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Five energy generations of tall buildings: an historical analysis of energy consumption in high-rise buildings

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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. These factors have been influenced by regulatory changes, developments in technology and materials, changes in architectural thinking and economic and commercial drivers. Developments such as the New York Zoning Law of 1916, the postwar 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 energy and the way in which it was consumed in tall buildings of the time. This paper examines 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 their energy consumption characteristics.

Introduction

Over the past one hundred and twenty 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 and commercial drivers. Developments such as the New York Zoning Law of 1916, the postwar 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 energy and the way in which it 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 built environment is a significant contributor to global greenhouse gas emissions, with buildings accountable for 30–40% of all primary energy used worldwide,[1] and carbon dioxide emissions in buildings increasing at an annual rate of 2% between 1971 and 2004.[2] Recent years have also seen a boom in tall building construction unprecedented in terms of its global scale, with more — and taller — high-rise buildings being constructed than ever before. Figures suggest that by 2010, 59 of the tallest 100 buildings in the world as documented in 2006, only four years

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beforehand, will be new. The combined height of these 100 buildings will have increased by over five kilometres, or 17%, compared to 2006.[3]

In the light of this, attention has turned towards the environmental impact of tall buildings, which are still seen by many as inherently anti-environmental due to their typically high operating energy requirements, reliance on artificial lighting and conditioning, high embodied energy and increased maintenance costs,[4] and frenzied research has been — and continues to be — undertaken in order to reduce their future primary energy needs. However, it is also interesting, and necessary, 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. This paper examines 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 their energy consumption characteristics.

The first energy generation: from the birth of tall buildings in 1885, to the 1916 Zoning Law

Born out of a desire to maximise the financial return of a given plot of land, combined with developments in structural steel framing and the invention of the lift in the mid-nineteenth 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.

Primary energy was predominantly consumed in the heating of occupied spaces and providing vertical transport between floors. Ventilation was achieved naturally through opening windows and artificial lighting levels were very low: typically between 22 and 43 lux[5] in office buildings in 1913 due to the inefficiencies of lighting technologies of the time.[6] The quality and rentability of office space thus depended on large windows and high ceilings that allowed daylight to penetrate as deeply as possible into the interior.[7] Windows occupied some 20% – 40% of the façade in first-generation buildings (see Table 4 at end), which, whilst high for the time, is still significantly lower than modern high-rise buildings with their glazed curtain walls allowing values of 50–75% façade transparency.[8]

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 rôle, were often quite thick, of masonry construction, with an internal finish of dense plasterwork. Whilst this construction suffers from a lack of thermal insulation (ie, 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 upon their primary energy usage; typically those constructed prior to the 1916 Zoning Law were bulky, compact forms, the result of repetitive stacking of large floor plates 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. However, these bulky forms disguised relatively shallow lease spans with a maximum of 6.1 to 8.5 metres almost universally observed[9] maintaining natural light penetration into office spaces.

These characteristics of dense, solid façade and compact, bulky shape are best reflected in the Equitable Building of New York, completed in 1915 (Fig. 1). This building — the vertical extrapolation of an H-shaped floor plan over 40 storeys — is an immense volume, whilst its façade consists of limestone cladding, backed by thick masonry, with punctured windows.

Figure 1. The Equitable Building, New York, 1915.

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. However, their energy performance still benefits to a certain extent from their shape (compact and bulky) and their envelope construction (solidity and thermal mass).

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.[10] 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 increase steadily, 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

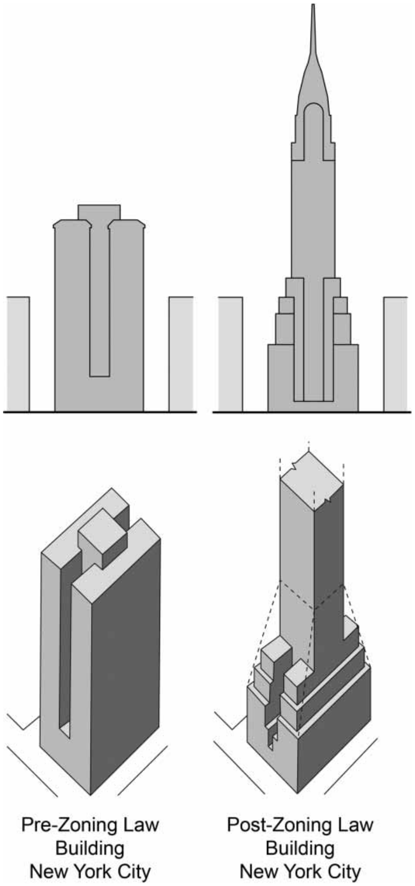

Figure 2. The 1916 Zoning Law: impact on tall building form and mass.[11]

