ENVIRONMENTAL SUSTAINABILITY IN THE DESIGN OF ICONIC HIGH-RISE BUILDINGS

TUĞBA AKA

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ABSTRACT

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Aka, Tuğba

Master's Program in Architecture

Advisor: Asst. Prof. Dr. Athanasios STASINOPOULOS

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Population growth causes urbanization and turns the city into a high density of clustered buildings with the worst environmental damage to the environment and human life. High-rise buildings have become an excellent solution to create fewer buildings but more density in the same place. Since the common environmental damages are caused by the consumption of embodied and operational energy of high-rise buildings, this study represents the ways to achieve energy-efficient high-rise buildings. In the pursuit of sustainable high-rise architecture, it is crucial to examine energy efficiency in high-rise buildings. Thus, the paper indicates some design features, which help to achieve environmentally sustainable high-rise buildings with minimum energy consumption as; built form and configuration, building orientation, double-skin façade design, green wall design, water management technologies, renewable energy resources, and material selection. The application of these design features was shaped by the function and climatic conditions of the high-rise buildings. The study includes five eco-iconic high-rise buildings which were selected from different climatic zones with different purposes, to represent how the environmental design strategies have been applied in their design. In-depth research has been done within the scope of environmentally sustainable high-rise buildings by questioning if it is possible to build environmentally sustainable high-rise buildings and how these design methods were applied. In this thesis, topics such as the history of high-rise buildings, their environmental effects, sustainable architecture, sustainability in high-rise buildings, and selected case studies were investigated by comprehensive literature research and comparative methods. Inferences were made by considering the environmental design perspective of iconic high-rise buildings. This thesis provides a new perspective on high-rise architecture and aims to be a guide in minimizing environmental damage and energy consumption in high-rise buildings.

Keywords: High-rise buildings, climatic and environmental design, energy efficiency, sustainable high-rise architecture, eco-iconic high-rise buildings.

ÖZET

İKONİK YÜKSEK BİNALARIN TASARIMINDA ÇEVRESEL SÜRDÜRÜLEBİLİRLİK

Aka, Tuğba

Mimarlık Yüksek Lisans Programı

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Ekim, 2022

Kentleşmeye neden olan nüfus artışı dünyamızı çevreye ve insan yaşamına en büyük zararı veren büyük gri bir blok haline getirir. Yüksek binalar aynı şehirde minimum taban alanıyla maksimum insanın bir arada yaşamasını sağlayarak bina yerine kullanılacak alanların yeşillendirilmesine olanak tanıyor. Bu çalışma, enerji verimi sağlayan yüksek binaların tasarlanmasına yardımcı olan faktörleri içermektedir çünkü yüksek katlı binalar inşaat sırasında ve sonrasında yüksek miktarda enerji tüketirler. Sürdürülebilir yüksek bina mimarisi arayışında, yüksek binalarda enerji verimliliğini incelemek çok önemlidir. Bu nedenle bu makale, minimum enerji tüketimi ile çevresel açıdan sürdürülebilir yüksek binalar elde etmeye yardımcı olan bazı tasarım özelliklerini içermektedir. Bu tasarım özellikleri yapılı form ve konfigürasyon, bina yönelimi, çift cidarlı cephe tasarımı, yeşil duvar tasarımı, su yönetimi teknolojileri, yenilenebilir enerji kaynakları ve malzeme seçimidir. Yüksek binaların işlevi ve bulundukları şehrin iklim koşulları bu özelliklerinin uygulanmasında önemli bir rol oynar. Bu çalışma farklı işlevlere ve iklim koşullarına sahip beş eko-ikonik yüksek binayı çevresel tasarım stratejilerinin nasıl uygulandığını anlamak için incelemiştir. Bu çalışmanın amacı, çevresel açıdan sürdürülebilir yüksek binalar inşa etmenin mümkün olup olmadığını anlamak ve bu tasarım yöntemlerinin nasıl uygulandığı incelemektir. Bu sebeple, çevresel açıdan sürdürülebilir yüksek binalar kapsamında derinlemesine araştırma yapılmıştır. Bu tezde yüksek yapıların tarihçesi, çevresel etkileri, sürdürülebilir mimari, yüksek yapılarda sürdürülebilirlik ve seçilmiş bina çalışmaları gibi konular kapsamlı literatür araştırması ve karşılaştırmalı yöntem kullanılarak incelenmiştir. İkonik yüksek binaların çevresel tasarım perspektifi dikkate alınarak çıkarımlar yapılmıştır. Bu tez, yüksek mimariye yeni bir bakış açısı kazandırılmış ve yüksek binalarda çevresel zararın ve enerji tüketiminin en aza indirilmesinde yol gösterici olmayı amaçlamıştır.

Anahtar Kelimeler: Yüksek binalar, iklimsel ve çevresel tasarım, enerji verimliliği, sürdürülebilir yüksek katlı mimari, eko-ikonik yüksek binalar.

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LIST OF ABBREVIATIONS

BREEAM: Building Research Establishment Environmental Assessment Methods

CTBUH: Council on Tall Buildings and Urban Habitat

DSF: Double-skin façade

GHG: Greenhouse gases

HRBs: High-rise buildings

LEED: Leadership in Energy and Environmental Design

NetZEB: Net-zero energy building

OE: Operational Energy

UNEP: United Nations Environment Program

CHAPTER 1 : INTRODUCTION

The term high-rise buildings (HRBs) are used in architecture to describe a structure having a considerable height beyond the common height of most other buildings. A similar term is ‘Skyscraper’ (S) which refers to a building of many stories on a relatively small footprint having commercial purposes mostly. Skyscrapers appeared with the development of structural technologies (mainly steel) and the development of elevators.

During the last 100 years, HRBs appear around the world in growing numbers as an efficient way to accommodate the fast-rising populations in contemporary cities. But the more people, the more Earth resources are consumed. Population growth causes global environmental issues such as air and ecological pollution, water scarcity, the greenhouse phenomenon primarily from CO2 emissions, extreme weather phenomena, and diminishing of natural resources which create an advancing environmental degradation.

Some researchers like Glaser (2009) and Yeang (1999), believe that vertical urbanism and eco-friendly buildings can solve and minimize environmental problems. These beliefs supported by Borck’s (2016, p.13) statement by Glaser which is:

“To save the planet build more skyscrapers”

This statement indicates high-rise buildings can minimize environmental damage The eco-skyscrapers are supposed to be one of the environmentally designed building types and promoted as potentially socially and economically successful solutions with minimum land usage.

On the other hand, Yeang, (1999) has a counter-view to Glaser, (2009) defining that, very high-rise buildings or skyscrapers are not ecological building types. Yeang and Richards’ (2007, p.20) thoughts about skyscrapers in environmental perspective is:

“Right at the outset, we should be clear that high-rises or skyscrapers are not an ecological building type. It is one of the most unecological building types. The tall building over and above all built typologies uses a third more energy and material resources to build, operate, and eventually.”

The paper suggests a solution to minimize the environmental problem related with population growth. In response to growing needs for space and new lifestyle trends, the popularity of HRBs is rising. To counteract their negative environmental side effects, they should be designed as ecologically friendly as possible. The sustainable tall building concept has started with the awareness of the accelerating depletion of natural resources (partially due to buildings) and the degradation of living environments. The negative side effects on environment started with environmental pollution – which caused by people, products manufacturing and car uses and inefficient building designs. Green or sustainable architectural design can alleviate the adverse effects of buildings.

1.1. Research Topic

This paper mainly focuses on tall buildings of different heights and functions from an environmental prism. Also, the paper surveys various design elements that might be implemented to introduce environmental sustainability in high-rise buildings. For that objective, this work reviews the evolution of tall buildings and also the environmental design strategies that can be applied according to their function, height, and location in chapter 5. These elements aim to mitigate the negative effects that HRBs might have on the environment and the health and comfort of the population. The level of sustainability provided by such methods is gauged by certification systems like Leadership in Energy and Environmental Design, Building Research Establishment Environmental Assessment Methods, etc., which are covered in chapter 3. In spite of such accreditations, the question remains: How HRBs can be sustainable?

1.2. Research Question

The research paper aims at answering the following questions. The first two are to understand if and how high-rise buildings can be a solution to the growing population without aggravating the environmental problems. The third one is the main question about ways to minimize the negative environmental effects of high-rise buildings if possible.

1 - What are the advantages and disadvantages of constructing high-rise buildings from an environmental perspective?

2 - What are the principles of environmentally sustainable design that can be applied to heigh-rise structures?

3 - Is it possible to build environmentally sustainable high-rise buildings? If not why? How can we mitigate their ecological footprint? Are there such examples? If there are, what can we learn from them?

These questions are related to all types of high-rise buildings; however, this paper focuses on a special category of them: Those that incorporate environmentally sustainable design features, and also have an advanced architectural quality that makes them exemplary -or “iconic”- paradigms among the building professionals and the public.

1.3. Aim of the Study

The primary aim of this thesis is to emphasize the environmental sustainability approach in the design of iconic high-rise buildings.

In line with the information obtained during the research, the thesis aims to review high-rise buildings and understand the environmental drawbacks of high-rise construction. This work is not about promoting or rejecting HR but surveying all sides, to balance good and bad aspects. High-rise buildings become a common architectural type in cities. However, the negative effects of high-rise buildings related to the environment were not studied in the design phases. These high-rise buildings should include strategies for sustainable high-rise buildings. This thesis has the aim of shedding light on the design approaches of an environmentally sustainable high-rise building and discussing the environmental design strategies and applications with five eco-iconic high-rise buildings.

1.4. Methodology

This study aims to review high-rise buildings and explore "environmental sustainability" features that can be associated with high-rise architecture. Also, the paper exemplifies such architectural approaches through selected HRBs in different cities with various sustainable features. That is achieved through literature reviews and comparative methods.

The comprehensive literature survey, involves material from scientific publications from online collections like Science Direct and ResearchGate, conference proceedings, the Council of Tall Building and Urban Habitat database, academic dissertations, architectural and ecological books, and other publications on the theme of environmental design and high-rise buildings. Of major importance are the appraisal criteria of sustainable certifications like; Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Methods (BREAM).

The literature reviews will help to understand is the relation between high-rise buildings and sustainability, followed by an analysis of five exemplary cases selected according to certain criteria (Chapter 5). The comparative methods of case studies will help to answer the main research question on *the possibility of creating environmentally sustainable high-rise buildings.'*

1.5. Thesis Structure

This thesis defines high-rise buildings (HRBs) as tall buildings that have more than 100m in height. The paper's subject is to survey methods for minimizing the environmental drawbacks of the HRBs and at the same time, for achieving more efficient livable places by using sustainability strategies in their design. Overall, the research aims to find an answer to the key question 'Is it possible to build an eco-friendly/environmentally sustainable HRBs?'.

