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Five Energy Generations of Tall Buildings: A Historical Analysis of Energy Consumption in High Rise Buildings

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Philip Oldfield received his Bachelor of Architecture degree and Diploma in Architecture from the University of Nottingham, England, obtaining First Class honours at undergraduate level and a Distinction for his Diploma portfolio. Currently he is studying a PhD in tall buildings entitled “Towards Carbon Neutral”, sponsored by Ove Arup Ltd. The aim of this research is to design a hypothetical, carbon neutral tall building through the incorporation of relevant design strategies, material choices, environmental technologies and energy generation techniques. The operational and embodied carbon performance of this design will then be modelled against a ‘benchmark’ building of the same size, function and location.

Philip is a member of the Tall Buildings Teaching and Research Group (www.tallbuildingstarg.com) and has taught high-rise design studio projects at both the University of Nottingham and Illinois Institute of Technology, Chicago, where he is currently on secondment as part of his PhD studies. In conjunction with this, Philip is also Research Coordinator for the Council on Tall Buildings and Urban Habitat.

Dario Trabucco

Dario Trabucco, born in Venice in 1980, graduated cum laude in architecture from the IUAV University of Venice, Italy in October 2004. He qualified as an architect in January 2005. In December that year he also graduated as an “Expert in Logistics and Transportation”, with an emphasis on vertical mobility, after completing a one year-long research programme at the IUAV University of Venice, with an EU scholarship.

In 2006 he began a PhD in Building Technology, focussing his research on tall buildings, specifically on the design of service cores. His research examines the benefits generated through using an integrated design approach for the various elements of tall building service cores.

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Abstract

Whilst there have been numerous categorisations of high-rise buildings according to their function, architectural style, height or structural strategy, historically little work has been undertaken to classify them based on factors affecting their energy performance – their shape and form, façade, attitude to natural lighting, ventilation strategies, etc. This paper aims to rectify this by examining the history of energy use in tall buildings, from their origins in North America in the late 19th century to the present day. In doing so, it categorises tall buildings into five chronological ‘generations’, based on their energy consumption characteristics.

Keywords: Tall Buildings, History, Energy Consumption, Building Form, Envelope Performance

Introduction

Over the past 120 years, the high-rise typology has undergone a variety of paradigm shifts, influenced by regulatory changes, developments in technology and materials, changes in architectural thinking and economic issues. Developments such as the New York Zoning Law of 1916, the post-war innovations in curtain wall façades and the energy crises of the 1970s have all impacted on the way tall buildings of the time were designed and operated. These events also had a significant impact on the quantity of, and way in which, energy was consumed in tall buildings of the time.

In today’s context, with climate change arguably the greatest challenge of the modern world, it is well known that the creation, running and maintenance of the built environment accounts for more than 50% of greenhouse gas emissions globally (Smith, 2005). In light of this, frenzied research has – and continues to be – undertaken in order to reduce the carbon footprint of high-rise buildings. However, it is also interesting to look back at the energy consumption characteristics of tall buildings throughout history; to examine how and why these changed and to learn possible lessons for the future.

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

Born out of developments in structural steel framing and the invention of the elevator in the mid-19th century, tall buildings quickly spread across North America, becoming the symbol of economic growth and prosperity. The Home Insurance Building, completed in Chicago in 1885, is generally regarded as the first of these high-rises, although debate continues regarding its

credentials for this title. We can state that this first generation of tall buildings originally required relatively little operating energy as technologies such as air-conditioning and fluorescent lighting were not yet developed. Energy was predominantly consumed in the heating of occupied spaces and providing vertical transportation between floors. Ventilation was achieved naturally via opening windows and artificial lighting levels were very low – typically between 2 and 4 foot-candles¹ in office buildings in 1913 due to the inefficiencies of lighting technologies of the time (Osterhaus, 1993).

Whilst these buildings utilised the latest structural innovations, their envelope construction remained heavily influenced by traditional, load-bearing technology; external walls, although freed from any structural role, were often quite thick, of masonry construction, with an internal finish of dense plasterwork. Windows remained as small punctured holes within walls, occupying only 20% - 30% of the façade area. Whilst this construction suffers from a lack of thermal insulation (i.e. due to the use of single glazing) and poor air tightness, it does however provide a high degree of exposed thermal mass. This would assist in creating comfortable internal environments by maintaining warmth in the winter and absorbing excess heat gains in the summer months.

The form and shape of these early high rise buildings also impacted their energy usage; typically

¹ A foot-candle is a measurement of illuminance common in the American building industry. One foot-candle is equivalent to 10.764 lux.

those constructed prior to the 1916 Zoning Law were bulky, compact forms, the result of repetitive stacking of large floorplates to maximise rentable floor area. These buildings were large volumes, but had relatively small envelope surface areas, allowing them to retain a high degree of heat in the winter, but at the expense of natural light penetration. These characteristics of dense, solid façade and compact, bulky shape are best reflected in the Equitable Building of New York, completed in 1915 (see *Figure 1*). This building – the vertical extrapolation of an H-shaped floor plan over 40 stories – is an immense volume, whilst its limestone clad façade, backed with thick masonry, has a glazing ratio of just 25%, compared to values of 50 - 70% typical in modern high-rise buildings².