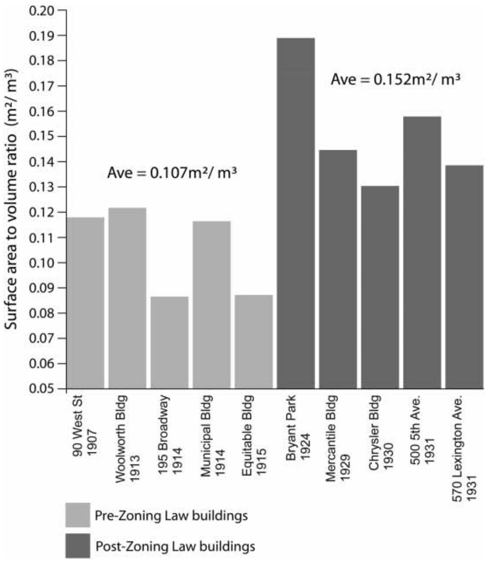

Figure 3. Façade surface area to volume ratios for New York high-rise buildings completed prior to, and after the 1916 Zoning Law. See also Table 4 at end.

buildings, requiring them to preserve the penetration of light and air onto the streets below. The subsequent ‘set-backs’ prescribed by the law created the familiar ‘wedding cake’ skyscraper style that would dominate future skylines (Fig. 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 following formula:

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

In this instance, *SA* is the envelope surface area of the building and *V* is its volume. The results of this analysis are outlined above (Fig. 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*[12] 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 heating requirements due to an increased quantity of envelope area facilitating heat loss.

However, at the same time, the slender Zoning Law buildings have smaller floor plans compared to '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 at the higher floor levels. However, despite this greater potential, artificial lighting standards actually increased in this second generation time period; whereas in 1916 the recommendation by the New York City Department of Health for adequate lighting levels in offices was 86-97 lux, it rose to 108-129 lux in the 1920s and, spurred on by the aggressive sales tactics of large power companies, some experts urged up to 269 lux by the 1930s.[13]

So, it can be seen that the 1916 Zoning Law directly influenced the primary 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 requirements for space heating (due to increased heat loss through higher quantities of envelope), but with increased natural light penetration at the higher floor levels.

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 in 1902 prior to the Zoning Law, has a surface area to volume ratio of 0.17 m^2/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 m^2/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 forty 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 was not until the 1950s and 1960s that it became a standard feature.

The earliest high-rise office building that was completely air-conditioned was the Milam Building in San Antonio, Texas, which was built in 1928.[14] Shortly afterwards, a few existing skyscrapers were retrofitted to include air-conditioning. 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, 1933, the Tribune publisher directed the tower's management immediately to install air-conditioning to provide more comfortable internal conditions and to boost demand for vacant space in the tower.

> The Tribune believes, and has said, that the next great advance in human comfort will be achieved by air conditioning. . .The Tribune Tower will be air-conditioned as a contribution to the comfort and health of its occupants, as a contribution to the progress of air conditioning for all, as a contribution to the economic revival of the nation.[15]

Whilst Second Generation buildings suffered increased primary energy needs through a change in shape, higher artificial 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 dense plasterwork.[16]

The third energy generation: from the development of the glazed curtain wall, 1951, to the 1973 energy crisis[17]

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 and hence never realised.[18] 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 40% glazing within their façades (Fine Arts Building, Chicago, 1885: 40%; 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.[19]

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 (Fig. 4). This lightweight façade construction,