First, thesis covers an overview of sustainable principles and techniques applied on buildings After that, the case study method helped to define, collect, and assess information about "eco-iconic" high-rise buildings. The term consists of two architectural terms - eco architecture and iconic architecture. The term "eco architecture" is related to minimizing the environmental footprints of buildings during their construction and total life cycle. It is used as synonym of sustainable architecture. On the other hand, iconic architecture focuses on buildings by famous professional architects and have a special symbolic importance. Generally, the iconic buildings vary in their design, size, visual appeal, architectural style etc. This study focuses on iconic building which are ecologically designed.

1.6. Literature Review

The increasing population and economic development increase the urban densities and intensify the demand for living and working space. As a result of this, high-rise buildings and their construction became a common architectural type in the cities. At the same time, sustainability is rapidly becoming a guiding concept in architectural design. This work reviews the connection of high-rise buildings with green architectural design.

- ***History of High-rise Buildings***

Gerard Peet explains that high-rise buildings entered our life in Chicago in the late 1880s with the ‘world’s first skyscraper’ Home Insurance Building(44-meter height with 10 stories, demolished 1931) which is accepted as the first tall building by many scholars (Peet, 2011).

Montgomery Schuyler who was a journalist and architecture critic, in his book ‘The Evolution of the Skyscraper’ of in 1909 states that many buildings might be classified as the first tall building, such as The Equitable Life Assurance Building in New York (43-meter height and built in 1870 as an office building), The Tribune Building (70-meter height with 10 stories. Demolished 1966), and The Western Union Building(79-meter height with 10 stories, demolished in 1914) in New York (both built-in 1875), and he finally accepts Home Insurance Building as a first tall building (Peet, 2011).

Tatjana Anholts also agreed with Peet and other scholars. The first tall office building was called a skyscraper by contemporary authors, which had ten to twenty stories. However, from the literature review, it is obvious that the definition of tall buildings or high-rise buildings is open to discussion.

Dan Cortese defines that there is no clear definition of the term tall building. The definition of a tall building is shaped by the surrounding environment and the building. In daily life, the term tall building is used for a building with noticeable height (Cortese, 2018).

In the reviewed literature, there are many terms used to describe high-rise buildings as tall buildings, super-tall, mega-tall buildings, and skyscrapers. According to Council of Tall Building and Urban Habitat (CTBUH), tall buildings include sub-groups as, mega-tall and super tall. A building with a maximum 300-meter height is called tall, more than 300meter height is called super tall while a minimum of 600 meters and more is called a mega-tall building. Among them, skyscrapers are tower-like HRBs that are more than 300 meters tall and according to Dan Cortese (2018), skyscrapers have habitable floor space of more than 50% of their height. Cortese describes skyscrapers as a structure that are self-supporting without tension cables or supports to stand and includes habitable spaces around 50% of the height. Thus, this paper mainly uses the broad term "high-rise buildings" to prevent the possible misunderstanding or complications related to the terminology based on height.

- ***Advantages & Disadvantages of High-rise Building***

High-rise construction is a response to population growth having advantages and disadvantages (mostly on environment) as defined by some scholars. Pooya Lotfabadi states that HRBs have advantages like; Repetitive floor plans providing material savings, small land uses providing more habitable spaces, and the height of the structure provides frequently a landmark for people to wayfinding (Lotfabadi, 2014; Saroglu et al., 2017).

Moreover, Anthony Wood also agreed with them and added that multi-functional HRBs provides less transportation needs. However, Wood also indicates, HRBs come up with environmental problems; The construction of HRBs consume more energy as well as its own energy needs like air conditioning, and water usage. HRBs are related to the Urban Heat Island effects, and wind turbulences related to its height (Wood, 2013). Thus, as demonstrated in chapter 2.4 the drawbacks of HRBs undermine the advantages which led to the need of thinking how to minimize their environmental drawbacks.

- ***Sustainable Architecture***

Sustainability appeared as a catchphrase after the Brundtland Report "Our Common Future", known as Brundtland Report by the United Nations World Commission on Environment and Development in 1987. This report describes three aspects of sustainability as being environmental, social, and economical. Around the 20th century people are more interested in environment-related problems and aware of global challenges brought by energy and resources issues. Thus, people are seeking energy efficiency, good air quality, occupants' health, and greenery in the large-scale building schemes, requirements that led to some rating systems of environmental performance by different countries like LEED in the US, BREEAM in the UK, Green Star in Australia, DGNB in German, and others. These rating systems have different criteria but their common purpose is to rate the operational and embodied energy for a building including high-rise buildings too (Gui and Gou, 2020).

Yeang and Woo define that, sustainable design, also known as *eco-design/ green design/ or ecological de*sign of the human-built environment, managed nonrenewable sources and the ecosystem's progress through the eco-mimicry.[1] It mainly focuses on the physical and mechanical integration of buildings and infrastructures with the properties of ecosystems and site processes, as well as creating biological assimilation between the built and the natural environment. It also prevents the reduction of resources such as energy, water, raw materials, and environmental damage to facilities and their infrastructure (Yeang and Woo, 2010). In other words, sustainable design is a design that minimizes the destructive impacts on the environment by integrating any physical, systematical, or temporal forms with natural environments and their living process. Building construction substantially impacts inhabitants' natural environment and social life, occurring not only during the construction and operation of buildings but also after their disposal.

Giving priority to sustainable architecture helps to minimize natural and social harm and create a sustainable living environment. The aim of designing eco-friendly buildings is to minimize the environmental damage related to the construction and operation of the building and to create a positive and convenient contribution to the social environment where the buildings are placed and addressed (Sassi, 2006).

According to Sant Chansomsak and Brenda Vale, sustainable architecture can be classified into three types: architecture *about* sustainability, architecture *for* sustainability, and architecture *as* sustainability which are seen as separate terms but, in practice, are merged to meet the objective of sustainability.

- ***Architecture about Sustainability*** embodies both buildings and the built environment, including sustainable components as building materials/systems or sustainable design tools as *(Leadership in Energy and Environmental Design (LEED) or BRE Environmental Assessment Method (BREEAM), environmental impact assessment (EIA), life cycle assessment (LCA)* to help build a link between the built environment and environmental effects embedded in architectural programming.

[1] practice of designing socially and environmentally responsible technologies based upon the characteristics of animals, plants and ecosystems of the particular region.

- ***Architecture for Sustainability*** focuses on sustainable techniques, and it gives importance to the creation and architectural improvements to have a healthy environment. It defines *sustainability* as an objective project and utilizes techniques for satisfying essential design criteria.
- ***Architecture as Sustainability*** is outlined as a transformative architecture process towards sustainability. Sustainable architecture is a subsystem of whole sustainable practices, and it aims to design buildings as more closed and less open systems. Also, sustainable architecture focuses to decrease the environmental effects and raises the living standards for people (Chansomsak and Vale, 2008).

\- ***Sustainable High-rise Buildings***

Ken Yeang has been working on minimizing the environmental damages caused by high-rise building construction, even though he believes that the HRBs are not an ecological building regardless of the sustainability rating system. Thus, Ken Yeang suggested some design modes minimizing buildings' energy and improve the indoor comfort as passive mode, mixed mode, full mode, productive mode, and composite mode in his book "The Green Skyscraper".

- The **passive** mode includes developed comfort over external conditions without using electromechanical systems. The building orientation and configuration are related to the local climate and façade design (this will be covered in chapter 4.2). Passive mode design provides energy efficiency even if there were no electricity inside the building that's why it is more important.
- **Mixed** mode strategies include some electromechanical system as ceiling fans, and evaporative cooling, while
- the **full** mode strategy includes all electromechanical systems to increase interior comfort. On the other hand,
- the **productive** mode consists of a building system that generates its energy like solar by photovoltaic systems or solar panels, etc., and wind energy by wind tribunes (Yeang and Powell, 2007; Yeang, 1999).
- the **composite** mode includes all the modes and systems that are changeable over the seasons of the year as listed above.

Since climatic conditions are significant for environmentally sustainable high-rise buildings, Oldfield came up with 4 main climatic regions, as Olgyay proposed in his pioneering book "Design with Climate." He worked on design strategies for how high-rise buildings can minimize environmental damage in different climatic conditions such as cold & temperate, tropical and hot & arid zones and, he supported these strategies with some case studies (Oldfield, 2019). In all these regards, sustainability and high-rise buildings can be integrated but, the sustainability of buildings must not be a part of greenwashing.

CHAPTER 2 : HIGH-RISE BUILDINGS

Humans have been eager to build higher constructions over centuries, from the mythical Tower of Babel to the iconic Burj Khalifa (figure 1). Historically tall structures emphasize the power of religious and political rulers. For example, the Giza pyramids (figure 2) were built approximately in the fourth dynasty in Northern Egypt, where the tomb of Pharaoh Khufu was located. However, these historical tall constructions are smaller than the contemporary tall buildings.

Figure 1. Left- Burj Khalifa 828m (Source: SkyscraperCenter, 2021)

Figure 2. Right- Great Pyramids; A-Menkaure 65.5m, B-Pharaohs Khufu 146.5m, C-Khafre 143.5m, D-Queens Pyramids (Source: National Geographic, 2021)

2.1. High-rise buildings Definition

The terms ‘tall’, ‘high-rise’, or ‘skyscrapers’ are generally used to describe structures based on their height. However, the terms tall and skyscrapers have a different meaning. Tall buildings were considered to be 10 to 20 stories structures in towns or cities with a low population in the 1880s when the city was surrounded by structures that had lower heights with a maximum of 20 stories buildings. It could be noticed that the definition of tall changes over time depending on the overall building height in the city. For example, a building considered as tall in one city might not be considered as such in another. For example, if the city typically has 10-storey structures, then 20-storey buildings can be called tall buildings. However, if the city typically has 80 or 100-story buildings, the ten or 20-storey buildings cannot be classified as tall structures.

In daily life, we use the term tall to define a structure with noticeable height compared to its neighbors. However, there is no exact definition of tall buildings. There are many opposing views about the proper name of buildings according to their height (Tohumcu and Zeytun Çakmaklı, 2017).

On the other hand, Cortese proposes that the building could be called a skyscraper if its structure has at least 150-meter height. He believes the habitable floor spaces is a key factor in defining skyscrapers as much as the height criteria. He states the building should support itself alone and should not have tension cables or be surrounded by supportive structures called 'skyscrapers.' Moreover, it must have living spaces that reach a minimum of 50% of the total structure height. For example, the CN Tower in Toronto in Canada (figure 3) has a 553-meter height, but the habitable floor spaces are lower than 50% of its height, so it cannot be called a skyscraper. On the other hand, the Petronas Towers in Kuala Lumpur in Malaysia (figure 4), which has a 451-meter height with more than 50% habitable spaces, can be classified as a skyscraper (Cortese, 2018).