Figure 1. The Equitable Building, New York, 1915. [Source: Trabucco]

In more recent times, buildings of this era have experienced massive refurbishments to improve lighting, enhance façade and glazing performance and introduce mechanical space conditioning. Whilst today such buildings suffer from a reliance on artificial lighting due to their low façade glazing ratio, their energy performance still benefits to a certain extent from their shape (compact and bulky) and their envelope construction (solidity and thermal mass).

² Façade glazing ratios refer to the percentage of glazing within a typical section of building façade. All data calculated by Authors from a variety of photos and drawings. See also *Table 3*.

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

The construction of the Equitable Building in New York marked a significant watershed in high-rise design. This massive building, covering an entire city block would, according to its detractors, “steal” light and views from surrounding buildings (Weiss, 1992). In fact similar concerns about skyscrapers of the time had been growing for years; the lack of planning legislation for this new typology had allowed the number and size of tall buildings in Manhattan to steadily increase, blocking sunlight from streets and other buildings, culminating in the construction of the Equitable Building which casts a seven acre shadow across its surroundings. In response, the New York City authorities developed the landmark Zoning Law of 1916, restricting the bulk of tall buildings, requiring them to preserve the penetration of light and air onto the streets below.

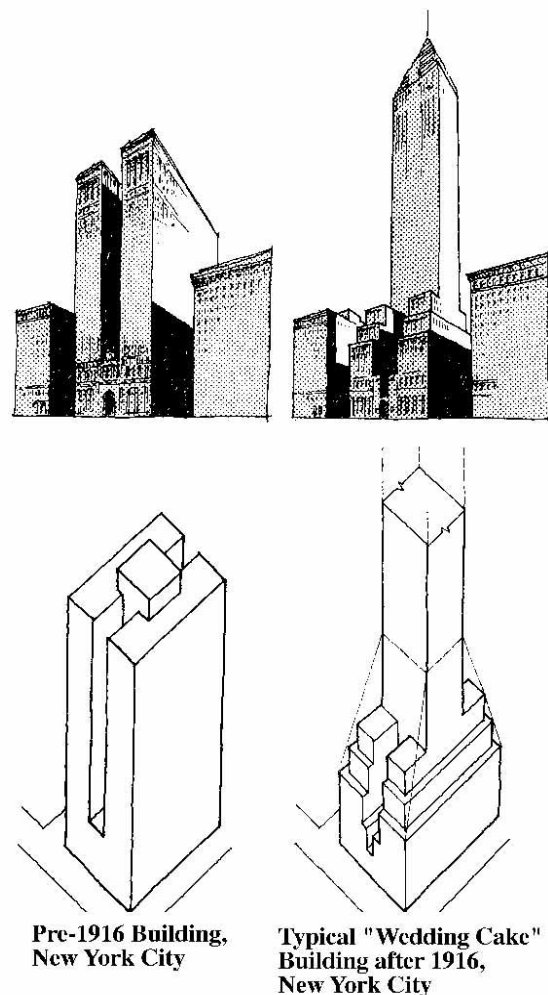


Figure 2: The 1916 Zoning Law; Impact on tall building form and mass. [Source: Barnett, 1982]

The subsequent ‘set-backs’ prescribed by the law created the familiar ‘wedding cake’ skyscraper style that

would dominate future skylines (see *Figure 2*).

In order to determine the impact the 1916 Zoning Law had upon the energy consumption of tall buildings, ten New York skyscrapers – five predating the law and five in its aftermath – have been studied. For each building a calculation of its envelope surface area to volume ratio (AVr) was made using the formula outlined below:

$$AVr = \frac{SA}{V} \quad (\text{m}^2/\text{m}^3)$$

In this instance, SA is the envelope surface area of the building and V is its volume. The results of this analysis are outlined in *Figure 3*.

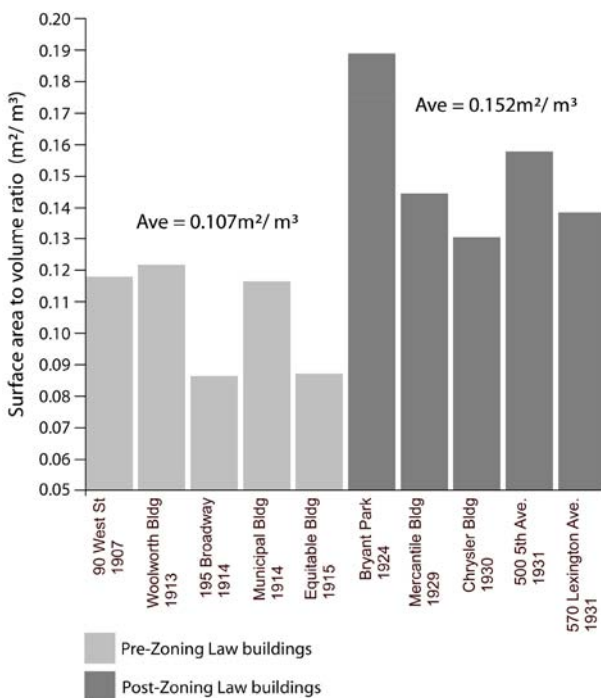


Figure 3. Facade surface area to volume ratios for New York high-rise buildings completed prior to, and after the 1916 Zoning Law. See also *Table 3*.