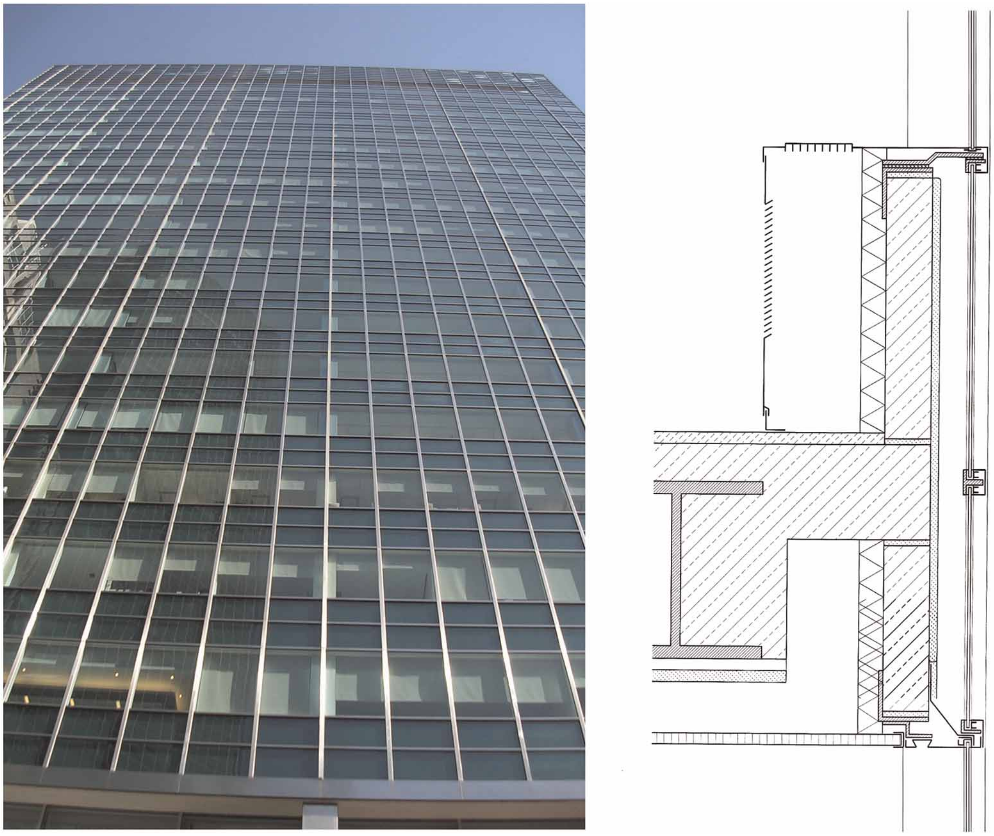

Figure 4. Lever House, New York, 1952. From left a) view of the curtain wall façade; b) cross-section through the building envelope highlighting the use of single-glazing with a concrete upstand for fire legislation purposes.[20]

made possible only by the use of fixed single glazing, has a significantly inferior thermal/insulation performance compared to the heavyweight façades of first- and second-generation buildings. For example, the façade of Lever House has a U-value of approximately 3.3W/m^{2}K, compared to 2.6W/m^{2}K for the Empire State Building, completed twenty years previously (see Table 1 at end). 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/m^{2}K, compared to values of 1.1W/m^{2}K and below, common in modern high-rise office buildings.[22]

The problems suffered by buildings with large quantities of single glazing 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 primary 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 design, it could not operate without it.[23]

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 have suffered higher quantities of unwanted heat gain in the summer months, compared to other buildings with brick or lighter coloured façades (see Table 2 at end). The result is that the black skyscraper would further rely on gas-guzzling air-conditioning plant to create a comfortable internal environment.

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 primary energy consumption would probably be detrimental; despite the high quantities of glazing in the façade, low amounts of natural light would actually penetrate into the office spaces beyond due to the poor light transmission properties of the dark-coloured glass (see Table 3 at end). This in turn would increase reliance upon artificial lighting.

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 property 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 m^2/m^3 and 0.13 m^2/m^3, similar to those built prior to the Zoning Law (see Table 4 at end). 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 compromise that allowed a 20% density bonus for buildings that created a public plaza on a portion of their plot.[26]

Whilst the bulky form of these buildings would be beneficial in colder climates, reducing heat loss in winter months through the low-performance curtain walling, the deep floor plans would also restrict the passage of natural light into office spaces. Recommended office lighting levels also rose dramatically in this generation; whereas in the 1930s the recommended levels were around 269 lux, the *1960 Recommended Practice for Office Lighting* guidelines advised illuminance levels of between 1076 – 1615 lux.[27]

> 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.[28]

Figure 5. Average primary energy consumption of 86 office buildings constructed in Manhattan between 1950 and 1970.[30]

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 primary 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 buildings' primary energy consumption grew dramatically in this period as demonstrated by a study on 86 office buildings constructed in Manhattan between 1950 and 1970.[29] The results of the study show that, on average, buildings completed in the late 1960s have primary energy requirements more than double those of buildings constructed in the early 1950s, less than twenty years previously (Fig. 5).

The fourth energy generation: from the energy crisis of 1973 to the present day

The popularity of the single-glazed curtain wall façade, 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 primary energy these buildings required 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.[31] In fact, the strong criticism the single-glazed curtain wall faced resulted in many changes to façade design.

> Triggered by the two oil crises, the energy issue now took the spotlight overnight. The all-glass facade was called into question and even the humble window considered an energy leak. But this temporary rejection of glass forced the industry to act. A great bout of research activity led to the development of more effective insulating and solar-control glasses...Coloured and mirrored glasses were now much less in demand; the clear transparent varieties had taken centre stage owing to their better daylight transmittance.[32]

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/m^{2}K, the use of double glazing, low-e coatings and argon-filled cavities reduced these figures to between 1.0 – 1.5W/m^{2}K in fourth-generation buildings. At the same time, the move away from dark-tinted glazing 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 25–50% decrease in office illuminance levels, due to the rising energy costs and environmental concerns brought about by the energy crises.[33]

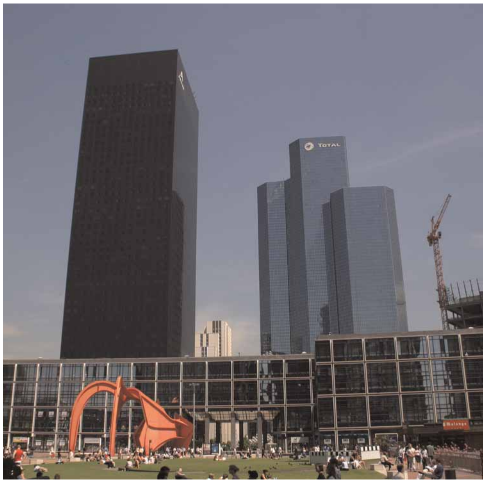

Figure 6. Tour Fiat (left) and Tour Elf, La Défense, Paris. The original design of the Tour Elf called for a twin tower to the Tour Fiat.[34]

