analysis above assumes that the case study building has operational emissions typical of a modern office building[28]. However, due to increased environmental awareness, stricter building regulations and technological advances operational emissions in buildings are likely to reduce significantly in the coming years. In tall buildings we are already seeing completed and under construction towers that claim to have large reductions in operating energy requirements as compared to the norm. For example, the Bank of America Tower, New York will use 50% less energy than the norm (Fox, 2008); the DIFA Lighthouse Tower, Dubai, also 50% less energy than the norm (Atkins, 2009); the Pearl River Tower, Guangzhou 58% less than the norm (Frachette & Gilchrist, 2008). It is clear that such examples will become more typical in the future, and as they do, embodied emissions will play a much greater role in the tall building life-cycle environmental impacts.

> *"At the moment the consensus is that a building consumes much more energy during its lifetime than is involved in extraction, manufacture and transportation. However, it will increasingly be the case that the embodied energy will be a significant fraction of the total as buildings become more energy efficient."* [Smith, 2005]

[28] Assumed to be 'Good practice prestige air-conditioned' as per ECON19 (BRECSU, 2000).

**Strategies to Reduce Embodied Energy / Carbon in High-Rise**

Through extensive research, the author has identified a number of strategies to decrease embodied energy / carbon in tall buildings. These can be categorised under the following three headings; reduce, recycle and retrofit.

**Reduce**

It is obvious that reducing the quantities of materials used in tall buildings will have a beneficial impact on their embodied carbon, especially in terms of structural materials, services and finishes. In fact significant work is undertaken on many tall building designs to optimise structure, for example making subtle changes to building form, or column and beam layouts, to reduce structural requirements and thus reduce materials, embodied carbon and cost (for more on structural optimisation see paper 5).

Additional strategies to reduce material quantities also exist. Structural fire engineering is the process of modelling a building's structure under realistic fire conditions to determine how it will react in a fire scenario and where fire protection is and isn't required. Compared to prescriptive methods that often dictate fire protection on *all* structural elements, this strategy can lead to a design that is not only more predictable in fire scenarios, but also one which uses less building materials as fire protection is only applied where it is needed[29].

To examine the quantitative impacts of structural fire engineering, the author has undertaken the initial embodied carbon analysis of the fire protection of Kings Place, London – an eight storey, 37,000m² GFA building. Two scenarios were considered; the first considers a typical prescriptive approach to fire engineering where all beams and columns are provided with intumescent paint for fire resistance of two hours. The second considers a structural fire engineering scenario where intumescent paint is only applied where it is needed following fire scenario modelling[30]. The results are outlined in *figure 18*.

[29] For more on structural fire engineering see Bailey, 2004.

[30] The analysis considers all the $CO_2$ emissions until the end of building construction, within a *cradle-to-site* boundary. The data used to undertake the study has been drawn from a number of sources. King's Place was chosen as a case study due to the availability of data, with information on the building column and beam layout, fire protection thickness and where this is applied in both scenarios supplied by Arup Fire, London. The embodied carbon of paint was taken from Hammond & Jones, 2008, with the carbon impact of freight transportation taken from DEFRA, 2008. Data on the energy requirements of the application of intumescent paint via airless spray was courtesy of a personal communication with Garry Dowling of High Tec Spray Ltd, UK. A $CO_2$ emission factor for delivered electricity to site of 0.54055 $KgCO_2/kWh$ is also used (DEFRA, 2009).

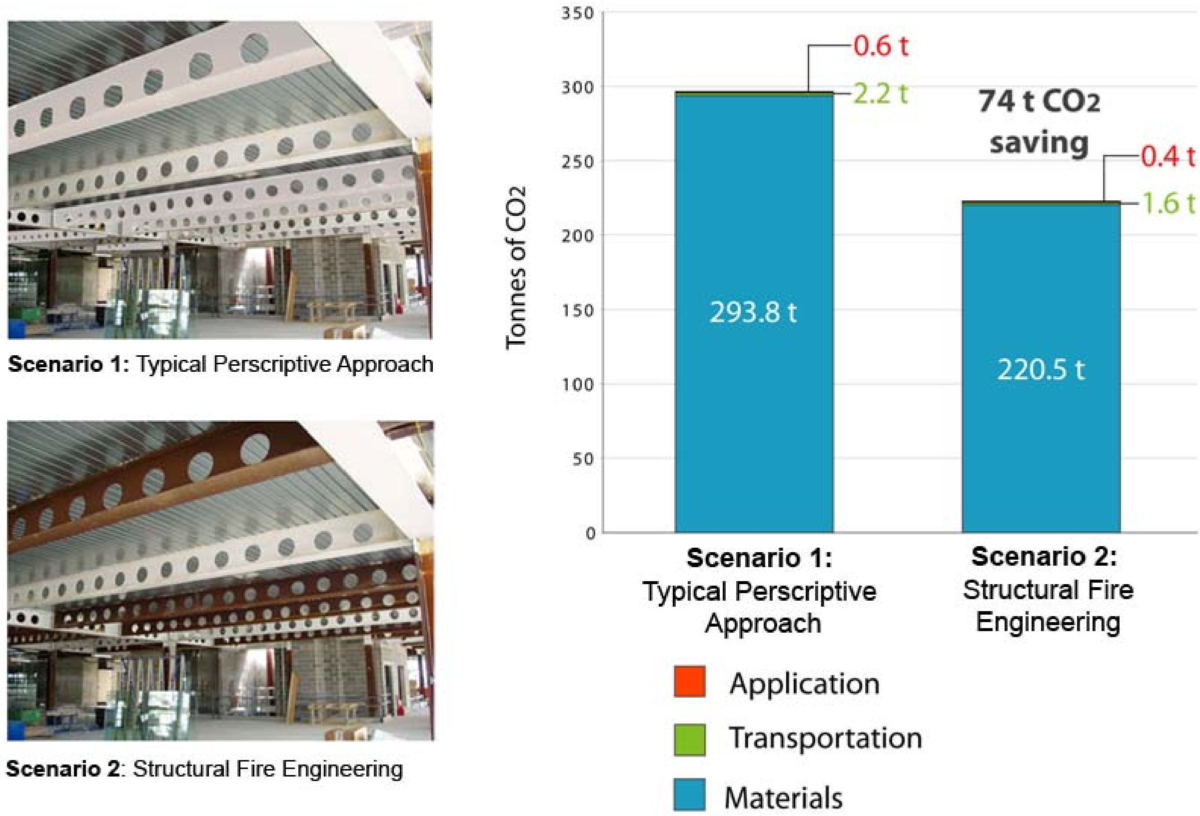


**Figure 18:** Initial embodied carbon analysis of the structural fire protection of King's Place, London, demonstrating the embodied carbon impact of structural fire engineering (Source: author)

The results demonstrate that using a structural fire engineering approach saves 74 tonnes of $CO_2$, or 25% of the initial embodied carbon of the structural fire protection. Not only would this result in reduced cost, materials and environmental impact, but also to increased safety as the building's structural performance is more predictable in fire situations. Such a strategy therefore benefits not only environmental, but also economic and social sustainability.