As could be expected, tall buildings constructed after the Zoning Law have an increased amount of envelope surface area per unit volume compared to those that predate the law, which are typically more bulky. So what does this mean in terms of energy use? Studies by Depecker et al (2001) show that in a climate with cold, severe winters – such as New York – a building's energy requirement for space heating is proportional to its surface area to volume ratio (AVr); the higher the ratio, the higher the energy consumption due to an increased quantity of envelope area facilitating heat loss. However, at the same time, the slender Zoning Law buildings have shallower floor plans compared to the 'first generation' buildings, at least at the higher levels. As the proportion of glazing within the façade stayed similar across both

generations, this would result in greater natural light penetration, potentially reducing artificial lighting loads. However, despite this potential, artificial lighting levels actually increased in this time period; whereas in 1916 the recommendation for adequate lighting levels was 8-9 foot-candles, it rose to 10-12 foot-candles in the 1920s and spurred on by the aggressive sales tactics of large power companies, up to 25 foot-candles by the 1930s (Willis, 1997).

So, it can be seen that the 1916 Zoning Law directly influenced the energy consumption of tall buildings. Prior to its inception, high-rise buildings were large rectilinear blocks, designed with a high degree of compactness. Those that followed the law were increasingly slender, resulting in greater energy requirements for space heating (due to heat loss through higher quantities of envelope), but increased penetration of natural light to internal spaces.

It is worth noting that while these attributes are consistent with the majority of tall buildings in New York, there are obviously a few exceptions to the rule. For example, the Flatiron Building, constructed prior to the Zoning Law in 1902, has a surface area to volume ratio of $0.17\text{m}^2/\text{m}^3$, a figure characteristic of the more slender post Zoning Law buildings. The Empire State Building (1931), arguably the most famous of the 'wedding cake' skyscrapers, has a ratio of $0.09\text{m}^2/\text{m}^3$ which shows a high degree of compactness similar to buildings that predate the law. However, both these examples can be seen as unusual; the Flatiron's slender form is obviously influenced by its unique site, whilst the Empire State was a massive building on an unprecedented scale – the tallest in the world for over 40 years.

For reasons of depth, quality and number of buildings affected, this study has focused solely on the Zoning Law of New York, however it is reasonable to assume similar characteristics in other North American cities with cold winters. By the late 1920s many cities had developed their own zoning laws based on the New York system of set-backs and volumetric controls. Whilst these regulations were not identical to those in New York, the architectural results were the same – an increased slenderness of tall buildings – whether they were in Chicago (Palmolive Building, 1929; Chicago Board of Trade, 1930), Detroit (Penobscot Building, 1928) or Cincinnati (Carew Tower, 1931).

It is also within this generation that air-conditioning started to become more commonplace in tall buildings, although it wasn't until the 1950s & 60s that it became a standard feature. For example, the Chicago Tribune Tower, completed in 1925, was originally designed to be naturally ventilated through opening windows. However, following record high summer temperatures in June 1931, the Tribune publisher directed the tower's management to immediately install air-conditioning to provide more comfortable internal conditions. In doing so, the building's value at the time increased from \$2.5 per square foot to \$4 per square foot.

Whilst Second Generation buildings suffered

increased energy requirements through a change in shape, higher lighting requirements and a part-shift to mechanical ventilation, they still benefited greatly from the continued use of traditional façade materials, such as stone, brick and dense plaster, providing a high degree of thermal mass to assist in occupant comfort. For example, the envelope construction of the Empire State Building consisted of vertical bands of brick back-up masonry faced with limestone, alternating with vertical bands of steel framed windows with cast aluminium spandrel panels and an internal finish of plasterwork (Nacheman, 2006).

The Third Generation: From the Development of the Glazed Curtain Wall, 1951³, to the 1973 Energy Crisis

Mies van der Rohe's 1921 skyscraper design for the Friedrichstrasse in Berlin was arguably the first vision of the fully-glazed tall building, far ahead of the technical capabilities of its time. However, after the Second World War, technological innovations gave rise to the realisation of such proposals – a development that dramatically changed the high-rise typology. Whereas tall buildings completed prior to the war had between 20% and 35% glazing within their facades (Equitable Building, New York, 1915 – 25%; Chrysler Building, New York, 1930 – 32%), 'third generation' buildings had a significantly higher ratio, between 50% and 75% (Lake Shore Drive Apartments, Chicago, 1951 – 72%; Lever House, New York, 1952 – 53%). These rectilinear glass boxes quickly spread around the world, regardless of site, climate or orientation, becoming symbols of reconstruction and economic wealth.

"Towering, glazed office blocks became fashionable as company headquarters... Glass curtain walls became the status symbol of confident companies and the silhouette of glass towers the sign of a prosperous city."

[Schittich et al, 2007]

The Lever House in New York was one of the first high-rise buildings to utilise this technology. Its façade build-up consisted of a tinted, single-glazed curtain wall with low-level spandrel panels backed by a concrete upstand for fire legislation purposes (see Figure 4). This lightweight façade construction, made possible only by the use of fixed single glazing, has a significantly inferior thermal / insulation performance compared to the heavyweight facades of first and second generation buildings. For example, the façade of Lever House has a U-value of approximately 3.3W/m²K, compared to 2.6W/m²K for the Empire State Building, completed

twenty years previously⁴. Other buildings of this period, with greater proportions of single glazing suffered a further reduction in façade performance; the Lake Shore Drive Apartments, for example, had a U-value of approximately 4.2W/m²K, compared to values of 1.1W/m²K and below, common in modern high-rise office buildings.