Figure 3. CN Tower in Toronto (Source: Go!Toronto, 2022)

Figure 4. Petronas Towers in Malaysia. (Source: Flickr, 2010)

According to Council on Tall Buildings and Urban Habitat (CTBUH), the definition of tall buildings and skyscrapers is no longer adequate to define the latest version of high-rise buildings. CTBUH identifies that we are in an era of 'super-tall' and 'mega-tall.' to describe the brand-new structures. The buildings with a maximum of 300-meter heights are called tall buildings, over 300-meter are called super-tall, and 600-meter or taller structures are defined as mega-tall buildings by the height criteria of CTBUH (figure 5). The figure includes the 30th Mary Axe with 180-meter height, Bank of China with 331-meter height, and Burj Khalifa with 828-meter height can be defined respectively as tall, super-tall, and mega-tall buildings. (Cortese, 2018). This thesis will cover high-rise buildings with different heights and functions discussing the effects of height and function in the design of environmentally sustainable HRBs. A brief history of the gradual development of the HRBs follows next.

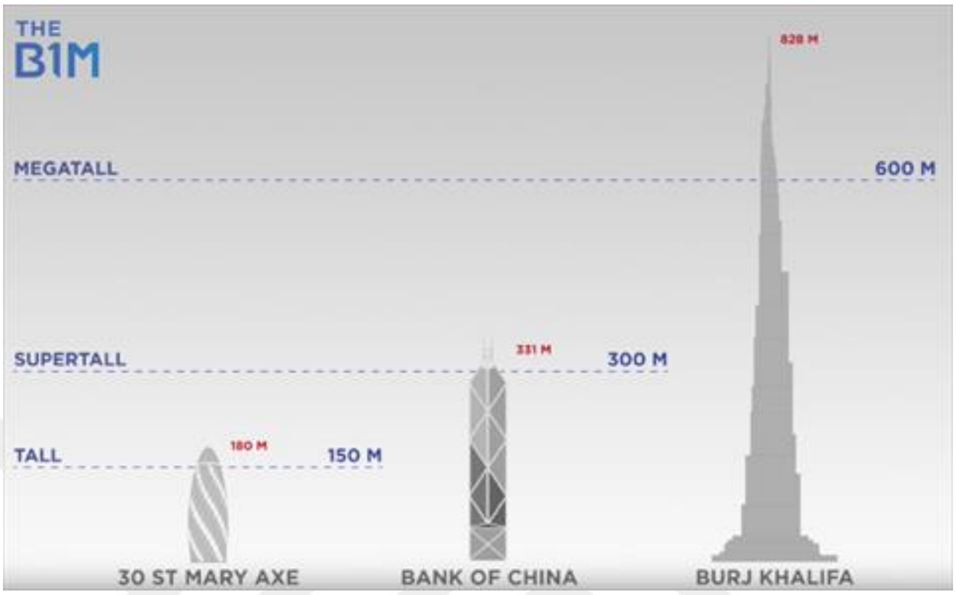


Figure 5. Classification of Building based on height - (Source: Cortese, 2018)

2.2. Early High-rise Buildings

The first high-rise buildings in Chicago were called Chicago School or Commercial Style–a movement or tendency–led by architects; Henry Hobson Richardson, Daniel Burnham, John Wellborn Root, William Le Baron Jenney, Louis H. Sullivan-the father of skyscrapers, Frank Lloyd Wright and Holabird and Roche firm. The first high-rises were built by using heavy masonry. However, the constructions became lighter with economic and well-engineered steel frames covered with stone or terra-cotta and glass with the help of technological developments. The Home Insurance Building (figure 6), is considered as the first skyscraper (first high-rise commercial building) of the industrial era in Chicago, having been built in 1884 – after the great fire of Chicago in 1871 by William Le Baron Jenney. It had 12 stories at that time and was called a skyscraper (Anholts, 2012). The great fire of 1871 caused 300 deaths, 18.000 buildings to be destroyed, 2.000 acres and 1/3 of the city to be destroyed, and 100.000 people to become homeless. The city had been rebuilt, and its people wanted to make Chicago better than before. The construction of new buildings was similar as before. They had 4 or 5 stories, but architects and engineers had to build higher structures because of the higher land prices. They managed to do that with the help of Elisha Otis, who first developed new techniques of fireproof steel-iron construction and safety elevators in the Haughwout Building in New York in 1857. However, the first elevator came to Chicago 30 years later, and more than 3.000 elevators in Chicago's high-rise buildings were used till 1895 (Anholts, 2012).

Figure 6. Home Insurance Building, Chicago 1885 (demolished at 1931) (Source: Bellis, 2020)

The development of tall buildings started with Englishman Henry Bessemer, who invented mass-produced steel at low prices. This innovation assisted builders in building taller structures, and it can be seen nowadays that the use of mass-produced steel is still exists in the construction and developed with today's modern technology. George A. Fuller developed the idea of using mass-produced steel while designing the Tacoma Buildings (figure 7) in 1889. Fuller realized that using Bessemer steel elements inside the buildings as a load-bearing frame can carry more weight, making it possible to build higher constructions. This innovation was used later to have steel cages in skyscrapers' designs. Besides this innovation, taller buildings became possible when the first elevator appeared (Bellis, 2020). The Monadnock Building (figure 8) in 1891, with 17 stories, was the tallest masonry building without a steel frame. The Reliance Building (figure 9) in 1894 by Daniel Burnham and John Wellborn Root could be given as an example of the Chicago School period. The building was an important example because it was built entirely of steel for the first time in that period, which created an opportunity to include more oversized windows on the exterior (Anholts, 2012).

Figure 7. Left – Tacoma Building. (Source: Chicagology, 2022)

Figure 8. Middle – Monadnock Building. (Source: Anholts, 2012)

Figure 9. Right – Reliance Building. (Source: Anholts, 2012)

2.3. *Late High-rise Buildings*

The term high-rise buildings gave its place to the term skyscrapers which keeps changing specifications as time passes. Builders started exploiting technological developments at the end of the 19th and the beginning of the 20th century. Although today's architectural standards accept over 300 meters to 600 meters as skyscrapers, the first skyscraper had 55 meters, which was an essential factor in urban development and construction in the 1880s (Bellis, 2020). As time passing, the skyscrapers began to symbolize the powerful images of the city. Carol Willis, an architectural historian, stated that 'form follows finance' because many developers of high-rise office buildings in the early 1900s tried to figure out how to create maximum habitable floor spaces in dense city sites. Building a skyscraper instead of lower buildings has advantages that these developers wanted. The new architectural and technological developments help us to build longer and taller buildings. For example, the Kudrovo apartment complex in Russia and The Line megacity (at proposal stage now) planned for the deserts of Saudi Arabia (figure 10 and 11). These structure types are also called high-rise; however, this thesis covers tower-like buildings with low footprint-to-height ratio.

Figure 10. The Line, 500 meters tall and 200 meters wide planned for 170-km stretch across the desert of Saudi Arabia. Representation of high-rise buildings with extreme dimensions, especially length. (Source: Japantimes, 2022)

Figure 11. Apartment complex in Kudrovo, Russia in 2015. It includes 3,708 apartments, 35 entrance and 25 floors. (Source: Russia Beyond, 2021)

According to CTBUH, Hong Kong (1.104 km^2 area) is the 'tallest' city in the world meaning it has the largest number of HRBs, including 2.963 buildings higher than 150m, 964 buildings above 200m and 102 buildings above than 300m, with 78% of the tall buildings used for residential purposes. New York City (469 km^2) follows the list of 'tall' cities at second place with 857 buildings over 150m, 232 buildings over 200m, 29 buildings over 300m. 50% of those buildings are used for commercial purposes (see table below) (CTBUH, 2022). In this study, five case studies were chosen from Asia and Europe based on their height and function to compare their design approach as supposedly "environmentally sustainable buildings". Among the many HRBs, the selected iconic examples stand out since;

- they have certificates about their environmental features,
- their advance architectural qualities can inspire many architects (see chapter 5)

Table 1. Top 15 Countries of High-rise Buildings. It includes cities where many high-rise buildings were constructed, listed by the height (Source: SkyscraperCenter, 2022)

RANK	COUNTRY	Number of Buildings			TALLEST CITY
		150m+	200m+	300m+	
1	China	2,963	964	102	Hong Kong
2	United States	857	232	29	New York City
3	United Arab Emirates	314	136	32	Dubai
4	South Korea	276	79	7	Seoul
5	Japan	271	47	1	Tokyo
6	Malaysia	266	56	5	Kuala Lumpur
7	Australia	140	49	2	Melbourne
8	Indonesia	129	48	0	Jakarta
9	Canada	124	33	0	Toronto
10	Thailand	124	26	3	Bangkok
11	Philippines	121	38	0	Makati
12	India	101	24	0	Mumbai
13	Singapore	96	34	0	Singapore
14	Turkey	67	11	0	Istanbul
15	Panama	66	24	0	Panama City

2.4. *Advantages and Disadvantages of High-rise Buildings*

High-rise buildings were seen as a symbol of American corporate power when the International Style was spread in the early 1950s. Internationalism formulated the concept of skyscrapers with clean geometric qualities of the International Style. Besides the power symbolism, tall structures occupy less land but accommodate more habitats.Since the 2000s, more people live in towns or cities rather than rural areas, and when the 2050s comes, the number of people in cities will increase further (Anholts, 2012). Thus, it seems that HRBs would offer a solution to the increasing urban population without expanding the urban areas.

In our era, structures are becoming safer and more energy-efficient with the use of advanced technology. One of the effects of increasing high-rise dwellings is the change in occupants' behavior. People have started to prefer living in tall buildings designed well to reflect better living conditions. The amount of people who live in high-rise buildings in Hong Kong, Sydney and Singapore are respectively 95%, 27.5% and 84% (Abd Wahab, Ibrahim, Al-Saqer, Fahad, 2016). Also, the mixed-use HRBs can decrease the daily travel distance, and GHG emissions that might occur from the transportation. However, high-rise buildings have significant influence on environmental conditions as explained below.