**Recycle**

A further strategy to reduce embodied carbon in tall buildings is to use recycled materials in place of virgin / non-recycled materials. In particular, recycled metals (steel, aluminium, copper, etc) and cement replacements in concrete such as fly ash or blast furnace slag, can have a significantly reduced embodied carbon as compared to their virgin / non-recycled content equivalents. To examine the carbon impact of recycled materials in tall buildings, an initial embodied carbon analysis is undertaken on the structural elements – the greatest contributor to total embodied carbon in high-rise – of 30 St Marys Axe. Three scenarios are considered; typical recycled content of materials, zero recycled content of materials, and maximum recycled content of materials[31]. The results are outlined in *figure 19*.

[31] Recycled material rates are taken from Hammond & Jones, 2008. The recycling methodology used in this analysis is the 'Recycled Content' approach, which allocates the full environmental benefits of recycling to the quantities of recycled materials within a product, with no consideration of its future recyclability. For more on this see *paper 4*, p.181.

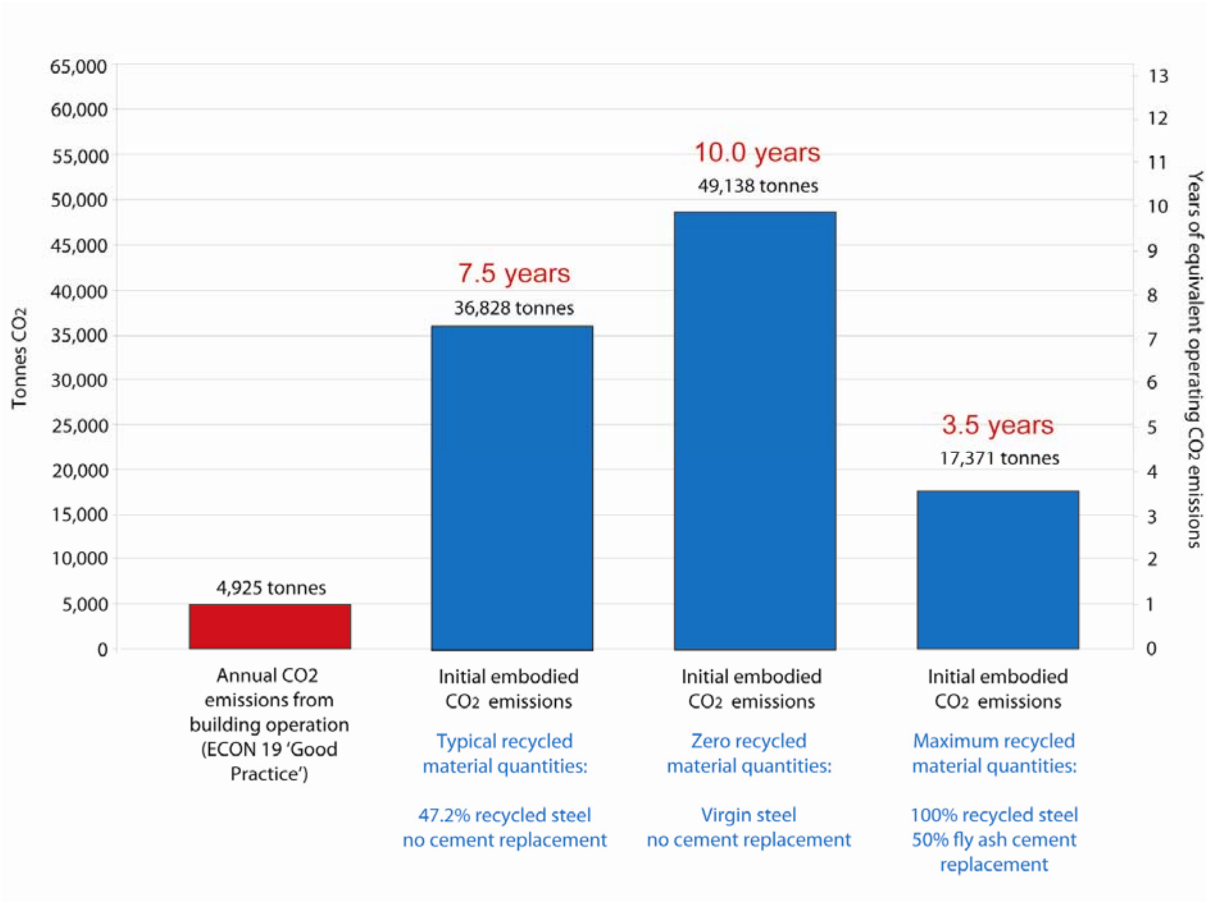


**Figure 19:** Initial embodied carbon of the structural elements – structural frame, substructure and upper floors – of 30 St Mary Axe, London, demonstrating potential impact of recycled material use (Source: author)

These results clearly show the dramatic impact recycled material use can have on embodied carbon. The maximum recycled materials scenario has 53% less embodied carbon than the typical recycled materials scenario, and 65% less embodied carbon than the zero recycled materials scenario. This equates to savings of 4 years and 6.5 years of equivalent operating emissions respectively. However, whilst this seems promising in theory, the availability of recycled materials does not always match demand. The high demand for steel, for example, means not enough steel is returned from service to produce all steel from recycled content[32] (International Iron and Steel Institute, 2005). However, it is clear that the use of recycled materials, particularly in structural elements, can go a long way to reducing tall buildings' embodied energy / carbon.

[32] It is of course still possible for a building to be constructed of 100% recycled steel, but this approach would potentially be at the expense of others who also wished to use recycled steel. From a global perspective any environmental 'benefit' of using 100% recycled steel is somewhat reduced by the lower recycled content steel remaining in the market place (Hammond & Jones, 2011).

**Retrofit**

The upgrading and retrofitting of existing structures can also be used to reduce embodied carbon requirements over a tall building's lifetime. Whilst many construction elements such as facade, services, finishes, etc, need regular replacement, a tall building's structure may last for hundreds of years, allowing for a building to be upgraded or improved, without the need for total demolition and replacement at a greater environmental cost. Many high profile tall buildings including Taipei 101, Taipei, the Empire State Building, New York and Willis Tower, Chicago are following such a route, improving their environmental performance without demolishing the entire building and starting again (for example, see Yang, 2011).

Whilst this is a strategy used across all typologies, tall buildings do have an inherent advantage in this case. Whereas low-rise buildings are regularly pulled down and replaced, tall buildings are very rarely demolished due to their iconic stature in cities and the high investment that goes into every project – both financially and professionally. As shown in *table 5*, very few tall buildings have actually ever been demolished. In fact, there have been 727 tall buildings of 200m or greater in height and 2,573 of 150m or greater in height constructed globally as of September, 2011. Of these only one building 200m or taller has been demolished, and only five 150m or taller demolished[33]. So, whilst the construction of a tall building may be a significant carbon investment, their long life-cycles are beneficial in terms of embodied energy / carbon.