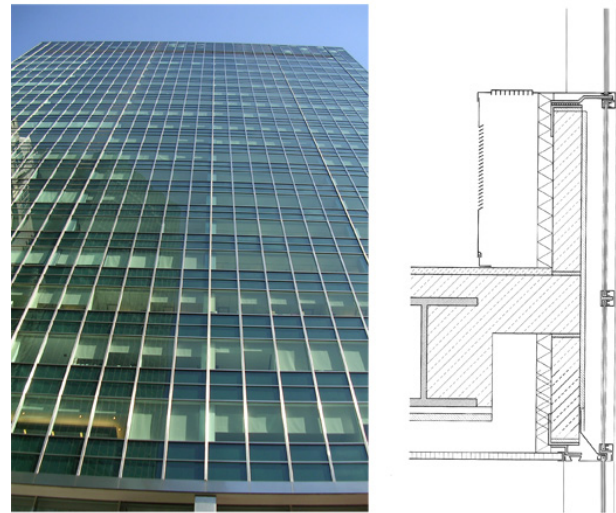


Figure 4. Lever House, New York, 1952. From left a) View of the curtain wall façade. b) Cross section through the building envelope highlighting the use of single-glazing with a concrete upstand for fire legislation purposes. [Sources: a) Trabucco b) from Schittich et al, 2007]

The problems buildings with large quantities of single glazing suffer are well documented; internal spaces experience vast heat losses in the winter, but also overheat from excess solar gain in the summer. If compensated for by air-conditioning alone, this leads to excessively high building energy consumption. In fact, due to its façade performance, the Lever House tower was one of the first office buildings where air-conditioning was so fundamental to the building design, it could not operate without it (Arnold, 1999).

A further interesting characteristic of this period is the high number of black skyscrapers constructed. Influenced by the 'International Style' represented in van der Rohe's designs such as the Lake Shore Drive Apartments (1951), the Seagram Building (1958) and the Toronto Dominion Bank Tower (1967), these black monoliths spread not just across North America, but to many cities and climates around the world such as Paris (Tour Fiat, 1974) and Tokyo (Shinjuku Mitsui Building, 1974). Due to the high solar absorption characteristics of black or dark-coloured cladding, these buildings would

³ The first tall buildings constructed with glazed curtain wall façades were the 1951 Lake Shore Drive Apartments in Chicago, designed by Mies van der Rohe.

⁴ Unless stated otherwise, all U-value data is calculated by the Authors from published technical details and descriptions of the building façade construction. Figures refer to the average U-value of the façade, including both glazed and solid wall elements.

have suffered higher quantities of unwanted heat gain in the summer months, compared to other buildings with brick or lighter coloured facades (see *Table 1*). The result is that the black skyscraper would further rely on gas-guzzling air-conditioning plant to create a comfortable internal environment.

Table 1. Solar absorptance values for a variety of different coloured materials. [Data from Yeang, 2006]

Material	Solar Absorptance
Flat black paint	0.95
Dark grey paint	0.91
Red bricks	0.70
Uncoloured concrete	0.65
Light buff bricks	0.60
White semi-gloss paint	0.30

In addition to black cladding, many of these buildings also incorporated bronze or dark-tinted glazing. In his seminal Seagram Building, van der Rohe utilised iron oxide and selenium in the glass melt to give the glazing a bronze hue to match the bronze sections of the curtain walling. This strategy was copied in virtually all the black skyscrapers of the period, many utilising grey or bronze tinted glass to create the required aesthetic. The impact this strategy would have on the building's energy consumption would likely be detrimental; despite the high quantities of glazing in the façade, low amounts of natural light would penetrate into the office spaces beyond due to the poor light transmittance properties of the dark-coloured glass (see *Table 2*). This in turn would increase the artificial lighting loads.

Table 2. Light transmission values for coloured and clear glazing. [Data courtesy of Pilkington Glass]

Glazing Colour (Float glass, 6mm thick single-glazing with no coatings)	Light Transmission (%)
Clear	88
Green	75
Bronze	50
Grey	44

In terms of shape and form, tall buildings of this period were predominantly large rectilinear boxes, with deep office floor plans – a response to the economics of real estate in city centre areas. No longer slender like the Zoning Law inspired buildings, these new towers typically displayed shape characteristics similar to first generation buildings with a high degree of bulk and compactness. Generally, their surface area to volume ratio was between $0.085\text{m}^2/\text{m}^3$ and $0.13\text{m}^2/\text{m}^3$, similar to those built prior to the Zoning Law (see *Table 3*). This change in building form was made possible by the creation of public plazas adjacent to high-rise buildings. The 1961 New York Zoning Law replaced the 1916 'wedding cake' setback requirements with restrictions based on floor area

ratios, but in recognition of the corporate need for deep floor plans (as many firms found floor areas in the slender towers of the 1920s too shallow for their needs) granted a comprise that allowed a 20% density bonus for buildings that created a public plaza on a portion of their lot (Weiss, 1992). Whilst the bulky form of these buildings would be beneficial in colder climates, reducing heat loss in winter months through the low-performing curtain walling, the deep floor plans would also restrict the passage of natural light into office spaces. It is no surprise then that with deep floors plans and dark-tinted glazing that office artificial lighting loads rose dramatically in this generation; whereas in the 1930s the recommended office lighting levels were around 25 foot-candles, the 1960 *Recommended Practice for Office Lighting* guidelines advised illuminance levels of between 100 – 150 foot-candles (Osterhaus, 1993).