2.5. The Environmental Effects of High-rise Buildings

The growing population causes the proliferation of HRBs in big cities. They are mostly isolated towers and they do not blend well with the rest of the city because of their form and height. HRBs have a reduced footprint thus helping to reduce urban sprawl preplacing many low-rise buildings, since they provide more indoor living space for less land. Moreover, HRBs have an environmental advantage, such as better access to sunlight and wind, assisting natural ventilation and the use of special elements like solar panels and wind turbines in their design. In assertion to such benefits, HRBs might have detrimental effects on the microclimate around them because of the wind channeling and turbulence that might make people uncomfortable on the ground level (Al-Kodmany and Ali, 2013; Ibrahim, 2007).

The option of being multi-functional can reduce travel time and turns the city into a denser one, which helps to reduce transportation needs (Wood, 2013). Toranomon Hills in Tokyo (figure 12), Japan is an example of how mixed-use tall buildings help to decrease transportation. It was designed in 2014 by Nihon Sekkei and it includes offices, residential and hotel functions. Generalova et al., (2018), states that the building has an active use of underground which is linked with a highway. Approximately 38.000 vehicles use the Tsukiji-Toranomon highway. Thus, the underground tunnel mitigates the traffic density. The underground spaces of the Toranomon Hills are actively used to provide a connection between the transportation system of the city and the buildings functions. Another example of mixed-use structures that help to decrease transportation is the Shard in London, UK built in 2013 (figure 13). The structure is located near the National Rail Service Stop. People can use trains or the underground as transportation means to access The Shard and its surroundings, thus promoting less car usage. The tower has residential, office and hotel quarters and is located near a major transportation hub in the city (Generalova et al., 2018).

Oldfield states that, multi-functional buildings can provide energy sharing and create a diminishing peak load opportunity. Mixed-use buildings can utilize the heat created by the high internal loads of the building which are *people, machinery and lighting*, similarly in office high-rise buildings. This heat can be harnessed and used to supply hot water or space heating for apartments which reduces the energy requirements (Oldfield, 2019).

Figure 12. Toranomon Hills in Tokyo, Japan. (Source: Toranomon Hills, 2022)

Figure 13. The Shard in London designed by Renzo Piano in 2013. (Source: Max Frank Building Common Ground, 2022)

Any kind of building might be harmful if it is not designed to incorporate energy-efficient solutions in heating, cooling, and ventilation systems. Something that applies even more to tall buildings (Al-Kodmany and Ali, 2013). For example, Antony Wood (2013) agreed with Oldfield that it is not only commercial high-rise buildings that contain more embodied energy but any type of HRBs. Further than that, the operation, maintenance, and cleaning of the HRBs create more energy consumption which causes damage to the environment. For example, the rows of high-rise buildings in narrow streets lead to poor air quality and heat trap which creates and Urban Heat Island (UHI) effects (Oldfield, 2019). These natural ventilation problems in the city blocks occur because of the 'wall effect' as the tall buildings impede sea breezes.

The environmental effects of high-rise buildings include topics like the *wind effects and solar access, discussed next with a summary of high-rise buildings from an environmental perspective.*

2.5.1. Wind effects of High-rise Buildings

High-rise buildings have some environmental impacts *as mentioned in chapter 2.4,* like contribution to UHI phenomenon, air pollution etc. This section focuses on the impact of high-rise buildings on urban wind.

The length of the wind shadow is increased by the height of a building, decreasing the air flow in the leeward direction. Extending the building depth is not effective as much as the increase of the height (figure 14). Also, the local wind speed around the high-rise buildings is higher in winter and summer. High density urban areas and similar building height create better ventilation than the lower density areas and same building heights (Yin, 2015). A horizontal urban mass with gradient height, protect the street level from the solar radiation and provide air flow and nocturnal ventilation. High-rise buildings prevent wind and reflect solar radiation on low-rise buildings. Moreover, they absorb the reflected solar radiation from the low-rise buildings (they also receive reflected radiation reflected on the ground even without any buildings around them) and convert it into heat (figure 15).

2.5.2. Solar access of High-rise Buildings

When most urban buildings are approximately the same height, the long-wave radiation emission from the roof resembles an open field and the intensity of radiant loss from the buildings is maximized. On the other hand, when there is different height in a group of buildings, the facades of a higher structure absorb reflected and emitted radiation and block part of the sky This reduces the amount of solar reflection and long wave emission from the roofs of the lower buildings. These lead to decreasing overall radiant heat through the urban canopy (figure 15) (Givoni, 1998).

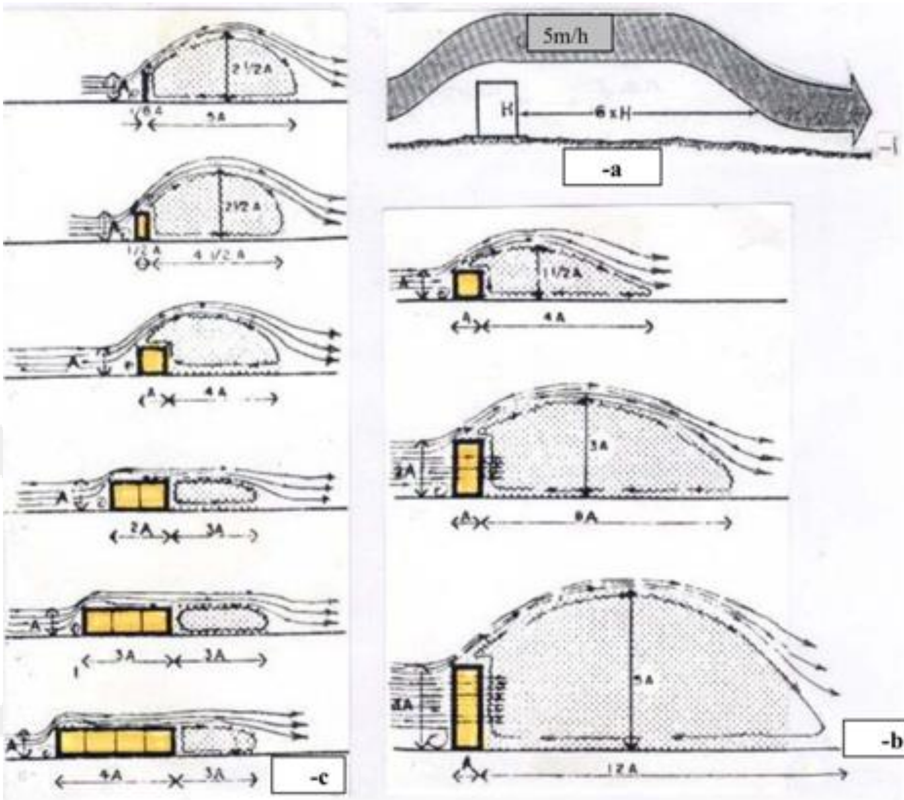


Figure 14. The ways for increasing wind shadow by a: rising the air velocity, b: increasing the building height, c: maximizing the building depth till four time of the height. (Source: Yin, 2012).

Figure 15. The wind and radiation effect of high-rise buildings on low-rise buildings. HRBs prevents wind and reflect solar radiation. (Source: Yin, 2012).

2.5.3. A summary of HRBs from an environmental perspective.

Yeang (1999) and other scholars as Wood (2013) and Saroglu et al. (2017), describe the drawbacks of HRBs as consuming significantly high amounts of energy and materials because of their height , thus harming the natural environment and becoming inherently non-green building types (Yeang, 1999). According to Saroglu et al. (2017), the higher buildings dispose of a significant level of Operational Energy (OE) than low-rise buildings because of their more extensive volume.

Table 2 summarizes the positive and negative effects of high-rise buildings which are becoming a common building type. However, Yeang, (1999) believes HRBs can also be green to some extent, which is the main topic of this work. The design and construction of tall buildings with the aim of environmental sustainability might be achieved by basic design principles , which will be discussed in chapter 4.

The environmental effects of high-rise buildings not only are related with the urban wind and radiation but also with the external spaces in terms of materials used. Buildings interact with environmental conditions through their envelope and the thermal qualities of the façade materials (Saroglu et al., 2017). Moreover, environment is related with the climatic conditions of the surrounding which were discussed in following with design criteria for high-rise buildings in three climatic zones.

Table 2. Positive and Negative effects of HRBs

Positive Effects	**Negative Effects**
The reduction of transportation by having mixed-used and less travel distance. [For mixed-use high-rise buildings]	Big amount of embodied energy is used to build higher construction Also, consume more energy to operate elevators and maintain and clean the buildings and provide circulation through the water pumps.
Material efficiency by having standard floor slab, in some cases prefabrication materials, recycled materials etc. [For low-rises too]	Having a tremendous amount of occupant lead to the need for developed infrastructure and urban services.
Stack effect, which is the air movement into buildings through the outside of the buildings, was seen with the help of having a giant atrium that provides natural ventilation based on the climatic conditions. [For HR and S]	Creating a wind downdraught, blocking the sun in the surrounding. Urban Heat Island intensification source.
Glazed facades and floor plans bring internal daylight into the building. It increases the productivity of people, especially on office floors. [For office/mixed-use HR, S and low-rises too]	Peel structure and façade designs
Thermal features provide natural ventilation, heating, and cooling systems inside the building as well as the low-rise buildings might have the same advantages.	The possible power cut creates problems with vertical circulation and safety. Having an unsafe environment during the construction.
Having extra heights increase the visibility from a distance that helps people find their way in the neighborhood by acting as a landmark. [For HR and S]	Lack of shared spaces for people to socialize. [Depends on function]

2.6. Climate Design of High-rise Buildings

Tall buildings directly affect the terrain's microclimate and the metropolitan areas' environmental conditions as covered in chapter 2.6. Many architects aim at linking the urban surroundings with the HRBs and to blend them with the environment. For this, designers resort to the design strategies for ' Sustainability.' Regardless of the intensions, the construction of high-rise buildings consumes many resources and energy and creates considerable waste (Anholts, 2012).

According to Oldfield (2019), the climate plays a significant role in designing tall buildings and their impacts on the existing environment. For this reason, Oldfield worked on some design approaches for tall buildings in different climatic zones. These are; cold and temperate, tropical, and hot climates. According to the Köppen climate classification there are five main climate groups *which are; tropical, arid, temperate, continental and polar* (figure 16) divided based on seasonal precipitation and temperature patterns (Peel, Finlayson and McMahon, 2007). This paper focuses on design strategies for different climatic zones as, temperate (includes also cold zones), tropical, and arid.