**Table 5:** World's ten tallest buildings ever demolished, as of September 2011 (CTBUH, 2011). Note: the list does not include World Trade Centers 1, 2 & 7 as these were destroyed, rather than demolished.

| Rank | Name | City | Completed | Demolished | Height (m) |
|---|---|---|---|---|---|
| 1 | Torre de la Escollera | Cartagena | Unknown | 2007 | 206 |
| 2 | Singer Building | New York City | 1908 | 1968 | 187 |
| 3 | Morrison Hotel | Chicago | 1925 | 1965 | 160 |
| 4 | Deutsche Bank | New York | 1974 | ongoing | 158 |
| 5 | One Meridian Plaza | Philadelphia | 1972 | 1999 | 150 |
| 6 | City Investing Building | New York | 1908 | 1968 | 148 |
| 7 | The Ritz-Carlton | Hong Kong | 1993 | 2009 | 142 |
| 8 | Hennessy Centre | Hong Kong | 1983 | 2008 | 140 |
| 9 | Ardmore Park Old Block 1 | Singapore | 1978 | unknown | 137 |
| 10 | Ardmore Park Old Block 2 | Singapore | 1978 | unknown | 137 |

[33] Calculations by author, with initial data taken from CTBUH, 2011.

## 2.5 Paper 5: From the Orthogonal to the Irregular: The Role of Innovation in Form of High-Rise Buildings

Reference: OLDFIELD, P. & WOOD, A. (2010). **From the Orthogonal to the Irregular: The Role of Innovation in Form of High-Rise Buildings**. *Urbanism and Architecture*, No. 73, October 2010, Heilongjiang Science and Technology Press, Ha'erbin, China, pp.27 – 31, ISSN: 1673-0232.

The final paper of the submission examines tall building form, and the role it can play in the development of sustainable high-rise. Whilst much is written about irregular tall building form, notably on the structural challenges and the environmental possibilities it presents, this research adds to the knowledge by considering broader sustainability issues such as building cost, embodied energy and social sustainability.

There have been significant developments in tall building form over the past couple of decades, with advances in design and analysis tools (such as parametric modelling), building materials and structural systems liberating the designer from the orthogonal forms of the past. Today, seemingly impossible tall building shapes and unusual forms are created, as twisted, tilted, tapered and free form towers appear on skylines around the world.

Whilst these new opportunities are clearly a positive development, in the author's opinion they have not yet been realised to their full potential. Many of these new irregular towers seem to be designed merely as icons, or symbols on the city skyline, with little in the way of a relationship to the urban and environmental realm within which they sit. Whereas in the past height has played the primary role in creating a tall building icon, today form plays an equal if not greater role as cities around the world clamber for their own twisted, leaning or articulated towers.

It is important to note at this point that the author is not suggesting tall buildings should not be iconic – their very nature in rising above the city makes them inherently iconic – but that they should be more than *just* iconic. Nor is the author suggesting that all tall building forms should revert to the orthogonal towers that litter many urban centres today. In fact, the author strongly believes that innovation in tall building form can vastly improve the urban realm and the holistic sustainable credentials of high-rise, through using form to respond better to place and the environment, achieve greater heights with less materials and accommodate new functions in the sky. As such, the paper outlines three directions for development of more sustainable tall building form;

1. **Response to climate and the environment**
   Innovation in form should be used to generate tall buildings that better respond to the local climate – the sun path, wind direction (for example, to promote natural ventilation), to generate energy on-site from low and zero-carbon sources, etc.

2. **Response to wind and structural engineering**
   As outlined previously, the embodied carbon of the structural elements of tall buildings contributes significantly towards their total life-cycle environmental impact. Innovative and irregular forms can be used to reduce wind loads, and as such, reduce structural material requirements, embodied carbon and cost. The paper refers to the 632-metre-tall Shanghai Tower, due to be complete in 2014, the spiralling asymmetrical form of which reduces wind loads by 24% and thus structural materials by 32% (Gensler, 2009). Such a reduction would most likely be equivalent to many years of operating carbon.

3. **Connectivity and Conjoined Towers**
   As discussed in paper 2, the opportunities for providing connectivity and links at height between towers are numerous. In particular, as new functions such as sports, parks, schools and farms are proposed vertically, it will be challenging to accommodate these in the footprint of traditional orthogonal towers. The development of tall building forms that can house such functions is essential to the future evolution of the typology. One solution is to conjoin towers, thus creating larger spaces at height.

The paper concludes with a series of student design projects developed by the authors' respective studios that demonstrate some of these opportunities.

## 2.6 Conclusions and Future Research

Throughout this extended abstract, and the five submitted papers, a whole host of opportunities and challenges for improved sustainability in tall buildings are presented and discussed. In particular though, the author highlights below three main recommendations that should be drawn from this body of work. Three recommendations for future research are also identified.

**Recommendation 1: Greater consideration of the holistic sustainable design of tall buildings**

The key recommendation presented here, and the narrative that ties together this body of research, is the need for a greater consideration of the holistic sustainable design of tall buildings, encompassing economic, environmental and social issues. In particular, there is a need to understand that strategies designed primarily to impact one aspect of sustainability – for example, incorporating a double-skin facade to facilitate natural ventilation at height with the aim of reducing operating energy requirements – can have significant benefits and costs in other areas that may not seem obvious at first. In the double-skin facade example (explored in more detail in paper 4), there are well known operating energy benefits from reduced air-conditioning requirements, but also embodied carbon and economic costs in terms of the additional layer of envelope. However, in addition, there is the potential for less-well-known embodied carbon and economic savings through reduced plant space and M&E requirements, reduced floor-to-floor heights and increased lettable floor area.

Then there are the difficult to establish benefits to the occupants. Collins *et al*. (2008) note that over an office building's whole life cycle, the salaries of the occupants can make up 85% of total costs, with the building construction cost a mere 6.5%. Sustainable strategies designed to improve the environmental performance of a building – for example, promoting daylight, fresh air and natural ventilation – can also benefit the occupants' well being, and thus increase productivity and staff satisfaction and reduce absenteeism (Singh *et al.*, 2010), a potentially significant economic benefit. The Bank of America Tower, for example, included significant environmental features meaning it will use 50% less energy than the norm (Fox, 2008), but at an estimated upfront cost of an additional $60 million (Aston, 2007). It is hoped this cost can be offset by both operating energy savings and increased staff productivity from a better quality of internal environment, with a mere 1% reduction in illness-related absenteeism among the bank's anticipated staff of some 5,000 people delivering an estimated $10 million annual boost in productivity (Aston, 2007).