"In the 1950s, advances in technology and changes in architectural ideology liberated the tall office building from its dependence on nature and site. Fluorescent lighting and air conditioning were as important to the transformation of post-World War II skyscrapers as were elevator and steel-cage construction to the first tall office buildings of the late nineteenth century"

[Willis, 1997]



Figure 5. Average energy consumption of 86 office buildings constructed in Manhattan between 1950 and 1970. [Graphic by Author, data from Stein, 1977]

The paradigm shift from a traditional, solid façade construction with punctured windows, to the new,

lightweight glazed curtain wall, had a significant impact on the energy consumption of tall buildings of this period. High rises became hermetically sealed glass boxes, completely reliant on air-conditioning and fluorescent lighting to compensate for overheating, excessive heat loss and poor natural light penetration. These characteristics were only exaggerated by the high number of black skyscrapers constructed at the time. In fact, tall building energy consumption grew dramatically in this period as demonstrated by a study on 86 office buildings constructed in Manhattan between 1950 and 1970 (Stein, 1977). The results of the study show that on average, buildings completed in the late 1960s have energy requirements more than double those of buildings constructed in the early 1950s, less than 20 years previous (see Figure 5).

The Fourth Energy Generation: From the Energy Crises of 1973 to the Present Day, 2008

The popularity of the single-glazed curtain wall facade, so prevalent in the previous generation, was abruptly interrupted by two major events in the 1970s; the energy crises of 1973 and 1979. Whereas prior to these crises it was still considered sophisticated to isolate the tall building from its surroundings, generating a comfortable internal environment with gas guzzling air-conditioning and artificial lighting alone, the amount of energy these buildings consumed suddenly became a major issue. Responding to this new attitude towards energy, many developed nations now brought in building energy performance codes, forcing a widespread switch to double-glazing (Johnson, 1991). In fact, the strong criticism the single-glazed curtain wall faced, resulted in many changes to the design of high-rise façades.

“Following the two oil crises of the 1970s, the fully glazed curtain façade was criticised for its poor energy performance and reliance on mechanical systems to provide a comfortable climate in hermetically sealed buildings. This brief setback to the use of glass in tall buildings forced architects and engineers to act – research led to the development of better insulating and solar control glass. Furthermore the demand for coloured and mirror glazing dropped significantly, in favour of clearer glass with better daylight transmittance.

[Schittich et al, 2007]

These developments led to a significant improvement in tall building façade performance; where third generation buildings had façade U-values in the range of 3.0 – 4.2W/m²K, the use of double glazing, low-e coatings and argon filled cavities reduced these figures to between 1.0 – 1.5W/m²K in fourth generation buildings. At the same time, the move away from dark tinted glazing no doubt reduced artificial light loads,

which were further diminished by a reduction in overall recommended lighting levels for offices of the period. The 1982 revision of the *American National Standard Practice for Office Lighting* proposed roughly a 25 to 50 percent decrease in office illuminance levels, due to the rising energy costs and environmental concerns brought about by the energy crises (Osterhaus, 1993).

This new energy conscious era also claimed a major tall building casualty in the form of the original design for the Tour Elf in Paris. Initially proposed as a twin tower for the adjacent Tour Fiat completed in 1974, it was later redesigned with energy efficiency in mind and completed in 1985. Comparing these two designs indicates some of the major differences between third and fourth generation tall buildings (see Figure 6); The Tour Fiat is a monolithic box clad in black granite, where deep office floors only benefit from minimal natural lighting through dark tinted windows. Alternatively the redesigned Tour Elf required good levels of natural lighting for all office workers. This was achieved by specifying a glass that allows for a good standard of light transmission, yet is still well insulated, a reflection of the strides forward made by the glazing industry after the energy crises. This, in conjunction with a computerized building management system resulted in a building of the same height and gross floor area as its predecessor, but one that is half as expensive to heat, light and maintain (Ayers, 2004).



Figure 6. Tour Fiat and Tour Elf, Paris. From left a) The initial proposal of black twin skyscrapers. b) The completed buildings with the redesigned Tour Elf on the right. [Sources: a) <http://www.defense-92.fr> b) © Hans-Peter Kneip]

It is not only the original Tour Elf proposal that was shunned in this era, but black skyscrapers in general became increasingly unpopular due to their inherent energy efficiency flaws. At their peak in 1971, seventeen black skyscrapers were completed in the major American cities (see Figure 7). However, following the first energy crisis, this figure had fallen to only three in 1976 and zero the following year.

Whilst tall buildings of this generation benefited greatly from improvements in façade performance, and a

reduction in the number of black skyscrapers, technological developments in office equipment would have a negative impact on building energy consumption. For example, the dramatic rise in use of computers in this era not only required an additional energy input for their power, but their use also increases internal heat gains. In fact, latest figures suggest electronic equipment in office spaces provides on average 17.5W/m^2 of additional heat gains⁵ – a figure that is compensated for by increasing levels of mechanical conditioning at significant energy cost.