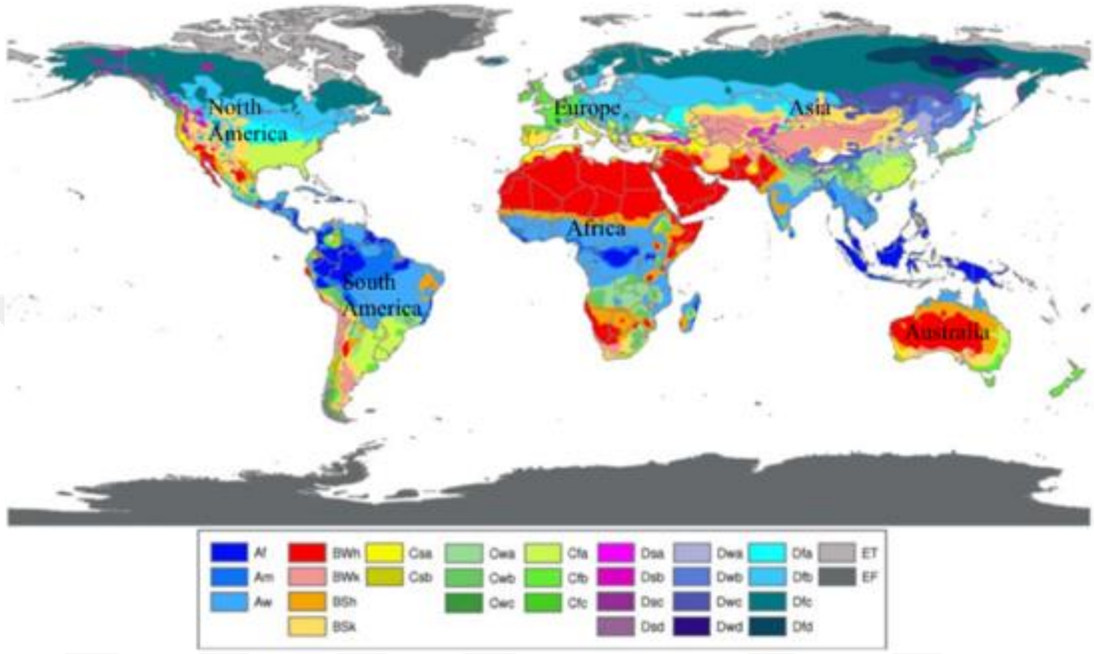


Figure 16. Map of Climates: A- Tropical, B- Arid, C- Temperate, D- Continental, E- Polar (Source: Peel, Finlayson and McMahon, 2007)

- ***Cold and Temperate Zones***

These two zones as; cold *–where the average temperature in winter is below 0°C, summer moths ranging cold to hot such as Beijing, Chicago and Seoul*; temperate *– is milder with cold and cool in winters, warm and hot in summers as New York, Rome and Sydney,* are similar in many aspects (Peel, Finlayson and McMahon, 2007). According to Peel et al the Köppen climate classification classified these zones under the continental group. In both cold and temperate zones, it is required to minimize heat loss in winter and to control heat gain (the sun is an important contributor for heat gain) in summer. High-rise and low-rise buildings in these climate zones should be adaptable for seasonal changes of climatic external conditions in order to provide indoor thermal comfort without significant amount of energy consumption. Convenient functions for these climatic zones are residential buildings with passive solar gains. On the other hand, an office building requires less solar gains because of the high amount of internal heat gains by occupants, mechanical and electrical devices and artificial lighting while the energy need in the night is not much as in the day.

Oldfield (2019), summarize the recommended design features for **cold and temperate** climate zones as;

- Sunshades on the façades directly facing the sun. These sunshades should be aimed to limit direct solar radiation in summer whereas it provides heat in winter by allowing low-angle sun to pass inside the building *(see case 3 – 30st Mary Axe)*.
- Inclined facade design provides free heating in winter by admitting solar rays inside the building, and shading blocking solar gain in summer time (figure 17). The figure represents that inclined façade reduces the heat inside the buildings in summer so the use of HVAC for cooling also decreases. Also, the angled concrete structure and glass facades provides solar path and get sunlight inside the building.
- Use of geothermal heating systems brings free heat from underground *(see case 1 – One Central Park and case 5 – Shanghai Tower).*
- Optimize building layout for solar orientation. Having office floor plan in temperate northern hemisphere are exposed to less solar gain. Thus, if they are facing north, they can benefit from reduced cooling loads. In cold zones, solar radiation might reduce the heating demands in the office buildings in winter.
- Residential and office towers decrease the heat loss in winter by their compact form and a low ratio of exposed surface area to volume of each floor.
- Building form and layout design is important to reduce over-shading of public areas and minimize the downwind currents that can cause pedestrian disturbance.
- Optimize openings and location. Larger openings on the South provides passive solar gain.
- Double Skin Facades, and the use of atria provides cross ventilation for residential, office and public buildings types. Especially office buildings, the blinds on the external façades provides a natural ventilation by taking air inside the building, reducing the energy needs for air conditioning *(see case 3- 30st Mary Axe and case 4- Commerzbank Tower).*
- Minimizing thermal bridges e.g., by avoiding balconies on the façade.

Figure 17. Left; Solstice on the Park designed by Jeanne Gang in Chicago in 2018. Right; inclined façade section located on the South façade. (Source: Oldfield, 2019)

- ***Tropical Zones***

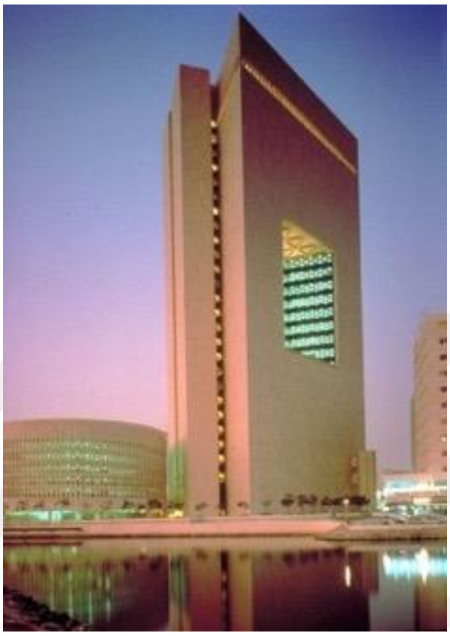
Peel, Finlayson and McMahon, (2007) define tropical climates as the zones where the average temperature is above or equal to 18°C in every month and having high temperatures during the year as *Mumbai, Singapore and Miami.* These zones include high humidity, high sun movements because of their location around the equator. Oldfield defines these cities as cities of HRBs and suggests that, the main design strategies for tropical HRBs is achieving minimum heat gain and maximum free cooling by natural ventilation. Richard Hassell and Mun Summ Wong suggest that the aim to achieve thermal comfort in tropical zones by the increase of wind speeds, and by casting large shadows in open spaces of tall buildings are only appliable for tropical climates. The sun path has an important role for tropical high-rise building designs as well as in other climates. The common feature of tropical zones is the high amount of solar radiation coming from the east and west (Wong and Hassell, 2009). The building height and verticality brings advantages as the increased wind speed and the reduced air pollution –provides natural ventilation for cooling– in hot and humid cities like Bangkok where the average temperature is above 26°C and maximum temperature reaches 35°C.

Oldfield (2019), summarize the design strategies for **tropical** high-rise buildings as below;

- Permeable building forms which increase cross ventilation and help thermal comfort and humidity. The orientation of building should be done according to prevailing breezes
- Place building shapes to have minimum exposure of east-west facades (to reduce solar gain) with service cores, atriums or shading devices on the east and west side of the building.
- Void funnels and shaded areas provide cross ventilation and access to light and air for the core in the center. Also, double-loaded corridors on either side of the building increases the cross ventilation.
- Use of maximized shading elements reduces unwanted solar heat gain and provides daylight inside the building.
- Lush vertical greenery and vegetation provide diminishing the Urban Heat Island (UHI). It creates shade, and improved thermal comfort reducing energy demand for cooling *(see case 1- One Central Park and case 2- Bosco Verticale).*
- Placing circulations as corridors, elevators and stairs in semi-open areas inside the buildings like the spaces which are not uses during the day of such spaces by occupants, reduces air-conditioned floor area around 20%. Thus, the energy demand would be decreased.

- ***Arid Zones and Warm Deserts***

According to Peel et al the Köppen climate classification “hot desert climate” is classified under the arid group. Hot/warm desert zones are the zones where the average annual temperature is equal or above the 18°C.These climates are generally are dry and hot in summer with temperatures reaching 45°C to 50°C as *Las Vegas, Dubai and Jeddah* which is home to high number of high-rise buildings. According to SkyscraperCenter (2017), the number of high-rise buildings is increased around 25% in the Middle East by the ned of the 2017 (Oldfield, 2019). Before the widespread use of transparent glass façade on high-rise buildings, the vernacular architecture included thick walls with small openings and shaded areas to protect internal spaces from intensive solar radiation. The reduction of window-to-wall ratio (WWR), using thermal mass as a solar buffer and façade insulations is important to improve tall building energy performance in hot zones. However, minimizing glass on the façade would not the only way to improve energy performance. For example, National Commercial Bank in Jeddah includes v shaped floor plan with a one large opening on the façade provides ventilation and light inside the building without using transparent glass façade (figure 18).



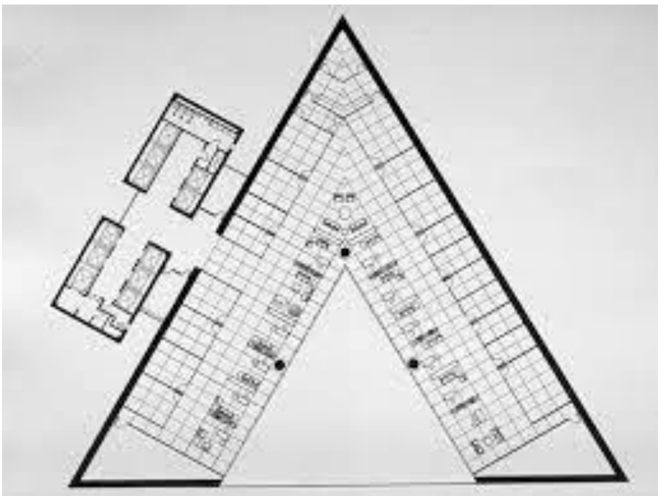


Figure 18. Top – National Commercial Bank in Jeddah with 126m height. Bottom – Having a V-shape plan layout (Source: Oldfield, 2019)

Oldfield (2019), proposes guidelines for environmental high-rise buildings in **arid and warm zones**;

- Increasing shading and opacity in the façades through the diminishing of window-to-wall-ratio (WWR) as in National Commercial Bank in Jeddah (figure 18), or through external shading systems providing daylight inside the building while the use of thermal mass as a solar buffer and façade insulations provide improvement for energy performance.
- Placements of buildings to minimize the width of east and west facades and locating service cores or shading devices on the east and west sides to minimize solar gain.
- Orientation of buildings towards the prevailing breezes and evaporative cooling of incoming air provides thermal comfort which lessens the air-conditioning usage in milder winter months.
- External thermal mass as a solar buffer is needed. The external placements of concrete structural shells, cores or structural elements provide shaded areas inside the building. Moreover, covering this external mass with lighter colors or high solar reflectance coating helps to decrease the heat inside the building.
- Recycling water technologies and the use of water capture systems help in diminishing the carbon intensive generation of fresh water, since the water management is important for sustainability.
- Locating air intakes at upper levels for supporting natural ventilations.
- Photovoltaic systems are recommended for on-site energy generation because of the intensive solar radiation.