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 (Fig. 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

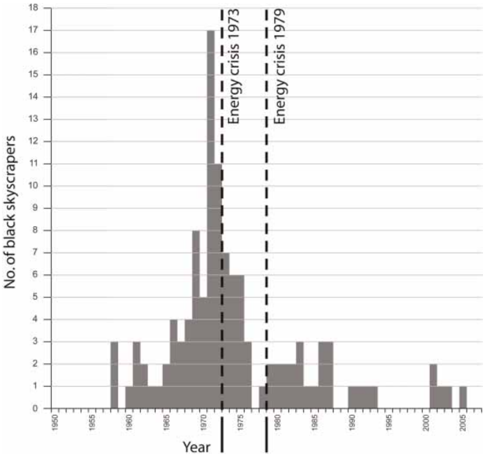

Figure 7. Number of black skyscrapers constructed in North America since 1950. Buildings over 100 m in height and located in Atlanta, Chicago, Houston, Los Angeles, Miami, New York and San Francisco considered.

well insulated, a reflection of the strides forward made by the glazing industry after the energy crises. This, in conjunction with a computerised 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.[35]

It was 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 (Fig. 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 buildings' primary energy consumption. For example, the dramatic rise in the use of computers in this era not only required additional electricity 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 gains[36] — a figure that is compensated for by increasing levels of mechanical conditioning at significant primary energy cost.

The fifth energy generation: from the rise of an environmental consciousness (1997) to the present day

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 primary 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,[37] this change cannot occur quickly enough.

Arguably the first significant tall building reflecting these new environmentally conscious principles was the Commerzbank in Frankfurt (by 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

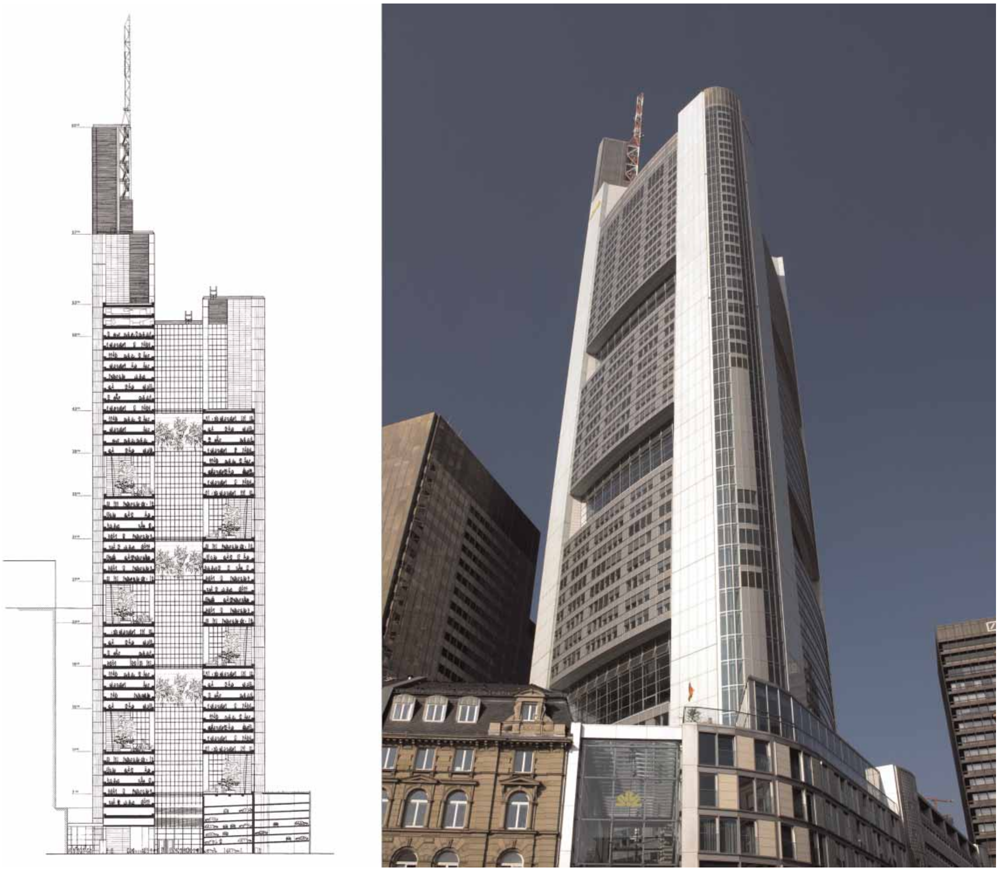

Figure 8. Commerzbank Tower, Frankfurt, 1997. From left a) building section showing the full-height central atrium and staggered sky gardens providing natural lighting and ventilation to internal office spaces; b) Tower in context.[39]

in Oklahoma (1956) as earlier examples of 'sustainable' high-rise design.[38] The Commerzbank (Fig. 8) incorporates a high degree of primary 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 sky gardens further to increase daylight penetration to office areas.