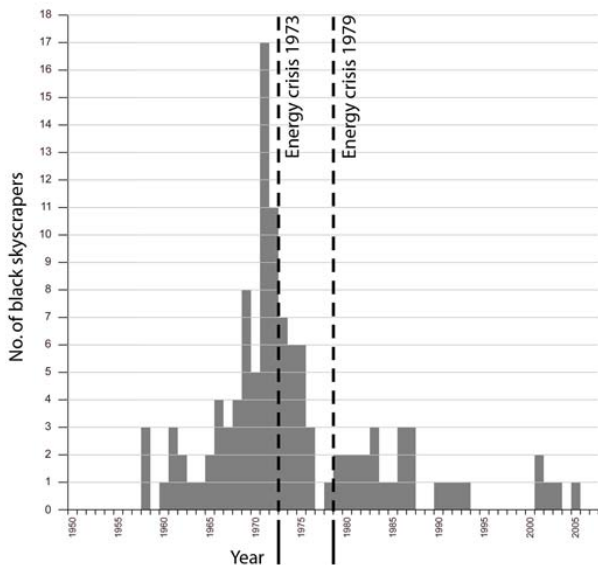


Figure 7. Number of black skyscrapers constructed in North America since 1950. Buildings over 100m in height and located in Atlanta, Chicago, Houston, Los Angeles, Miami, New York and San Francisco considered.

The Fifth Energy Generation: From the Rise of an Environmental Consciousness (1997) to the Present Day, 2008

Whilst the majority of tall buildings constructed today continue to demonstrate ‘fourth generation’ characteristics – meeting regulatory energy performance criteria, but not bettering these by any substantial amount – there is a growing number of high rise designs and completed buildings that aim to go above and beyond the norm in terms of reducing energy consumption. In an age where climate change is arguably the greatest challenge to the modern world and bodies such as the IPCC are predicting a temperature increase of between 1.8°C and 4°C by the end of the century (IPCC, 2007), this change cannot occur quickly enough.

Arguably the first significant tall building

⁵ In comparison, prior to the use of computes in the workplace, non-climatic internal heat gains in office buildings would mostly arise from people (8.5W/m^2 , assuming an average of 15m^2 of floor space per person) and lighting (13W/m^2). All data from Knight & Dunn, 2003.

reflecting these new environmentally conscious principles was the Commerzbank in Frankfurt (Foster and Partners, 1997), although one could look to the bio-climatic skyscrapers of Dr. Ken Yeang, SOM’s National Commercial Bank in Jeddah (1984), or even Frank Lloyd Wright’s Price Tower in Oklahoma (1956) as earlier examples of ‘sustainable’ high-rise design (Wood, 2008). The Commerzbank (see Figure 8) incorporates a high degree of energy reducing design strategies and technologies that include:

- A full building height central atrium, providing natural lighting and ventilation to internal office spaces.
- The use of large, open skygardens to further increase daylight penetration to office areas.
- A façade design that allows for natural ventilation for over half the year via operable windows (known as the Klima-façade).
- A water-based cooling system of chilled ceilings.

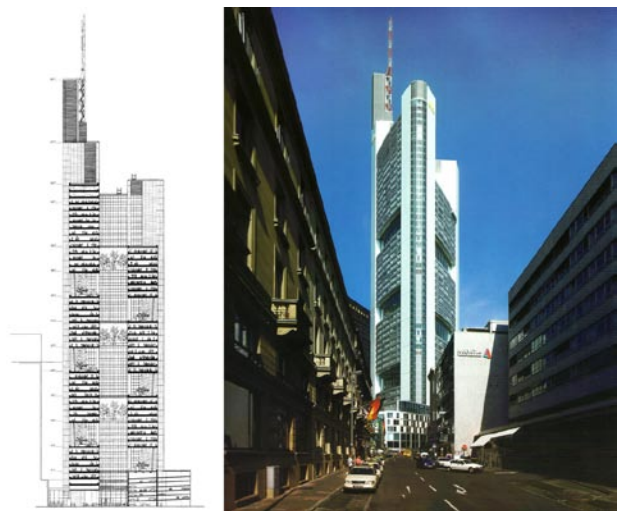


Figure 8. Commerzbank Tower, Frankfurt, 1997. From left a) Building section showing the full height central atrium and staggered skygardens providing natural lighting and ventilation to internal office spaces. b) Tower in context. [Source: Menges, 1997]

In fact many qualities of the Commerzbank are typical of fifth generation skyscrapers. In terms of form and shape, tall buildings of this category have a high surface area to volume ratio – typically between $0.10\text{m}^2/\text{m}^3$ and $0.22\text{m}^2/\text{m}^3$ – compared to around $0.09\text{m}^2/\text{m}^3$ for the more bulky fourth generation buildings (see Table 3). This is achieved by utilising shallow floor plans (i.e. GSW Headquarters, Berlin, 1999) or by using large atria to effectively reduce the depth of deeper floorplates (i.e. Deutsche Post Tower, Bonn, 2002 & ‘Swiss Re’ Tower, London, 2004), allowing air and natural light to penetrate deep into office spaces. Although this increase in surface area to volume ratio would reduce artificial lighting loads and make natural ventilation a possibility, winter heating loads in these

buildings would also rise as previously discussed. Artificial lighting requirements in these towers are further reduced by the use of photo and motion-sensors that adjust overhead lights, turning them down or off when natural lighting levels are sufficient, or when rooms are empty. For example, in the Bank of America Tower (New York, 2008) this technology will help reduce the demand for electric lighting by 25% (Aston, 2007).

A further characteristic common in many of these tall buildings is a move away from the total reliance upon air-conditioning to strategies that utilise natural and mixed-mode ventilation where climatic conditions allow – for the first time in around fifty years tall buildings are again being designed with opening windows that form part of the internal conditioning strategy. For example, the GSW Headquarters in Berlin (designed by Sauerbruch Hutton Architects) utilises a west-facing, double-skin façade that acts as a thermal flue; air in the façade cavity rises due to buoyancy, and when windows are opened used air is drawn out from the office spaces into the flue and is replaced with fresh air from the east façade (see *Figure 9*). This strategy allows the building to be naturally ventilated for around 70% of the year, significantly reducing air-conditioning energy usage.