In the author's opinion, this joined-up thinking in terms of sustainability is especially important for the *realisation* of sustainable tall buildings. In particular, identifying the future benefits and impacts of design strategies and technologies across the full spectrum of economic, environmental and social sustainability will give developers, architects and engineers the information to be able to decide whether their integration into a tall building is appropriate or not. Collins *et al.* (2008) support this notion, suggesting that a lack of awareness of the future financial benefits of sustainable strategies in particular often leads to these being value engineered out of designs.

The research presented here not only promotes this joined-up, holistic thinking in terms of tall building sustainability, but also highlights specific links between economic, environmental and social sustainability in high-rise, from the larger scale issues of density and form, to the smaller scale issues of facade design and materials. The two recommendations below build on this, highlighting specific areas where the author feels such holistic thinking is especially important.

**Recommendation 2: Greater consideration of the environmental impacts of tall buildings across their entire life cycle, including embodied energy / carbon**

Paper 1 begins the research presented here by highlighting the need to consider the environmental impacts of tall buildings beyond their operations. These ideas are expanded throughout the papers and the supporting research which demonstrates that whilst at present the majority of tall buildings' environmental impacts occur during their operation, embodied carbon still plays a significant role in tall building sustainability, a role which will increase in importance in the future.

The research presented here identifies that strategies that reduce the environmental impact of the structural, services and finishes elements of tall buildings are the most important as they are the greatest contributor to tall building embodied carbon. However it also demonstrates how consideration of embodied carbon doesn't only impact environmental sustainability, but can have financial benefits too. The reduction of materials through structural optimisation (as outlined in paper 5) and structural fire engineering (as outlined in the supporting research of paper 4) for example, would reduce upfront building costs and make building tall more economically feasible in the first instance.

In the author's opinion one of the main reasons why embodied carbon is not considered enough in tall building design is the majority of regulations, goals and targets for building environmental performance gives embodied emissions too little focus. Casals (2006), for example, states that a common shortcoming of virtually all European building regulations and certifications is that they limit their energy assessment to building operations, with no consideration of embodied carbon or life-cycle impacts. Most published data on 'green' tall buildings in the literature also presents data on only their operational energy savings (for example, see Atkins, 2009; Fox, 2008; Frachette & Gilchrist, 2008) and as such, only presents a partial view of the their full life cycle environmental performance.

It is clear to the author then, that greater emphasis should be placed on embodied emissions and the full life cycle environmental impacts of tall buildings at regulatory and certification[34] levels and in published building performance reports. Such life cycle thinking is essential for more sustainable high-rise as it allows for an evaluation of how environmental impacts are distributed across the various stages of a building's life, allowing for a comparison between operating emissions and embodied emissions and how design changes made to impact one, may also affect the other. For example, this would allow for a true evaluation of a technology such as building integrated wind turbines at height, comparing whether the energy created would really offset the energy required for the construction, transportation and maintenance of the turbine and the associated materials and components over the building's life.

**Recommendation 3: More social / communal spaces in tall buildings**

In author's opinion it makes little sense creating tall buildings with all the benefits of environmental sustainability, and little or no consideration of social sustainability. It is clear that in many countries, families and other socio-economic groups are not attracted to high-rise living, with the suburban ideal instead providing a more attractive way of life. The vitality of low-rise communities will never exist in high-rise buildings until they can appeal to a wider section of society, and the key to providing this appeal is creating the social / communal spaces found on the ground – streets, gardens, parks – at height in tall buildings. Whilst this may seem a radical proposal to some, built and proposed examples of such buildings – particularly in Singapore – clearly show that such ideas are feasible.

[34] There is recent evidence that embodied emissions are beginning to be considered in some building environmental performance targets. For example, the '2030 Challenge' tasks all North America buildings to reduce their greenhouse gas emissions to zero by 2030, but originally only considered those emissions related to building operation (Boake, 2008). However, as of February 2011, the challenge expanded to also include building products, tasking designers to reduce the carbon emissions of materials by 50% below the current product category average by 2030 (Architecture 2030, 2011).

However, this argument is not just about creating vibrant communities, but is also an essential aspect of the broader environmental performance of high-rise. There are clear environmental benefits to encouraging dense living in compact cities (as outlined in paper 1) and until families and other socio-economic groups find such living as attractive as the suburban ideal, the environmental benefits of density provided in part by tall buildings will never be realised to its greatest possible extent.

One of the obvious barriers to the implementation of social / communal spaces at height is that of cost, and yet financial benefits through increased rent and sale price (as with the Pinnacle @ Duxton – see Teo, 2009), and improved worker productivity in office towers may provide a solution. In addition, such spaces could include revenue generating functions such as a crèche, corner shop, etc. Regulation could also provide financial incentives for the creation of such spaces. In Singapore, the Landscaping for Urban Spaces and High-Rises (LUSH) Programme allows for communal skygardens and associated support spaces to be exempt from gross floor area calculations, and as such, certain taxes, whilst also allowing buildings that incorporate such spaces to be taller in height than those without skygardens (Urban Redevelopment Authority, 2009).

The author would also highlight the skybridge as a useful design tool in improving high-rise social sustainability, through facilitating the construction of large open spaces above the city without the restrictions associated within the compact floorplates of typical towers. Connected towers would also potentially offer increased safety through a multitude of horizontal and vertical egress routes. As outlined in paper 2, such alternative evacuation routes could also have financial benefits, allowing for the omission of certain fire stairs and thus increasing lettable floor area.

**Future Research**

For the above recommendations to be feasible, additional research in the field of tall buildings and sustainability is necessary. Below, the author outlines three key areas where such research is required.

1. **Developing a holistic assessment framework for sustainable tall buildings**

   To consider the holistic sustainable design of tall buildings we need to be able to quantify, compare and contrast the various impacts that occur throughout a tall building's life across the full spectrum of economic, environmental and social sustainability. Existing mechanisms such as life cycle analysis and life cycle costing[35] do promote such thinking, and their application to more tall building projects would certainly go a long way to making the recommendations made here a reality.

[35] Life cycle analysis is an assessment of the environmental impacts of a product, building or service across its lifetime (ISO, 1997). Likewise, life cycle costing is a similar assessment but with the emphasis on cost.

However, such mechanisms can be complex and difficult to carry out, and are generally not practiced on most building projects (Collins *et al*., 2008). Holistic assessment of tall building sustainability needs to be carried out throughout the design process, from conception to completion, to inform decision making and the evolution of more sustainable high-rise design. The complexity of life cycle analysis and life cycle costing makes such repeat assessments more difficult, time consuming and costly to undertake. These mechanisms, although thorough, can also exclude certain sustainability issues such as safety, impact on local transportation and infrastructure, occupant satisfaction and community.

Perhaps then, a more simplistic but still thorough framework to assess tall building sustainability could be the way forward? One example that is worthy of note is the Sustainable Project Appraisal Routine (SPeAR) developed by Arup. This tool allows for the assessment of a building's sustainability and its impact on the local community, considering economic, environmental and social sustainability, as well as natural resources and embodied carbon considerations (Guthrie, 2008). Buildings are assessed over a range of indicators, with each designated a mark ranging from 'optimum' to 'worst case'. An example of a SPeAR assessment on the Shard at London Bridge tower is outlined in *figure 20* below.