CHAPTER 3 : SUSTAINABLITY AND ARCHITECTURE

In recent years, with the growth of the world population, greenhouse gases, extreme heat and cold waves, and the depletion of natural resources are rising worldwide. In this regard, renewable natural materials and renewable energy sources are increasingly used in construction fields to amend the negative environmental effects. Also, terms like sustainability, green architecture, energy-efficient, and high-performance buildings have become catchphrases worldwide in the campaign to minimize the environmental damage of buildings (Al-Kodmany, 2010).

3.1. Sustainability

Sustainability is a term that can be described as the ability to be permanent or long-lasting and indicates the harmony between different fields like agriculture, fashion, gastronomy, etc and nature. The sustainability agenda has entered our life and became popular in the form of sustainable development, for the first time in 1987, by Our Common Future - Brundtland Report that the (WCED) - World Commission wrote on Environment and Development (Şen, Alpaslan, and Kaya, 2018). Sustainable development was defined by WCED's (1983, p.37) as:

"Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Sustainability turned into a significant concept for different subjects after the Brundtland Report was published, and it can be described in three requirements;

- Sustainability must be economically feasible, and in doing this, the long-term usage of resources should be considered.
- Sustainability must concentrate on protecting the environment from humans and their actions.
- Sustainability must help to be equal in both humans and communities, especially those who are destitute and protect the emerging countries from exploitation (Şen, Alpaslan, and Kaya, 2018)

3.2. Sustainable Architecture

Sustainable design, also known as *eco-design/ green design/ environment-conscious design/ or ecological de*sign of the human-built environment, deals with reducing the use of nonrenewable resources and respect the ecosystem's balance. It mainly focuses on the physical integration of buildings, products, and infrastructures with the ecosystems and site processes, as well as creating biological assimilation between the built and the natural environment. It also prevents the reduction of resources such as energy, water, raw materials, and environmental damage to facilities and their infrastructure (Yeang and Woo, 2010). In other words, sustainable design is a design that minimizes the destructive impacts on the environment by integrating any physical, systematical, or temporal forms with natural environments and their living processes. Building construction substantially impacts inhabitants' natural environment and social life, occurring during and after the construction stage.

Thanks to the improvements in construction technology , environmentally friendly structures became common methods for minimizing the environmental damages. This chapter explains a few principles for designing sustainable buildings.

3.3. Sustainable Building Evaluation System

The priorities and objectives of sustainable buildings can be better understood by the systems that gauge and certify their environmental performance. A number of countries employ such certification systems under different names. For example, table 3 presents that, the US uses the LEED certification, the UK uses the BREEAM certification, China uses the Assessment Standard for Green Building (ASGB), and Japanese designers use the Comprehensive Assessment System for Built Environment Efficiency (CASBEE). Australia uses the Green Star certification, while the Germans use German Sustainable Building Council (DGNB) standards for evaluating the building’s sustainability (Gui and Gou, 2020).

Table 3. Green Building Rating Systems for Different Countries (Source: Gui and Gou, 2020)

Rating Tools	Country	Level	Indicators
LEED v4	U.S.	Certified; Sliver; Gold; Platinum	Location & Transportation; Sustainable Sites; Water Efficiency; Energy & Atmosphere; Material & Resource; IEQ; Innovation; Regional Priority; Integrative Process
BREEAM	Britain	Acceptable; Pass; Good; Very Good; Excellent; Outstanding (1–6 Stars)	Energy; Health & Well-being; Innovation; Land Use; Material; Management; Pollution; Transport; Waste; Water
ASGB 2014	China	Design One Star; Design Two Stars; Design Three Stars; Operation One Star; Operation Two Star; Operation Three Star;	Land Conservation; Energy Conservation; Water Conservation; Material Conservation; IEQ; Construction Management; Operational Management;
Green Star	Australia	1 Green Stars; 2 Green Stars; 3 Green Stars; 4 Green Stars; 5 Green Stars; 6 Green Stars	Management; IEQ; Energy; Transport; Water; Material; Land Use & Ecology
CASBEE	Japan	Superior (S), Very Good (A), Good (B+), Slightly Poor (B-), Poor (C)	Building Environmental Quality & Performance; Building Environmental Loadings
DGNB	Germany	Bronze; Silver; Gold; Platinum	Environmental Quality; Economic Quality; Sociocultural & Functional Quality; Technical Quality; Process Quality; Site Quality

The Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method are the most common rating systems. (BREAM) (see details in the next section). In the US, architects who aim at eco-friendliness usually use the LEED certification criteria as a guidance in their projects. The LEED system sets standards to decrease the environmental damage by buildings with a point-based ranking system. It helps developers to estimate how eco-friendly their building can be (Cidell, 2009).

- ***The Leadership in Energy and Environmental Design (LEED)***

In developed countries, buildings must meet specific criteria to be considered as ecological. In the U.S., many buildings are designed according to the LEED system, to measure the sustainability level of the buildings. The U.S. Green Building Council is a non-profit organization that creates domestic standards for designing more sustainable buildings. The LEED (Leadership in Energy and Environmental Design) program was established in 1998 by public and non-profit companies and private entrepreneurs who wished to rank buildings -even HRBs- according to how sustainable they are appraised with specific standards. These standards have been modified for use in other countries like Brazil, China, Canada, etc. (Cidell, 2009). The level of green certifications depends on the grades that buildings get aiming to reduce their negative environmental effects. The ‘greenness’ of buildings ranges as follows: for 40-49 percent – Certified; for 50-59 percent – Silver; for 60-79 percent – Gold; for 80 percent or more – Platinum.

The LEED program measures buildings' sustainability level according to five environmental protection categories as; (1) site planning, (2) water efficiency, (3) energy efficiency, (4) materials and resources, and (5) indoor environmental quality to give points to buildings. The mechanical systems and construction techniques must be graded by their effect on health, environmental sensitivity, and energy reduction, which are not enough. The building should also include state-of-the-art standards in energy conservation, indoor quality, recycling, and ecological manufacturing steps (El-Shorbagy, 2009). The five parameters of the LEED certification system are given in table 4 below.

Table 4. Table of the LEED Certification requirements compiled by the author (Source: Hasselbach, 2010 ; Kubba, 2016).

Category	**Aim**
Sustainable Sites (SS)	Reveals sustainable transportation options as walking and bicycling to keep car usage minimum. Constructing on a primitive natural zone as *greenfield* alleviate the exposed natural systems like wildlife, habitat and biodiversity of the site, prevents the impact of natural sources and provides advantages for site remediation and site remediation and exploit existing infrastructure (Kubba, 2016).
Water Efficiency (WE)	Eliminates portable water utilization at the site and discharge of wastewater from the site and has three subcategories; *Water Efficient Landscaping, Innovative Wastewater Technologies, Water Use Reduction* which will be defined below and they all serve decreasing the associated utility cost for the buildings and their habitant (Haselbach, 2010).
Energy and Atmosphere (EA)	Minimize the energy utilization at site and nonrenewable energy usage in both site and energy sources. It also intent to eliminate the global climate, atmosphere and environmental effects which are occurred by the activities at the site and energy sources off-site (Haselbach, 2010; Kubba, 2016).
Materials and Resources (MR)	Reduce the environmental impact of extraction, production and transportation of materials and resources. These environmental effects increase the air and water pollution and destroy natural habitats and deplete natural resources (Haselbach, 2010; Kubba, 2016).
Indoor Environmental Qualities (IEQ)	If the environmental quality is higher, people are becoming more productive and happier. Having and optimum IEQ is achieved by four different perspective as thermal, visual and acoustical comforts and indoor air quality. Many buildings and occupants are suffering from air pollution that caused by ventilation systems, energy consumption, thermal comfort issues and also from inadequate daylighting inside the buildings (Kubba, 2016).

- ***The Building Research Establishment Environmental Assessment Method (BREEAM)***

The British Building Research Establishment Environmental Assessment Method was founded in the United Kingdom in 1990. According to GreenBookLive Databases, in 2012, the BREEAM Rating system has been used in 33 countries. In the United Kingdom the system has been used in 2898 projects so far. There are new international versions of BREEAM around the world, and BREEAM International for New Construction Version 6 (INC 6) is the most recent to this day. The certification system has a total grading level based on percentages; 30% for Pass classification, 45% for Good, 55% for Very Good, 70% for Excellent, and 85% for Outstanding (Awadh, 2017). Designers who aim to get BREEAM certification need to cover all needs that

BREEAM requires. These requirements for new construction projects were classified into five main categories in table 5 that include; Governance, Social and Economic Wellbeing , Resource and Energy, Land use and Ecology and, Transport and Movement.

Table 5. Table of the BREEAM requirements by the author (Source: Awadh, 2017)

Category	**Aim**
Governance	Promotes community involvement in decisions affecting the design, construction, operation and long-term stewardship of the development
Social and Economic Wellbeing	To generate a good economy by thriving business and employment opportunities. To ensure socially cohesive community and reduce the envrionmental impacts on the health and welbeing of inhabitants.
Resource and Energy	Focuses on the sustainable use of natural resources like energy generating systems, water manageement and the minimising the carbon emissions.
Land Use and Ecology	Promotes sustainable land use and ecological enhancement.
Transport and Movement	Concentrates of the design and provision of transport and movement infrastructure to provide the use of sustainable modes of transport and to minimise the possible air pollution.

CHAPTER 4 : HIGH-RISE BUILDINGS AND SUSTAINABILITY

4.1. Scholar views on sustainable HRBs

Building heights were restricted by the abilities of masonry walls to support the weight of additional stories. Also height was a problem for inhabitants to access the upper floors especially elderly people. Technical advancements in building materials and an increased need for space in cities spurred the development of tall, multistoried buildings. After The International Style movement, high-rise buildings started to represent the dynamism of cities. Thus, architects tried to link the urban space with the HRBs and aimed to make them as a part of the environment (Anholts, 2012).