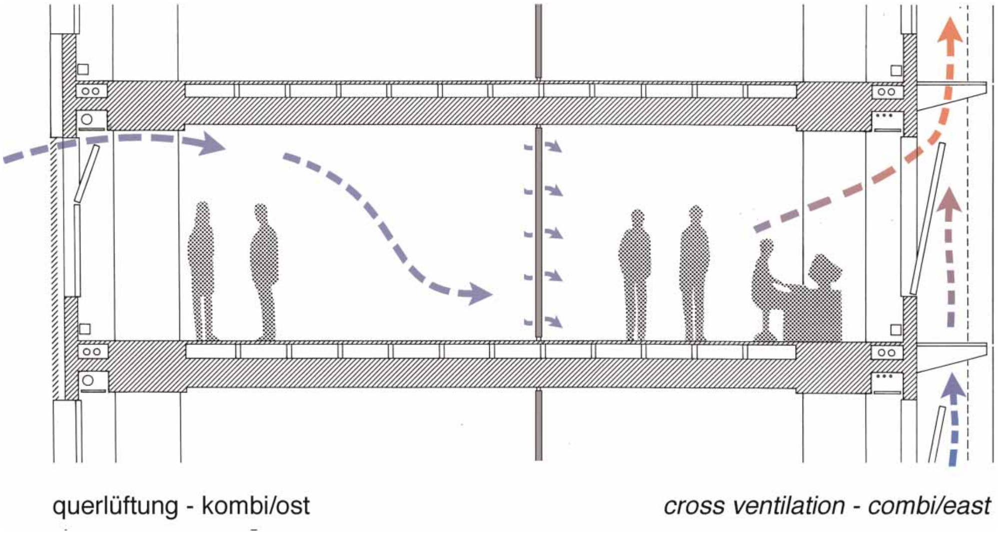

Figure 9. GSW Headquarters, Berlin, 1999. Part-section showing the natural ventilation strategy and double skin façade (to the right).[41]

- A façade design that allows for natural ventilation for over half the year through operable windows (known as the Klima-façade).
- A water-based cooling system of chilled ceilings.

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 high surface area to volume ratios — typically between 0.10 m^2/m^3 and 0.22 m^2/m^3 — compared to around 0.09 m^2/m^3 for the more bulky fourth-generation buildings (see Table 4 at end). This is achieved by utilising shallow floor plans (eg,. GSW Headquarters, Berlin, 1999) or by using large atria effectively to reduce the depth of deeper floor plates (eg, 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 to reduce the demand for electric lighting by 25%.[40]

A further characteristic common to 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 (Fig. 9). This strategy allows the building to be naturally ventilated for around 70% of the year, significantly reducing air-conditioning energy needs.[42]

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 primary energy consumption. One of the most exciting developments in this field of on-site energy generation is the construction of the Bahrain World Trade Center in Manama (Fig. 10). The aerofoil plan form of these towers accelerates the prevailing offshore wind between them and onto three 29 m diameter wind turbines. These, it is predicted, will generate approximately 11 – 15% of the building's total electrical energy needs.[44]

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.[43]

In part, this shift from fourth-generation to fifth-generation tall building design is being influenced by commercial and cultural drivers. Quality design, and, more recently, sustainable design, is being recognised as a significant factor in generating status and revenue, with companies much more prepared to pay a premium for quality designed space and an improved environment, especially with sustainable credentials. For example, a study by the CoStar group reveals that buildings which achieve a Leadership in Energy and Environmental Design (LEED) rating command a rent premium of \$11.24 per square foot greater than their non-LEED peers, and have 3.8% higher occupancy.[45]

New regulatory demands at city authority level are also driving this shift towards more sustainable tall buildings. The City of Chicago has created an expedited green building permit process, which offers a quicker and cheaper planning application procedure to buildings that demonstrate sustainable qualities.[46] In Dubai, green building specifications are also being implemented, demanding that all new residential and commercial buildings comply with internationally recognised environmentally friendly criteria, whilst in London planning regulations demand that all new major developments utilise on-site renewable energy to generate 10% of the building's requirements wherever feasible.[47]

Conclusion

Table 4 (at end) summarises the overall findings of this paper. Basically, we can note a number of trends affecting tall-building energy performance throughout history. Primary energy in first-generation buildings (1885–1916) was predominantly consumed in the heating of occupied spaces and providing vertical transport, 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.

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 penetration at the upper floors. Like first-generation buildings, these towers also benefited from thermal mass within the envelope construction.

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 20–40% 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 to the present day) benefited greatly from a widespread switch to double-glazing and increased technological developments in curtain wall façades. While envelope glazing percentages remained high, façade U-values decreased from around 3.0 – 4.2W/m^{2}K in third-generation buildings, to levels of 1.0–1.5W/m^{2}K. 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 0.07 m^2/m^3–0.12 m^2/m^3), high levels of façade glazing (40 – 85%) and a reliance on air-conditioning.