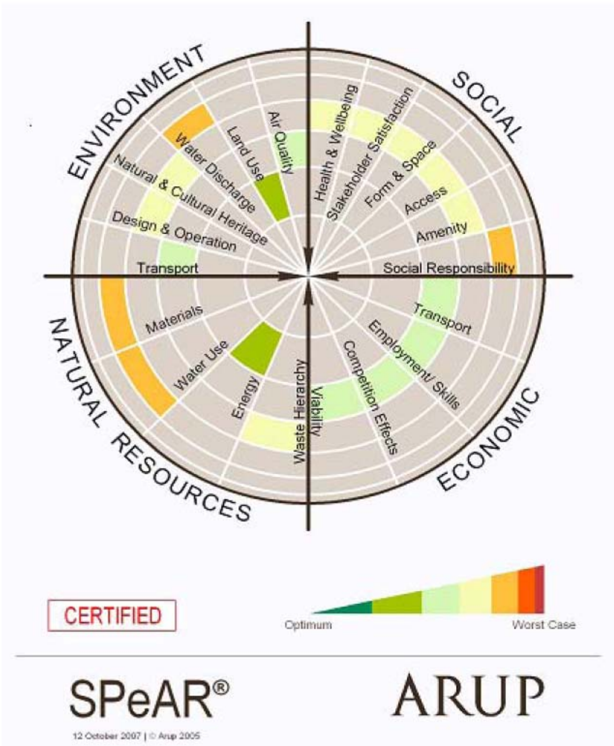


**Figure 20:** SPeAR assessment of the Shard at London Bridge (Guthrie, 2008)

The challenge is to advance such frameworks to allow for the various issues to be quantified numerically, perhaps using a common metric, or points scale. The development of such a framework should also be specific to tall buildings, covering the issues that are of the greatest importance and relevance to the typology, and acknowledging its continuing growth throughout the globe.

In addition, the development of a tall building assessment framework clearly needs to maintain a balance between completeness, covering the broad aspects of sustainability, and simplicity, or ease of use, thus promoting regular assessment throughout the design and construction process. Clearly, additional research in this field is necessary, in conjunction with making more data available on the various topics that together form holistic tall building sustainability (see also below).

**2. Improved embodied energy / carbon tools and datasets**

Recommendation 2 suggests that there should be more consideration of the environmental impacts of tall buildings across their entire life cycle, including embodied energy / carbon. However, whilst a building's operating carbon is relatively simply to quantify, the calculation of embodied carbon is far more time consuming, complicated and dependent on the chosen methodology. Compared to other 'products', buildings are large, complicated, and their 'production' is much less standardised than other manufactured goods because of the unique character of each building (Scheuer *et al.*, 2003). These challenges restrict the number of building embodied carbon considerations in practice (Langston & Langston, 2008). For tall buildings, with their higher quantities of materials, unique structural and mechanical systems and construction procedures at height, the challenge of evaluating embodied carbon is arguably all the more difficult.

However, there are a variety of tools and publically accessible datasets available which allow for the calculation of embodied carbon in buildings. In the UK context there is the 'Inventory of Carbon and Energy' (Hammond & Jones, 2008) and the 'Green Guide to Specification' created by the BRE (Anderson *et al.,* 2009). In North America there is software such as the 'Athena Impact Estimator' and 'BEES' (Athena Institute, 2012; Lippiatt, 2007), whilst in Europe there is the 'GaBi' database (Gabi, 2009). These provide much of the information necessary to undertake embodied carbon calculations[36], and along with a growing recognition of its importance in holistic building sustainability, have resulted in more of such calculations taking place.

[36] For a more significant list of life-cycle analysis tools and databases that can assist with embodied carbon calculations, see Seo, 200 2.

However, as outlined previously, particularity in paper 1, the vast majority of tall building construction is currently occurring in the Middle East, Asia and especially China (Hollister & Wood, 2012) and in these regions such data and tools are much less widely available. For example, in China, consistent, transparent, and verifiable sources for lifecycle impacts of materials and products are not publically available, with only scattered data published in academic articles, reports and student theses (Aden *et al*., 2010). It is important that published data on building materials is location specific, because the embodied carbon of materials can vary significantly with location, due to local manufacturing processes, availability of raw materials, etc. For example, the embodied energy of cement can vary from 3.2Gj/tonne in Japan, to 5.6Gj/tonne in Russia (UNEP, 2007).

It is clear then, that to promote more consideration of embodied carbon in tall buildings, additional research is vital, specifically to develop and publish data, tools and software for building embodied carbon calculations in the locations where construction is the greatest, specifically, China, Asia and the Middle East.

**3. Opportunities for Passivhaus thinking in tall buildings**

The research presented on pages 18 – 23 describes how tall buildings by nature of their compact form and low surface area to volume ratios can have reduced heating requirements as compared to other residential typologies in temperate climates. It also notes that due to this, tall buildings could meet Passivhaus heating targets much easier than low-rise buildings.

Additional research in this field is required to establish if due to these inherent advantages, tall buildings could meet Passivhaus criteria with reduced performance envelopes as compared to low-rise buildings, perhaps with much less insulation and maybe even double-glazing, instead of the standard triple-glazing? This would be beneficial as it would make Passivhaus high-rise more financially viable, reducing the cost of the typically very high performance facade. It would also reduce the embodied carbon of Passivhaus high-rise.

The author is currently undertaking this research, in addition to other investigations examining the opportunities and challenges for Passivhaus thinking in high-rise. These are outlined in more detail on page 23.

## 1.10 Extended Abstract Bibliography

*For the references in submitted papers, please refer to each paper's individual bibliography.*


ADAMS, W. M. (2006). *The Future of Sustainability: Re-Thinking Environment and Development in the Twenty First Century*. Report of the IUCN Renowned Thinkers Meeting, 29-31 January 2006.

ADEN, N. QIN, Y. & FRIDLEY, D. (2010). *Lifecycle Assessment of Beijing-Area Building Energy Use and Emissions: Summary Findings and Policy Applications*. China Energy Group, Lawrence Berkeley National Laboratory, Berkeley, California.

AÏTCIN, P. (2000). Review: Cements of Yesterday and Today, Concrete of Tomorrow. *Cement and Concrete Research*, 30, pp.1349 – 1359.

ANDERSON, J., SHIERS, D. & STEELE, K. (2009). *The Green Guide to Specification*. 4th Edition, BRE Press, Watford.

ARCHITECTURE 2030 (2011). *2030 Challenge for Products: Critical Points*. Architecture 2030, Santa Fe.

ASTON, A. (2007). *Bank of America Tower's Bold Statement in Green*. Internet WWW page at: <http://www.businessweek.com/bwdaily/dnflash/content/mar2007/db20070319_366263.htm> Created: 19/03/07; Accessed: 20/01/12.