Sustainable HRBs can be described as buildings that try to amend the environmental issues related with their design, construction, and operation stages. Of the numerous HRBs around the world, this paper covers selected sustainable iconic high-rise buildings in terms of their environmental design features. In general, there are some qualities regardless of buildings. The sustainable scheme must have; embracing high and stable levels of economic growth and employment, covering the environmental aspects, considering the use of natural sources, and admitting the need to help people to achieve social goals. These four qualities must be embodied with the high-rise building design like with all architecture. As mentioned under the chapter 2.4., the amount of energy and material consumption is higher when we compared with low-rise buildings.

Yeang and Woo (2010) defined basic principles – that would be applied in high-rise buildings as well – in their book, Dictionary of Eco-design, in order to create eco-friendly buildings, urban developments, or products;

- **Reducing dependency on non-renewable energy** to raise energy efficiency in bioclimatic design by using daylight, active and interactive walls, natural ventilation, passive solar systems, and green roofs/terraces.
- **Decreasing demolition or waste of resources** by using materials or components that can be reused or recycled, or materials that can be reintegrated back into nature.
- **Preserving the ecosystems and biodiversity** using land bridges, ecological corridors, and green infrastructure.

- **Using compact spaces** not only assists buildings to minimize the heat island effect and urban micro-climate effects but also minimizes the running cost of the building.
- **Managing water** by using drainage infrastructures, retention ponds, filter drains, and permeable surfaces to help decrease pollution and flooding and create buffer strips for wetland habitats that help water purification and recycling (Yeang and Woo, 2010).

Moreover, Yeang believes that having a verticality is more sustainable than enlarging a city horizontally and defines *HRBs* as 'vertical cities' with their pedestrian liaison and public zones. The term vertical cities is not a new word for architecture. It has been explored by many architects. Le Corbusier was one of them with his ideas on "Ville Radieuse" . It was an propasal for central Paris, which was never been built, yet it became a model for architecture in the post-WW2 period (Montavon, Steemers, Cheng and Compagnon, 2006). Markel J. explained it in these words Anholt's (2012, p.27);

"You map a tall building the same way you do a city, with zones for parking, offices, and social places."

Besides Ken Yeang there are other scholars who cover the environmentally design features like, Abdel-Moniem El-Shorbagy, Paola Sassi, Tatjana Anholts, and more...

Paola Sassi defines sustainable design principles under the importance of material selection;

- The material selection is vital in creating a sustainable living environment. The materials are divided into non-renewable (stone, coal, oil, metal mines) and renewable (timber, flax, hemp, cork). Generally, renewable materials are efficient and easy to find; however, they will be challenging if they are over-harvested.
- Replacing brick with clay or renewable components such as straw, synthetics insulation materials such as rigid foam with natural insulation materials such as cork, wood, or sheep's wool is the best way to reduce the environmental impact of the material needs of buildings. Also, preferring wood construction requires minimum energy, and it would reduce carbon emissions. Designers should prefer the possible recycled materials (Sassi, 2006).

Tatjana Anholts indicates the important topics in designing green eco high-rise buildings as;

- The building envelope and colors, and the openings which are important and should be related with the climatic conditions of the area
- The selection of materials and energy sources which are important in minimizing the building operational energy and embodied energy of the building.
- The use of vegetation on form of high-rise buildings and its effects.
- Potential waste management.
- High-rise buildings require systems like, electrical/mechanical system, fire-protection devices and vertical transportation systems (Anholts, 2012).

El-Shorgbagy (2009) mentions that the buildings consume more than 45% of the energy used in the United States, and the share of construction waste is almost 25% of landfill volume. Such numbers underline the importance of reducing the environmental footprint of buildings. HRBs and their level of sustainability can be achieved by defining *new design principles*. El-Shorbagy defines a sustainable high-rise building;

- High-rise buildings can reduce the energy consumption of transportation per people in the cities.
- It is important to link parks and public spaces with HRBs because the high-rise buildings might lead to lose the connection to the large public space since the green spaces in street provides people to interact with each other.
- High-rise buildings should have retail zones on the street level to enhance the urban fabric and social issues.

This chapter discusses how design strategies help to minimize the environmental problems caused by the escalation of HRBs in cities. It is divided in sections about; the green HRBs, net-zero energy buildings, and finally design strategies for sustainable HRBs.

4.2. Eco-High-rise Buildings

According to Ken Yeang, the HRBs cannot be classified as ecological building types. On the contrary, Yeang and Powell's (2007, p.411);

"it is the most unecological type of all building types in the world."

High-rise buildings need more material and energy resources for their construction, operation, and disposal. Having more floors than other buildings, containing more material content, requiring large amounts of energy for internal circulation, and having a strong structural system able to withstand lateral forces like wind pressure or quakes in the upper part of the building, convinced Yeang to name HRBs as 'un-ecological' building types (Yeang and Powell, 2007). Ken Yeang questioned if HRBs can ever be green, and if they can how their design should be. As mentioned by Wood (2013) and Yeang (1999), high-rise buildings consume a lot of energy and materials than low-rise buildings. Researh based on the Building Performance Database (BPD) showed that the ratios of Operational Energy (OE) in high-rise buildings are higher than low-rise buildings. Figure 19 illustrates that, with the exeption of heating, the other systems like cooling, lighting, interior equipment, fans, water systems, heat pumps in high-rise buildings require more energy than in low-rise buildings (Du et al., 2015).

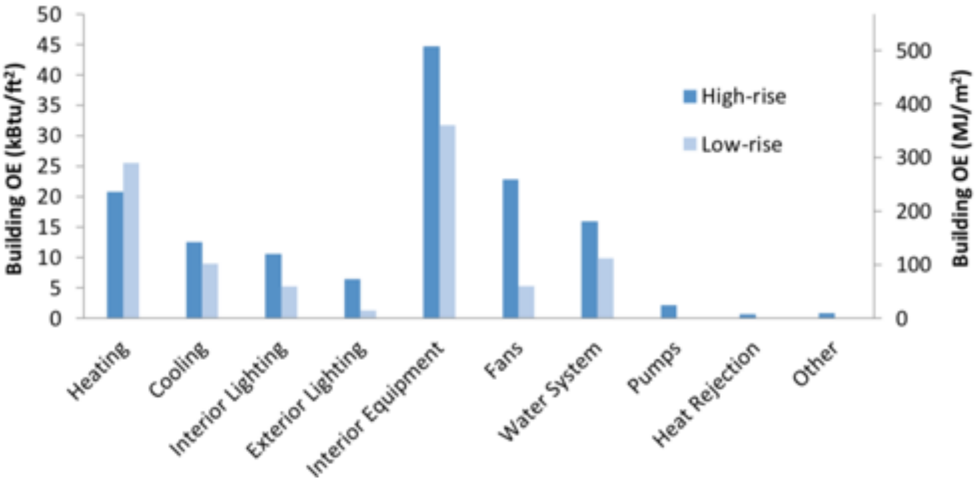


Figure 19. Operational Energy [OE] for high-rise and low-rise building cases (Source: Du et al., 2015)

Du et al., 2015, compared the energy consumption level at the Cool-Humid zone of Chicago, IL for single-family homes and residential appartmant buildings (RAB). acroding to Building Performance Databased (BPD)–available source of actual measured building energy performance –the RAB consumes an avarage of 1678 MJ/^{m2} per year while the single family dewllings consumed 889 MJ/m^2 per year.

Al-Kodmany (2010), emphasized the green HRBs by the expression by Ken Yeang: "The green meets the blue", meaning how architects assimilate the principles of eco-design with new material and technology into high-rise buildings. For example, architects exploit the use of energy-saving or energy-generating systems to create high level of indoor quality inside the building for its occupants.

The introduction of green design into the high-rise architecture has been identified as a 'green-scraper' by designers and researchers interested in sustainability in architecture. As HRBs have a powerful presence in the city, some of them have become iconic examples of HRBs embracing green design technologies. Like Wuhan Tower in Wuhan, 30 St Mary Axe in London, Pearl River Tower in China, Menara Mesiniaga in Malaysia, Shanghai Tower in China, Bosco Vertical in Milan and many more.

In the light of the above findings, HRBs are classified as non-green because of the harm to the environment that they cause. Yeang lists a few crucial issues of HRBs to find how they can be greener. Firstly, their scale creates an opportunity to make them examples of green design. Secondly, HRBs are a green alternative to low-rise buildings and land-consuming decentralized suburban structures. According to Yeang, the decentralized or clustered layout of the structure increases further transportation distance between the buildings. Researche shows that, there is a geometrical relationship between the building density and the reduction of energy consumption for transportation. According to figure 20 below, after 20 years the consumption of fuel per person in cities and its relation to the urban density remains the same. All in all, gasoline consumption decreases when urban density increases but, the obvious fact is that beyond a certain point, density has small effect on gasoline consumption.