Fifth-generation buildings (1997 to the present day) 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. Lastly, buildings of this category have recently begun exploring the potential to harness on-site energy generation from low- and zero-carbon sources.

An issue for further research would be to determine the quantitative implications on primary energy consumption of the changes in tall-building characteristics across these five generations. Tall-building envelope design in particular would benefit from such studies: determining whether future tall buildings may benefit from 'first and second generation' characteristics — such as increased opacity and thermal mass within the façade — in order to reduce their primary energy needs and assist in meeting the modern-day challenge of climate change.

Notes and references

1. UNEP, *Buildings and Climate Change: Status, Challenges and Opportunities* (Nairobi, United Nations Environmental Programme, 2007).
2. M. Levine, D. Ürge-Vorsatz, K. Blok, L. Geng, D. Harvey, *et al*, 'Residential and Commercial Buildings', *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, United Kingdom and New York, USA, Cambridge University Press, 2007).
3. A. Wood and P. F. Oldfield, 'Global Trends of the High-rise Building Design', *Urbanism and Architecture*, 10, 49 (Ha'erbin, Heilongjiang Science and Technology Press, October, 2008), pp. 14–16.
4. S. Roaf, D. Crichton and F. Nicol, *Adapting Buildings and Cities for Climate Change: A 21st Century Survival Guide* (Oxford, Architectural Press, 2005).
5. All measurements of illuminance within this paper are converted to lux from foot-candles.
6. W. K. E. Osterhaus, *Office Lighting: A Review of 80 Years of Standards and Recommendations*, Proceedings of the IEEE Industry Applications Society Annual Meeting, Toronto (October 2nd-8th, 1993).
7. C. Willis, *Form follows Finance: Skyscrapers and Skylines in New York and Chicago* (New York, Princeton Architectural Press, 1997).
8. Façade glazing ratios refer to the percentage of glazing within a typical section of building façade. All data calculated by the authors from a variety of photographs and drawings. See also Table 4 at end.
9. C. Willis, *Form follows Finance: Skyscrapers and Skylines in New York and Chicago*, *op. cit.*
10. M. A. Weiss, 'Skyscraper Zoning: New York's Pioneering Role', *Journal of the American Planning Association*, 58, 2 (1992), pp.201–212.
11. Image by the authors, based on a diagram from J. Barnett, *An Introduction to Urban Design* (New York, Harper Collins, 1982).
12. P. Depecker, C. Menezo, J. Virgone and S. Lepers, 'Design of Buildings Shape and Energetic Consumption', *Building and Environment*, 36 (2001), pp.627–635.
13. C. Willis, *Form follows Finance: Skyscrapers and Skylines in New York and Chicago*, *op. cit.*
14. M. Pauken, 'Sleeping Soundly on Summer Nights: The First Century of Air Conditioning', *ASHRAE Journal* (May, 1999), pp.40–47.

15. The Chicago Tribune announces its intent to install air-conditioning in the Tribune Tower: from Chicago Tribune, 'Air Conditioning for the Tribune Tower', *Chicago Daily Tribune*, (June 10th, 1934), p.14.
16. R. J. Nacheman, 'The Empire State Building: Façade Evaluation and Repair of an Engineering Landmark', *Structure Magazine* (January, 2006), pp.39–43.
17. 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.
18. C. Schittich, G. Staib, D. Balkow, M. Schuler and W. Sober, *Glass Construction Manual: Second Edition* (Basel, Birkhäuer Verlag AG, 2007).
19. *Ibid.*, p.30.
20. *Ibid.*, p.51: Figure 4b.(© DETAIL, used with permission.)
21. Façade construction make-up taken from R. J. Nacheman, *op. cit.* and C. Schittich *et al*, *op. cit.*
22. Unless stated otherwise, all U-value data is calculated by the authors from published technical details and descriptions of the building façade construction, as outlined in Table 1. Figures refer to the average U-value of the façade, including both glazed and solid wall elements.
23. D. Arnold, 'Air Conditioning in Office Buildings after World War II', *ASHRAE Journal* (July, 1999), pp.33–41.
24. Data from K. Yeang, *Ecodesign: A Manual for Ecological Design* (London, Wiley Academy, 2006).
25. Data courtesy of Pilkington Glass.
26. M. A. Weiss, 'Skyscraper Zoning: New York's Pioneering Role', *op. cit.*
27. W. K. E. Osterhaus, *Office Lighting: A Review of 80 Years of Standards and Recommendations, op. cit.*
28. C. Willis, *Form follows Finance: Skyscrapers and Skylines in New York and Chicago*, *op. cit.*
29. R. G. Stein, 'Observations on Energy Use in Buildings', *Journal of Architectural Education*, 30, 3 (1977), pp.36–41.
30. *Ibid.*, data, p.36; image by the authors.
31. T. E. Johnson, *Low E-Glazing Design Guide* (Stoneham, Massachusetts, Butterworth Architecture, 1991).
32. Christian Schittich, from C. Schittich, G. Staib, D. Balkow, M. Schuler and W. Sober, *Glass Construction Manual: Second Edition, op. cit.,* p.36.
33. W. K. E. Osterhaus, *Office Lighting: A Review of 80 Years of Standards and Recommendations, op. cit.*
34. © Steven Henry, used with permission.
35. A. Ayers, *The Architecture of Paris* (Germany, Edition Axel Menges, 2004).
36. In comparison, prior to the use of computers in the workplace, non-climatic internal heat gains in office buildings would mostly arise from people (8.5W/m^2, assuming an average of 15 m^2 of floor space per person) and lighting (13W/m^2). From I. Knight and G. Dunn, *Evaluation of Heat Gains in UK Office Environments*, Proceedings of CIBSE/ASHRAE Conference, Edinburgh (24th-26th September, 2003).
37. Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis. Summary for Policy Makers* (Cambridge, Cambridge University Press, 2007).
38. A. Wood, *Green or Grey: The Aesthetics of Tall Building Sustainability*, Proceedings of the CTBUH 8th World Congress, 'Tall and Green: Typology for a Sustainable Urban Future', Dubai (March 3rd-5th, 2008), pp. 194–202.
39. Figure 8a) © Foster+Partners, used with permission; Figure 8b) © Marshall Gerometta, used with permission.
40. A. Aston, 'A Skyscraper Banking on Green', *Business Week* (February 28th, 2007). Internet WWW page at: <http://www.images.businessweek.com/ss/07/02/0228_greenbuilding/index_01.htm
41. © Sauerbruch Hutton, used with permission.
42. N. Clemmetsen, W. Muller and C. Trott, 'GSW Headquarters, Berlin', *The Arup Journal* (February, 2000), pp.8–12.