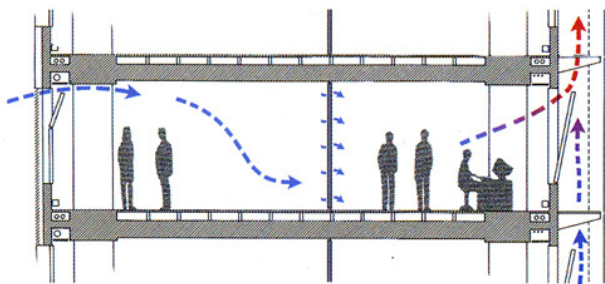


Figure 9. GSW Headquarters, Berlin, 1999. Part section showing the natural ventilation strategy and double skin façade (to the right).
[Source: Clemmetsen et al, 2000]

In more recent years, a new trend in fifth generation skyscrapers has been the exploitation of on-site energy generation from low and zero-carbon sources. Although the integration of many of these technologies into tall buildings is still at the experimental stage, increasing numbers of designs and some completed projects utilise technologies such as building augmented wind turbines, photovoltaic cells, co-generation and tri-generation systems, fuel cells and ground-source heat pumps to reduce overall energy consumption. One of the most exciting developments in this field of energy generation is the construction of the Bahrain World Trade Center in Manama (see *Figure 10*). The aerofoil plan form of these towers accelerates the prevailing offshore wind between them and onto three 29m diameter wind turbines. These, it is predicted, will generate approximately 11 – 15% of the building's total electrical



Figure 10. Bahrain World Trade Center, Manama. In recent years the exploitation of on-site energy generation from renewable sources has become a common characteristic of fifth generation tall buildings.
[Source: Smith & Killa, 2007]

energy consumption (Smith & Killa, 2007).

Conclusion

Table 3 on the next page summarises the overall findings of this paper. Basically, we can note a number of trends affecting tall building energy performance throughout history. Energy in first generation buildings (1885 – 1916) was predominantly consumed in the heating of occupied spaces and providing vertical transportation, as other technologies were not yet developed. These towers benefited from their compact and bulky shape (large volume vs. small surface area) reducing winter heat loss through the building envelope, which also contained a high degree of thermal mass. However, their shape and low quantities of façade transparency also significantly restricted natural light penetration.

Second generation buildings (1916 – 1951) were increasingly slender (small volume vs. large surface area) – a direct result of the New York Zoning Law of 1916. This change in shape would increase winter heat loss, but at the same time allow for a greater level of daylight in occupied spaces. Like first generation buildings, these towers also benefited from thermal mass within the envelope construction.

Table 3. Summary of data and findings. All values calculated by the Authors from a variety of sources, unless otherwise stated.