ATHENA INSTITUTE (2012). *Impact Estimator for Buildings*. Internet WWW page at: <http://www.athenasmi.org/tools/impactEstimator/> Accessed: 06/04/2012.

ATKINS (2009). *DIFA Lighthouse Tower*. Internet WWW page at: <http://www.atkins-me.com/ProjectDetail.aspx?ProjectID=136> Accessed: 01/06/11.

BAILEY, C. (2004). A Simplistic or Holistic Approach to Structural Fire Engineering. *Proceedings of the CTBUH Conference "Tall Buildings in Historical Cities - Culture & Technology for Sustainable Cities"*, Seoul, October 10 – 13th, 2004, pp. 1 – 11.

BOAKE, T. (2008). The Leap to Zero Carbon and Zero Emissions: Understanding How to Go Beyond Existing Sustainable Design Protocols. *Journal of Green Building*, 3-(4), pp.64 – 77.

BRECSU (2000). *Energy Consumption Guide 19: Energy Use in Offices.* BRE, Watford.

CASALS, X. G. (2006). Analysis of Building Energy Regulations and Certification in Europe: Their Role, Limitations and Differences. *Energy in Buildings*, 38, pp.381 – 392.

CHEN, T. Y., BURNETT, J. & CHAU, C. K. (2001). Analysis of Embodied Energy Use in the Residential Building of Hong Kong. *Energy*, 26, pp.323 – 340.

COLANTONIO, A. & DIXON, T. (2007). *Measuring Socially Sustainable Urban Regeneration in Europe*. Oxford Institute of Sustainable Development, Oxford Brookes University.

COLE, R. J. & KERNAN, P. C. (1996). Life-Cycle Energy Use in Office Buildings. *Building and Environment*, Vol. 31, No. 4, 1996. pp. 307 – 317.

COLLINS, A., WATTS, S. & McALISTER, M. (2008). The Economics of Sustainable Tall Buildings. *Proceedings of the CTBUH 8th World Congress, "Tall & Green: Typology for a Sustainable Urban Future"*, Dubai, March 3 – 5, 2008, pp.175 – 185.

CONWAY, J. D. (1977). *Human Response to Tall Buildings*. Hutchinson & Ross Inc., Pennsylvania.

COUSINS, F. (2007). Down to Zero! Understanding Zero Energy and Zero Carbon Across Scales*. The Arup Journal,* February 2007, pp. 23 – 29.

CTBUH (2011). *CTBUH Tall Buildings Database*. Internet WWW page at: <http://buildingdb.ctbuh.org/> Accessed: 01/09/11.

DAVIS LANGDON LLP (2009). *Embodied CO2 and CO2 Emissions from New Buildings and the Impact of Possible Changes to Energy Standards*. Report commissioned by the Building Standards Division, Directorate for the Built Environment, Scottish Government, August 2009.

DEFRA (2008). 2008 *Guidelines to DEFRA's GHG Conversion Factors: Methodology Paper for Transport Emission Factors.* July, 2008, DEFRA, London.

DEFRA (2009). *2009 Guidelines to DEFRA / DECC's GHG Conversion Factors for Company Reporting*. Version 2, Updated 30/09/2009.

DEPECKER, P., MENEZO, C., VIRGONE, J. & LEPERS, S. (2001). Design of Buildings Shape and Energetic Consumption. *Building and Environment*, No. 36, pp.627 – 635.

DIN-A4 (2009). *Housing Estate (Energy Efficient Construction) "Lodenareal", Innsbruck*. Internet WWW page at: <http://www.din-a4.at/presseseite/pdfs/0909_aussendung_pm_lodenareal.pdf> Accessed: 05/07/11.

FAY, R., TRELOAR, G. & IYER-RANIGA, U. (2000). Life-Cycle Energy Analysis of Buildings: A Case Study. *Building Research and Information*, Vol. 28, No. 1, pp. 31 – 41.

FEIST, W., (2007). *Passive House Planning Package 2007: PHPP 2007 – Requirements for Quality Approved Passive Houses*. Passive House Institute, Darmstadt.

FEIST, W., PEPER, S., KAH, O. & VON OESEN, M. (2005). *Climate Neutral Passive House Estate in Hannover-Kronsberg: Construction and Measurement Results*. PEP Project Information No.1, Proklima, Stadtwerke Hannover.

FISCHER, V., GRUNEIS, H., RICHTER, R. & MENGES, A. (1996). *Sir Norman Foster and Partners: Commerzbank, Frankfurt Am Main*. Edition Axel Menges, Germany.

FOWLER, E. P. (2008). Faulty Towers: Contrary to Popular Belief, High-Rises are Not the Answer to Higher Density Living. *Alternatives Journal,* Vol. 34, No.1, 2008, pp. 24 – 26.

FOX, R. (2008). Provocations: Sustainable Architecture Today. *Proceedings of the CTBUH 8th World Congress, "Tall & Green: Typology for a Sustainable Urban Future"*, Dubai, March 3 – 5, 2008, pp.354 – 361.

FRACHETTE, R. & GILCHRIST, R. (2008). Towards Zero Energy: A Case Study of the Pearl River Tower, Guangzhou, China. *Proceedings of the CTBUH 8th World Congress, "Tall & Green: Typology for a Sustainable Urban Future"*, Dubai, March 3 – 5, 2008, pp.252 – 262.

GABI (2009). *GaBI Software*. Internet WWW page at: <http://www.gabi-software.com/> Accessed: 01/03/2009.

GENSLER, A. (2009). Shanghai Tower: Completing a Supertall Trio. *CTBUH Conference "Evolution of the Skyscraper: New Challenges in a World of Global Warming and Recession"*, Chicago, 22nd – 23rd October, 2009.

GREEN, M. & KARSH, E. (2012). *The Case for Tall Wood Buildings: How Mass Timber Offers a Safe, Economical, and Environmentally Friendly Alternative for Tall Building Structures*. Canadian Wood Council, Ottawa.

GUTHRIE, A. (2008). Tall Buildings: Sustainability from the Bottom Up. *Proceedings of the CTBUH 8th World Congress, "Tall & Green: Typology for a Sustainable Urban Future"*, Dubai, March 3 – 5, 2008, pp.95 – 101.

HAMMOND, G. P. & JONES, C. I. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a*. University of Bath, Bath, UK.

HAMMOND, G. P. & JONES, C. I. (2011). *Inventory of Carbon and Energy (ICE), Version 2.0, Annex B: Methodologies for Recycling.* University of Bath, Bath, UK.

HOLLISTER, N. & WOOD, A. (2012). A Year in Review: Trends of 2011 – Skyscraper Completion Reaches New High for Fifth Year Running. *CTBUH Journal*, Issue 1, 2012, pp.38 – 42.

HONEY, B. G. & BUCHANAN, A. H. (1992). *Environmental Impacts of the New Zealand Building Industry*. Research Report 92-2, University of Cantabury, New Zealand.