43. © Robert Lau, used with permission.
44. R. F. Smith and S. Killa, 'Bahrain World Trade Center (BWTC): The First Large Scale Integration of Wind Turbines in a Building', *The Structural Design of Tall and Special Buildings*, 16 (2007), pp.429–439.
45. A. C. Burr, *CoStar Study Finds LEED, Energy Star Bldgs. Outperform Peers*. Internet WWW page at: <http://www.usgbc.org/News/USGBCInTheNewsDetails.aspx?ID=3637> (Updated: 26.03.2008.)
46. R. M. Daley and S. Johnston, *Chicago: Building a Green City*, Proceedings of the CTBUH 8th World Congress, 'Tall and Green:Typology for a Sustainable Urban Future', Dubai, *op. cit.*, pp. 23–25.
47. Greater London Authority, *Action Today to Protect Tomorrow: The Mayor's Climate Change Action Plan, Executive Summary* (London, Greater London Authority, 2007).
48. 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/sky garden 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: the figure does not include surface area/volume of the renovated ground floor lobby.
49. Figures from W. K. E. Osterhaus, *Office Lighting: A Review of 80 Years of Standards and Recommendations, op. cit.*; C. Willis, *Form follows Finance: Skyscrapers and Skylines in New York and Chicago*, *op. cit.*; and a personal communication with Wilson Dau, Head of the IESNA Office Lighting Committee. All measurements converted to lux from foot-candles.

Table 1. Envelope U-value calculations for the Empire State Building and Lever House.[21]

2nd energy generation: Empire State Building, 1931, New York	Thickness (m)	Thermal conductivity (W/mK)	Thermal resistance (m^2K/W)
1. Wall (52.4%)			
External surface	-	-	0.06
Limestone cladding	0.102	1.3	0.078
Brickwork	0.203	0.62	0.327
Dense plaster	0.024	0.5	0.048
Internal surface	-	-	0.12
Total resistance	-	-	**0.633**
U-Value of wall element = (1/0.633) = 1.58W/m^{2}K			
2. Spandrel panel (24.7%)			
External surface	-	-	0.06
Aluminium spandrel panel	0.04	237	0.00017
Brickwork	0.203	0.62	0.327
Dense plaster	0.024	0.5	0.048
Internal surface	-	-	0.12
Total resistance	-	-	**0.555**
U-Value of spandrel panel element = (1/0.555) = 1.802W/m^{2}K			
3. Glazing (22.9%)			
6 mm Clear single-glazing with no coatings			
U-Value of glazing element = 5.7W/m^{2}K			
(Figure courtesy of Pilkington Glass)			
Average envelope U-value = (0.524 x 1.58)+(0.247 x 1.802)+(0.229 x 5.7) = 2.578W/m^{2}K			

(*Table continued*)

Table 1. (Continued)

3rd energy generation: Lever House, 1952, New York	Thickness (m)	Thermal conductivity (W/mK)	Thermal resistance (m^2K/W)
1. Wall/Upstand (47%)			
External surface	-	-	0.06
Glazed spandrel panel	0.06	1	0.06
Air gap	-	-	0.18
Concrete upstand	0.125	1.4	0.089
Insulation	0.05	0.035	1.429
Internal surface	-	-	0.12
Total resistance			1.938
U-Value of wall/upstand element = (1/1.938) = 0.516W/m^2K			
2. Glazing (53%)			
6 mm Blue/green-tinted single-glazing			
U-Value of glazing element = 5.7W/m^2K			
(Figure courtesy of Pilkington Glass)			
Average envelope U-value = (0.47 x 0.516)+(0.53 x 5.7) = 3.264W/m^2K			

Table 2. Solar absorbance values for a variety of different coloured materials.[24]

Material	Solar absorbance
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

Table 3. Light transmission values for coloured and clear glazing.[25]

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

Table 4. Summary of data and findings. All values calculated by the authors from a variety of sources, unless otherwise stated.