	1st Energy Generation From the Birth of Tall Buildings in 1885, to the 1916 Zoning Law	2nd Energy Generation From the 1916 Zoning Law to the Development of the Glazed Curtain Wall, 1951	3rd Energy Generation From the Development of the Glazed Curtain Wall, 1951, to the 1973 Energy Crisis	4th Energy Generation From the Energy Crisis of 1973 to the Present Day, 2008	5th Energy Generation From the Rise of an Environmental Consciousness in 1997 to the Present Day, 2008
Typical Energy Performance Characteristics	<ul style="list-style-type: none"> - Compact shape (large volume vs. small façade area) - High levels of thermal mass in façade - Low percentage of façade transparency - Heating and elevators main consumers of energy 	<ul style="list-style-type: none"> - Slender shape (small volume vs. large façade area) - High levels of thermal mass in façade - Low percentage of façade transparency - The use of air-conditioning becoming more common 	<ul style="list-style-type: none"> - Compact shape (large volume vs. small façade area) - Low performance, single-glazed curtain wall façade systems - High quantities of façade transparency with tinted glazing - Total reliance on mechanical conditioning and fluorescent lighting - Large quantity of 'black skyscrapers' 	<ul style="list-style-type: none"> - Compact shape (large volume vs. small façade area) - Good performance, double-glazed curtain wall façade systems - High quantities of façade transparency with good solar transmittance - Total reliance on mechanical conditioning 	<ul style="list-style-type: none"> - Slender shape (small volume vs. large façade area) - High performance double-skin & triple glazed curtain wall façade systems - High quantities of façade transparency with good solar transmittance - Natural ventilation possibilities exploited - On-site energy generation promoted
Surface area to volume ratios (m²/ m³) ⁶	<ul style="list-style-type: none"> - 90 West Street, <i>New York</i>: 0.118 - Woolworth Building, <i>New York</i>: 0.122 - 195 Broadway, <i>New York</i>: 0.087 - Municipal Building, <i>New York</i>: 0.118 - Equitable Building, <i>New York</i>: 0.088 <p><i>Average: 0.107</i></p>	<ul style="list-style-type: none"> - Bryant Park Tower, <i>New York</i>: 0.189 - Mercantile Building, <i>New York</i>: 0.144 - Chrysler Building, <i>New York</i>: 0.130 - 500 5th Avenue, <i>New York</i>: 0.158 - 570 Lexington Ave, <i>New York</i>: 0.138 <p><i>Average: 0.152</i></p>	<ul style="list-style-type: none"> - Lever House, <i>New York</i>: 0.164 - Seagram Building, <i>New York</i>: 0.123 - City National Tower, <i>LA</i>: 0.089 - One IBM Plaza, <i>Chicago</i>: 0.088 - Tour Fiat, <i>Paris</i>: 0.089 <p><i>Average: 0.111</i></p>	<ul style="list-style-type: none"> - First Canadian Place, <i>Toronto</i>: 0.077 - Wells Fargo Plaza, <i>Houston</i>: 0.087 - One Canada Square, <i>London</i>: 0.079 - UOB Plaza, <i>Singapore</i>: 0.112 - Cheung Kong Center, <i>Hong Kong</i>: 0.084 <p><i>Average: 0.088</i></p>	<ul style="list-style-type: none"> - Commerzbank, <i>Frankfurt</i>: 0.161 - GSW Headquarters, <i>Berlin</i>: 0.221 - Deutsche Post Building, <i>Bonn</i>: 0.152 - Hearst Tower, <i>New York</i>: 0.100 - Bank of America Tower, <i>New York</i>: 0.096 <p><i>Average: 0.146</i></p>
Typical office lighting levels (foot-candles) ⁷	8-9	10 - 25	100 - 150	35 – 100	35 – 45
Typical façade U-values (W/m²K)	Information unavailable. Figures likely to be in 2.0 – 3.0 range.	- Empire State Building, <i>New York</i> : 2.6	<ul style="list-style-type: none"> - Lake Shore Drive Apartments, <i>Chicago</i>: 4.2 - Lever House, <i>New York</i>: 3.3 	<ul style="list-style-type: none"> - Wells Fargo Plaza, <i>Houston</i>: 1.5 - Cheung Kong Center, <i>Hong Kong</i>: 0.9 	<ul style="list-style-type: none"> - Deutsche Post Building, <i>Bonn</i>: 1.1 - Bank of America Tower, <i>New York</i>: 0.9
Transparency within façade	<ul style="list-style-type: none"> - Woolworth Building, <i>New York</i>: 21% - Equitable Building, <i>New York</i>: 25% - Municipal Building, <i>New York</i>: 29% 	<ul style="list-style-type: none"> - Chrysler Building, <i>New York</i>: 32% - Empire State Building, <i>New York</i>: 23% - 500 5th Ave, <i>New York</i>: 32% 	<ul style="list-style-type: none"> - Lake Shore Drive Apartments, <i>Chicago</i>: 72% - Lever House, <i>New York</i>: 53% - City National Tower, <i>LA</i>: 53% 	<ul style="list-style-type: none"> - Wells Fargo Plaza, <i>Houston</i>: 82% - One Canada Square, <i>London</i>: 43% - Cheung Kong Center, <i>Hong Kong</i>: 52% 	<ul style="list-style-type: none"> - Commerzbank, <i>Frankfurt</i>: 54% - Hearst Tower, <i>New York</i>: 63% - Bank of America Tower, <i>New York</i>: 71%
Ventilation strategies	Naturally ventilated via opening lights. Later renovated to be fully air-conditioned.	Naturally ventilated via opening lights. Later renovated to be fully air-conditioned.	Hermetically sealed and totally reliant on mechanical conditioning.	Hermetically sealed and totally reliant on mechanical conditioning.	Opportunities for natural and mixed-mode ventilation exploited. Double-skin facades often utilised where climatic conditions allow.

⁶ Values only include the tower element of projects and not adjacent low-level buildings that form part of the complex. Figures also do not include large atria / skygarden spaces, double-skin façade cavities and the ground floor footprint area as part of the calculations. Value for the Hearst Tower only includes the tower from the first office floor above – figure does not include surface area / volume of the renovated ground floor lobby.

⁷ Figures from Osterhaus (1993), Willis (1997) and a personal communication with Wilson Dau, Head of the IESNA Office Lighting Committee.

Third generation buildings (1951 – 1973) were heavily influenced by the development of glazed curtain walls; 50 – 75% of tall building façade area in this generation consisted of glazing, compared to 20 – 35% in the previous two generations. Subsequently, façade U-values increased due to the high proportions of single glazing used. Tall buildings of this generation were hermetically sealed boxes, totally reliant on mechanical conditioning and artificial lighting – despite high levels of façade transparency, tinted glazing and deep floor plans significantly restricted daylight penetration. At the same time, office illuminance recommendations were significantly higher in this era than at any other time.

Fourth generation buildings (1973 – Present) benefited greatly from a widespread switch to double-glazing and increased technological developments in curtain wall facades. While envelope glazing percentages remained high, façade U-values decreased from around 3.0 – 4.2W/m²K in third generation buildings, to levels of 1.0 – 1.5W/m²K. The majority of tall buildings constructed today, continue to demonstrate the characteristics of fourth generation buildings; compact shape (surface area to volume ratios of around 0.07m²/m³ - 0.12m²/m³), high levels of façade glazing (40 – 85%) and a reliance on air-conditioning.

Fifth generation buildings (1997 – Present) are still relatively rare, at least in completed form. Generally these towers have a high surface area to volume ratio (often achieved by the use of large atria) and high quantities of envelope transparency, allowing for excellent levels of daylight penetration, but at the cost of higher winter heating loads. The use of natural and mixed-mode ventilation strategies are also common in these towers, significantly reducing overall energy consumption. Lastly, buildings of this category have recently begun exploring the potential to harness on-site energy generation from low and zero-carbon sources.

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