HUXTABLE, A. L. (1982). *The Tall Building Artistically Reconsidered: The Search for a Skyscraper Style*. Pantheon Books, New York.

INTERNATIONAL IRON AND STEEL INSTITUTE (2005). *Steel: The Foundation of a Sustainable Future – Sustainability Report of the World Steel Industry 2005.* International Iron and Steel Institute, Brussels.

ISO (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION) (1997). *Environmental Management – Life Cycle Assessment – Principles and Framework.* ISO 14040, ISO, Geneva.

ISOVER (2011). *Isover Students Contest 2011*. Internet WWW page at: <http://www.isover-students.com/content/view/178/194/> Accessed: 26/03/12.

ISOVER (2010). *Build for the Future: The ISOVER Multi-Comfort House*. Saint-Gobain Isover UK, Loughborough.

JAHN, H., SOBEK, W. & SCHULER, M. (2004). *Post Tower*. Birkhäuser, Basel.

JOHNSON, T. E. (1991). *Low E-Glazing Design Guide*. Butterworth Architecture, Stoneham, Massachusetts.

KAUFMANN, W. (2009). *Power Tower*, *Konzernzentrale Energie AGLinz, Austria*. Building with Aluminium: Sustainability in Architecture, Linz, September 9th, 2009. Internet WWW page at: <http://www.initiative-metallbautechnik.at/rte/upload/im_day_090909/im-day_vortrag_kaufmann_der_power_tower.pdf> Accessed: 12/06/11.

KERNAN, P. C. (1996). *Life Cycle Energy Analysis of an Office Building*. A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Master of Advanced Studies in Architecture, The University of British Columbia, February, 1996.

KESTNER, D. (2010). Sustainability: Thinking Beyond the Checklist. *Structure Magazine*, June 2009, p.5.

RAWLINSON, S. & WEIGHT, D. (2007). Sustainability: Embodied Carbon*. Building Magazine*, 12th October, 2007, pp. 88 – 91.

KILAIRE, A. & OLDFIELD, P. (2010). Aluminium and Double Skin Facades. In KATGERMAN, L. & SOETENS, F. (eds.) (2010). *Proceedings of the 11th International Aluminium Conference 'INALCO': "New Frontiers in Light Metals"*, Eindhoven University of Technology, Holland, June 23 – 25, 2010, IOS Press, Amsterdam, pp.177 – 188.

KOFOWOROLA, O. F. & GHEEWALA, S. H. (2009). Life Cycle Energy Assessment of a Typical Office Building in Thailand. *Energy and Buildings,* 41, pp. 1076 – 1083.

LANGSTON, Y. L. & LANGSTON, C. (2008). Reliability of Building Embodied Energy Modelling: An Analysis of 30 Melbourne Case Studies. *Construction Management and Economics*, February 2008, (26), pp.147 – 160.

LARSON, E. (2003). *The Devil in the White City*, Crown Publishers, Chicago.

LEVINE, M., D. ÜRGE-VORSATZ, K., BLOK, L., GENG, D., HARVEY, S., LANG, G., LEVERMORE, A., MONGAMELI MEHLWANA, S., MIRASGEDOS, A., NOVIKOVA, J., RILLING, H. & YOSHINO (2007). Residential and Commercial Buildings. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds.)], Cambridge University Press, Cambridge, United Kingdom.

LEWIS, S. (2011). *Camden Passivhaus, London's First Passivhaus*. Presentation at the Good Homes Alliance, Technology Strategy Board – Building Performance Evaluation, July 12th, 2011.

LIPPIATT, B. (2007). *BEES 4.0: Building for Environmental and Economic Sustainability – Technical Manual and User Guide*. National Institute of Standards and Technology, Gaithersburg.

McLEOD, R., MEAD, K. & STANDEN, M. (2011). *Passivhaus Primer: Designer's Guide – A Guide for the Design Team and Local Authorities*. BRE, Watford.

NORMAN, J., MACLEAN, H. L. & KENNEDY, C. A. (2006). Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions. *Journal of Urban Planning and Development*, March, 2006, pp.10 – 21.

OFFICE FOR NATIONAL STATISTICS (1999). *Living in Britain: Results from the 1998 General Household Survey*. Social Survey Division, Crown Publishing.

OKA, T., SUZUKI, M. & KONNYA, T. (1993). The Estimation of Energy Consumption and Amounts of Pollutants due to the Construction of Buildings. *Energy and Buildings*, 19, pp. 303 – 311.

OLDFIELD, P. (2011). The Passivhaus Skyscraper - Opportunities and Challenges for 'Passivhaus' Thinking in Tall Buildings. *CTBUH 2011 World Conference "Why Tall? Green, Safety and Humanity"*, Seoul, South Korea, October 10 – 12, 2011.

OLDFIELD, P. (2010). The Carbon Impact of Tall – Embodied Energy and High-Rise. *CTBUH 2010 World Conference, "Remaking Sustainable Cities in the Vertical Age"*, Mumbai, India, 3-5 February, 2010.

OLDFIELD, P. & WOOD, A. (2010). From the Orthogonal to the Irregular: The Role of Innovation in Form of High-Rise Buildings. *Urbanism and Architecture*, No. 73, October 2010, Heilongjiang Science and Technology Press, Ha'erbin, China, pp.27 – 31.

OLDFIELD, P., TRABUCCO, D. & WOOD, A. (2009). Five Energy Generations of Tall Buildings: An Historical Analysis of Energy Consumption in High-Rise Buildings. *Journal of Architecture*, Vol. 14, No. 5, pp.591 – 614.

ORTIZ, O., CASTELLS, F. & SONNEMANN, G. (2009). Sustainability in the Construction Industry: A Review of Recent Developments Based on LCA. *Construction and Building Materials*, 23, pp.28 – 39.

OSTERHAUS, W. K. E. (1993). Office Lighting: A Review of 80 Years of Standards and Recommendations. *Proceedings of the IEEE Industry Applications Society Annual Meeting*, Toronto, October 2 – 8, 1993.

PASSIPEDIA (2011). *The Passive House Encyclopaedia*. Internet WWW page at: <http://passipedia.passiv.de/passipedia_en/start> Accessed: 12/07/11.

PAUKEN, M. (1999). Sleeping Soundly on Summer Nights: The First Century of Air-Conditioning. *ASHRAE Journal,* May, pp.40 – 47.

POWELL, K. (2006). *30 St Mary Axe: A Tower for London*. Merrell Publishers Limited, London.

RICHARD LEES STEEL DECKING (2009). *Ribdeck 80.* Internet WWW page at: <http://www.rlsd.co.uk/pdf/80span.pdf> Accessed: 30/08/09.

RICHARDS, I. (2001). *T. R. Hamzah & Yeang: Ecology of the Sky.* The Image Publishing Group, Victoria, Australia.

ROAF, S. (2004). *Closing the Loop: Benchmarks for Sustainable Buildings*. RIBA Enterprises Ltd., London.