	1st energy generation	2nd energy generation	3rd energy generation	4th energy generation	5th energy generation
	From the birth of tall buildings in 1885, to the 1916 Zoning Law	From the 1916 Zoning Law to the development of the glazed curtain wall, 1951	From the development of the glazed curtain wall, 1951, to the 1973 energy crisis	From the energy crisis of 1973 to the present day	From the rise of an environmental consciousness in 1997 to the present day
Typical energy performance characteristics	- Compact shape (large volume vs. small façade area) - High levels of thermal mass in façade - Low percentage of façade transparency compared to modern tall buildings - Reliance on natural light penetration - Heating and lifts main consumers of primary energy	- Slender shape (small volume vs. large façade area) - High levels of thermal mass in façade - Low percentage of façade transparency compared to modern tall buildings - Greater levels of artificial lighting - The use of air-conditioning becoming more common	- 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'	- 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	- 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

(*Table continued*)

Table 4. (Continued)

	1st energy generation	2nd energy generation	3rd energy generation	4th energy generation	5th energy generation
	From the birth of tall buildings in 1885, to the 1916 Zoning Law	From the 1916 Zoning Law to the development of the glazed curtain wall, 1951	From the development of the glazed curtain wall, 1951, to the 1973 energy crisis	From the energy crisis of 1973 to the present day	From the rise of an environmental consciousness in 1997 to the present day
Surface area to volume ratios (m^2/ m^3)[48]	- 90 West Street, *New York*: 0.118	- Bryant Park Tower, *New York*: 0.189	- Lever House, *New York*: 0.164	- First Canadian Place, *Toronto*: 0.077	- Commerzbank, *Frankfurt*: 0.161
	- Woolworth Building, *New York*: 0.122	- Mercantile Building, *New York*: 0.144	- Seagram Building, *New York*: 0.123	- Wells Fargo Plaza, *Houston*: 0.087	- GSW Headquarters, *Berlin*: 0.221
	- 195 Broadway, *New York*: 0.087 - Municipal Building, *New York*: 0.118	- Chrysler Building, *New York*: 0.130	- City National Tower, *Los Angeles:* 0.089	- One Canada Square, *London*: 0.079	- Deutsche Post Building, *Bonn*: 0.152
	- Equitable Building, *New York*: 0.088	- 500 5th Avenue, *New York*: 0.158 - 570 Lexington Ave, *New York*: 0.138	- One IBM Plaza, *Chicago*: 0.088 - Tour Fiat, *Paris*: 0.089	- UOB Plaza, *Singapore*: 0.112 - Cheung Kong Centre, *Hong Kong*: 0.084	- Hearst Tower, *New York*: 0.100 - Bank of America Tower, *New York*: 0.096
	Average: 0.107	*Average: 0.152*	*Average: 0.111*	*Average: 0.088*	*Average: 0.146*
Typical office lighting levels (lux)[49]	86–97	108–269	1076–1615	377–1076	377–484
Typical façade U-values (W/m^2K)	Information unavailable. Figures likely to be in 2.0–3.0 range.	- Empire State Building, *New York:* 2.6	- Lake Shore Drive Apartments, *Chicago*: 4.2	- Wells Fargo Plaza, *Houston*: 1.5	- Deutsche Post Building, *Bonn*: 1.1 - Bank of America Tower, *New York*: 0.9

			- Lever House, *New York*: **3.3**	- Cheung Kong Centre, *Hong Kong*: **0.9**	
Transparency within façade	- Fine Arts Building, *Chicago*: **40%**	- Chrysler Building, *New York*: **32%**	- Lake Shore Drive Apartments, *Chicago*: **72%**	- Wells Fargo Plaza, *Houston*: **82%**	- Commerzbank, *Frankfurt*: **54%**
	- Woolworth Building, *New York*: **21%**	- Empire State Building, *New York*: **23%**	- Lever House, *New York*: **53%**	- One Canada Square, *London*: **43%**	- Hearst Tower, New York: **63%**
	- Equitable Building, *New York*: **25%**	- 500 5th Ave, *New York*: **32%**	- City National Tower, *LosAngeles*: **53%**	- Cheung Kong Centre, *Hong Kong*: **52%**	- Bank of America Tower, *New York*: **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 façades often utilised where climatic conditions allow.