ROAF, S., CRICHTON, D. & NICOL, F. (2005). *Adapting Buildings and Cities for Climate Change: A 21st Century Survival Guide*. Architectural Press, Oxford.

ROODMAN, D. M. & LENSSEN, N. (1995). *A Building Revolution: How Ecology and Health Concerns are Transforming Construction.* Worldwatch Paper 124, Worldwatch Institute, Washington DC.

SAUTER (2008). *SAUTER Austria - Power Tower, Linz*. April 2008: Reference Report.

SCHEUER, C., KEOLEIAN, G. A. & REPPR, P. (2003). Life Cycle Energy and Environmental Performance of a New University Building: Modelling Challenges and Design Implications. *Energy and Buildings*, No. 35, pp. 1049 – 1064.

SEBREGTS, J. (2010). Greening the Machine. *Hinge Magazine*, Volume 181, Hinge Marketing Ltd, Hong Kong, pp.64 – 67.

SEO, S. (2002*). International Review of Environmental Assessment Tools and Databases*. Report 2001-006-B02. CRC for Construction Innovation, Brisbane.

SHAFII, F., BUKOWSKI, R. & KLEMENCIC, R. (eds.) (2003). *The CIB-CTBUH Conference on Tall Buildings: Strategies for Performance in the Aftermath of the World Trade Centre*. 20th – 23rd October, 2003, Kuala Lumpur, Malaysia, Published by the CIB Task Group on Tall Buildings – TG50.

SHUTTLEWORTH, K. (2008). Form and Skin: Antidotes to Transparency in High-Rise Buildings. *Proceedings of the CTBUH 8th World Congress "Tall & Green: Typology for a Sustainable Urban Future"*, Dubai, March 3 – 5, 2008, pp. 481 – 484.

SINGH, A., SYAL, M., GRADY, S. C. & KORKMAZ, S. (2011). Effects of Green Buildings on Employee Health and Productivity. *American Journal of Public Health,* September, 100 (9), pp.1665 – 1668.

SMITH, P. (2005). *Architecture in a Climate of Change: A Guide to Sustainable Design.* Second Edition, Oxford, Architectural Press, Oxford.

STAFFORD-SMITH, B. & COULL, A. (1991). *Tall Building Structures: Analysis and Design*. John Wiley & Sons, Hoboken, NJ, USA.

STEEMERS, K. (2003). Energy and the City: Density, Buildings and Transport. *Energy and Buildings*, 35, pp.3 – 13.

SUZUKI, M. & OKA, T. (1998). Estimation of Life Cycle Energy Consumption and CO2 Emission of Office Buildings in Japan. *Energy and Buildings*, No. 28, 1998, pp. 33 - 41.

SWAMY, R. N. (2001). Holistic Design: Key to Sustainability in Concrete Design. Internet WWW page at: <http://www.jsce.or.jp/committee/concrete/e/newsletter/newsletter13/paper2.pdf> Accessed: 01/07/09.

TEO, J. (2009). Pinnacle in Name, and in Pricing Too? *The Straits Times*, Tuesday September 8th, 2009, p.4.

TRELOAR, G. J., FAY, R. LLOZOR, B. & LOVE, P. E. D. (2001a). An Analysis of the Embodied Energy of Office Buildings by Height. *Facilities,* Vol. 19, No. 5/6, pp.204 – 214.

TRELOAR, G. J., FAY, R., LLOZOR, B. & LOVE, P. E. D. (2001b). Building Materials Selection: Greenhouse Strategies for the Built Facilities. *Facilities,* Vol. 19, No. 3/4, pp.139 – 149.

TROY, P. (2001). Sustainable Cities. *Proceedings of the CTBUH 6th World Congress: Cities in the Third Millennium*. Melbourne, Australia. Spon Press, London, pp. 143 – 158.

UK PARLIAMENT (2008). *Climate Change Act 2008.* Queen's Printer of Acts of Parliament, London.

UNEP (2007). *Buildings and Climate Change: Status, Challenges and Opportunities*. United Nations Environmental Programme, Nairobi.

UNHABITAT (2008). *State of the World's Cities 2008/09: Harmonious Cities*, Earthscan, London.

UNITED NATIONS GENERAL ASSEMBLY (1987). *Report of the World Commission on Environment and Development: Our Common Future*. Transmitted to the General Assembly as an Annex to document A/42/427.

URBAN REDEVELOPMENT AUTHORITY (2009). *Revised GFA Exemption Criteria for Sky Terraces to Encourage More Attractive Communal Spaces and Greater Provision for Planting*. Circular No: URA/PB/2009/12-DCG, Internet WWW page at: <http://www.ura.gov.sg/circulars/text/dc09-12.htm> Created: 29/04/2009; Accessed: 06/04/2012.

WATTS, S. & KALITA, N. (2007). Tall Building – Cost Model, April 2007. *Building*, Issue 17, April, 2007, pp. 12-18.

WELLS, M. (2011). Tall Timber Buildings: Applications of Solid Timber Construction in Multistory Buildings. *CTBUH Journal*, Issue 1, 2011, pp. 24 – 27.

WILLIS, C. (1995). *Form Follows Finance*. Princeton Architectural Press, New York.

WOOD, A. (ed.) (2008). *Proceedings of the CTBUH 8th World Congress, "Tall and Green: Typology for a Sustainable Urban Future"*. Council on Tall Buildings and Urban Habitat, Chicago.

WOOD, A. & OLDFIELD, P. (2008). Global Trends in High-Rise Design. *Urbanism and Architecture*, No. 49, October 2008, Heilongjiang Science and Technology Press, Ha'erbin, China, pp. 14 – 16.

WOOD, A. (2007). Sustainability: A New High-Rise Vernacular. *The Structural Design of Tall and Special Buildings*, 16, pp.401 – 410.

WOOD, A. & OLDFIELD, P. (2007). Bridging the Gap: An Analysis of Proposed Evacuation Links at Height in the World Trade Centre Design Competition Entries. *Architectural Science Review*, Volume 50.2, June 2007, University of Sydney, Australia, pp.173 –180.

WORRELL, E., PRICE, L., MARTIN, N., HENDRIKS, C., & MEIDA, L. O. (2001). Carbon Dioxide Emissions from the Global Cement Industry. *Annual Review of Energy and the Environment*, Vol. 26, November, 2001, p.303 – 329.

YANG, K. (2011). Becoming the World's Tallest Green Building – Taipei 101 Case Study. *CTBUH 2011 World Conference "Why Tall? Green, Safety & Humanity",* Seoul, October 10 – 12, 2011, Track 28.

YUEN, B., YEH, A., APPOLD, S., EARL, G., TING, J. & KURNIANINGRUM, K. L. (2003). To Live High or Low: Case Study of Singaporean Public Housing Residents. *Proceedings of the CIB-CTBUH Conference on Tall Buildings: Strategies for Performance in the Aftermath of the World Trade Centre*, 20th – 23rd October, 2003, Kuala Lumpur, Malaysia, pp.141 – 148.