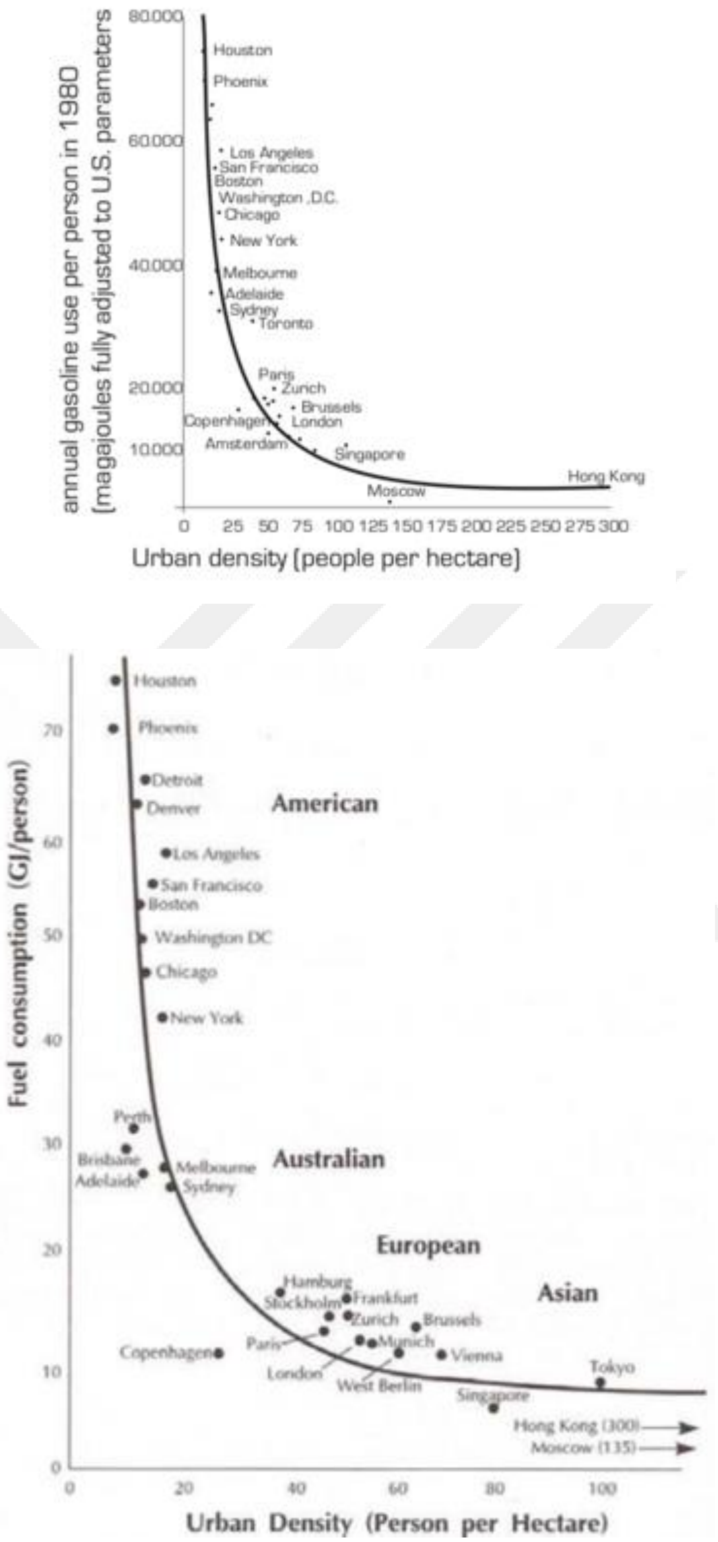


Figure 20. Top: Gasoline consumption and urban densities (1980s) Below: Represent the gasoline usage in different countries with the cities that consumes more than other cities in their country (2000) (Source: top; Robert Paehlke, 1989 and bottom; Pank, Girardet and Cox, 2002.)

Moreover, transportation creates important justification for dense cities with intensive HRBs. For example high-rise buildings have lower-energy results by vertical transportation as elevators in HRBs which are 40 times more energy-efficient.

Anholts (2012) states that, the need of car ownership and parking spaces can be reduced by adopting higher density working and living spaces in cities. It diminishes the urban travel and increses the public trasportation which also minimse the gasoline consumption in the cities. Thus, he states that, multi functional HRBS provide efficency in the city (Yeang, 1999). However, the HRBs are not enough to reduce travel time in the big cities where the numbers of HRBs increases yet, the worsening traffics problems still exist. This problem can be the reason why cities need dense building environments and vertical transportation as well (Anholts, 2012).

- ***Net Zero Energy in High-rise Buildings***

A new generation of tall building is improving the response to the environmental issues proposing solutions for the climate challenges. To lessen global warming caused by anthropogenic GHG emissions, designers should be aware of the net-zero energy (NetZEB) and carbon concepts, and use available technologies to reduce carbon emissions of new and existing building operations and constructions (see chapter 4.2.) (Oldfield, 2019). These need to be done by defining strategies for a true NetZEB, which means a building that generates the renewable energy it requires from the sun, wind and ground source energy, aiming to keep CO2 emissions at a minimum. The case studies in this work include NetZEB strategies (see chapter 5). However, having netZEB performance is more difficult in HRBs that low-rise ones because HRBs have more energy consumption per floor area than other buildings.

There are two essential steps (will be discussed in chapter 4.3.3) to achieve zero energy in buildings;

- Energy Efficiency – aiming to lessen the energy required for buildings. (Pearl River tower is 58% more efficient than other conventional high-rise buildings.)
- Energy Generating – to achieve energy balance by producing energy from renewable energy sources and from the energy that is used in buildings. (One Central Park and Shanghai Tower has its own renewable energy (trigeneration system, geothermal energy and wind energy.) (Aelenei and Gonçalves, 2014)

However, the energy generation from renewable sources creates challenges for designers as described in section 4.2.4

- ***Embodied Energy and Carbon in High-rise Buildings***

Many researchers emphasize that tall buildings consume more energy and generate greenhouse gas (GHG) emissions than lower buildings per square meter per their entire lifecycle, from the raw material extraction for their construction and operation to the disposal of materials after the demolition, Fay et al., 2000, mentioned that buildings' embodied carbon and energy include the extraction, transportation, and refining of the raw materials and manufacturing of building components. The total embodied carbon of any building can be measured as the sum of the building's initial embodied carbon and its recurring embodied carbon. As mentioned before, the excavation and processing of the construction materials consume natural resources and cause air and water pollution and emit CO2 and GHG into the atmosphere.

Due to the increasing population, the need for taller buildings is increasing correspondingly, and the need for more materials to resist structural loads is growing. (Oldfield, 2019). Thus, the embodied energy of the building increases after the construction of building envelope and structure are completed (Kaspersen, Lohne and Bohne, 2016). Zhao and Ma (2015), mentioned that according to the United Nations Environment Programme (UNEP), the energy consumption for construction generates approximately 30%-40% of the energy consumption worldwide.

Moreover, CTBUH stated that from 2013 to 2014, more than 800 super tall buildings had over 200m in height, which increased greenhouse gas emissions. The structural and non- structural building components increase GHG emissions in proportion with the height of the building such as materials for exterior walls and frame, and HVAC equipment as well as plumbing system.

According to Researchers at UCL's Energy Institute, the cost of operating tall buildings is almost 40% higher than the low-rise building constructions related with the Operational Energy (OE) (UCL, 2017). HRBs use up a significant amount of OE compared to the low-rise buildings compared with their scale. Most of the energy consumption occurs from the energy needed for using elevators. It is estimated that elevators consume energy in tall buildings between 5 to 25% of the total energy consumption of the building depending on the height of the structure.

Moreover, the energy for pumps distributing potable water, fire extinguishing, or heating and cooling water at higher altitudes is substantially high in High-rise Buildings, and the overall energy demand of S affects the conditions in the neighborhood.

Leung and Ray studied and researched about the energy consumption in high-rise buildings and accumulate data from the buildings where at least 80% uses as an office. The outcome of their research is that, low-rise buildings consume less energy than high-rise buildings -see figure 19 above. Another outcome is that, the energy use intensity in HRBs depends on the density of urban fabric. It is affected by the parameters like, solar shading, the average radiant loss, low or high wind speed affecting infiltration (Saroglu et al., 2017).

Since the embodied carbon and energy in high-rise buildings are important to minimize the GHG and environmental damages, Oldfield (2019) indicates some features should be considered to reduce the embodied energy and carbon impacts on the high-rise buildings;

- Using fewer materials – the structural system and materials should be decided early in the design by remarking the 'premium for height'[2]_– used in John Hancock Center and Willis Tower in Chicago, Illinois.
- Recycled material usage – or recyclable or waste materials such as steel, aluminum coopers, fly ash, and blast furnace slag instead of cement in concrete structures.
- Reused structures – the improving and retrofitting existing buildings reduce embodied carbon emissions for tall buildings.
- Replacing the materials with intensive carbon with low-carbon materials – timber (In the UK, Canada, USA, and Australia, timber started to be sported in terms of being low-corban material types (Oldfield, 2019).

4.3. Strategies of Sustainable High-rise Buildings

Green high-rise buildings are essential parts of urban improvements in a sustainable way. As mentioned, the HRBs–used for commercial, residential purposes as hotels,

[2] Known as the difference in material weight per gross floor area between the boundaries of the two phases of design (1st; designing the building for gravity loads without considering the effects of lateral loads. 2nd; the upper bound of design in terms of material weight per gross floor area.

museums, and schools–consume much energy, compared with low-rise buildings. In the USA, the need for commercial and mixed-use buildings increased with the growing population and activities in the cities in 1950s. Thus, the energy consumption for commercial buildings, increased from 11% to 18% (Pe´rez-Lombard Ortiz and Pout, 2008). Also, the energy consumption in countries was increased by the economic growth, the expansion of the building sector, and the intensification of mechanical services like heating, ventilation and HVAC systems in buildings. Table 6 represents the energy consumption share of commercial and residential buildings in countries. Table 7 indicates the basic sustainable design features for high-rise buildings.

Table 6. Energy consumption share of commercial and residential buildings in USA, UK, EU, Spain and the World (Source: Pe´rez-Lombard, Ortiz and Pout, 2008)

Final energy consumption (%)	Commercial	Residential	Total
USA	18	22	40
UK	11	28	39
EU	11	26	37
Spain	8	15	23
World	7	16	24

Year 2004. Sources: EIA, Eurostat, and BRE.

Based on data like above, there are some features related with the sustainable design of building criteria by some authors aiming to minimize energy consumption, therefore to minimize the environmental damage too. A number of such features are listed in table 6 together with some comments, followed by more explanations.

Table 7. General checklist of sustainable high-rise building features (height was not specified for this strategies) with comments by the author (Source: El-Shorbagy, 2009; Anholts, 2012; Yeang, 2012).

Features	Remarks
Building Shape Configuration	• Shapes do not affect only the structure but also the surrounding streets and buildings. Wind analysis can optimize the form of HRBs
Building Location-Orientation	• The orientation and plan are the first challenges. The openings and materials on the façade get benefits of free energy by sun in terms of light and heat. • The location of service core and its effects of overall building layout.
Façade Design	• Doubled façade, triple-glazing, and glass coating helps to reduce energy consumption. Also, double-skin façades aid in reducing heat loss in winter and heat gain in summer. The outer skin absorbs the diffuse radiation, while the inner skin transfers heat to interior environment.
Energy Efficiency	• To have minimum energy demand in the building, the diminishing of Carbon Emission and Energy should be achieved. Alternative renewable energy resources utilization is another way to achieve minimum non-renewable energy consumption.
Material Selection	• Prefer reused or recycled materials if it's possible, if it's not, prefer renewable (timber, flax, hemp, cork) materials .Local material selection with minimum transportation distance. Choose materials that have minimum CO_2 emissions.
Water Management	• Water management includes recycling gray water or runoff from ground surfaces and rainwater harvesting is essential mainly for residential HRBs and partly in commercial ones. Use of water efficient fittings like waterless urinals might help either even it is not effective than recycling and harvesting.

4.3.1. Built Form and Configuration

The form of HRBs should be shaped regarding energy use, matching the surroundings, and the climatic features of the area. In sustainable design, architects focus on minimum energy requirements for heating, cooling, etc., and this is not easy to solve with only renewable energy resources or the orientation of the building. The mass of the building and its surface to volume ratio are among the solutions that will help achieving low-energy consumption (Yeang and Powell, 2007). The climate change should be considered in the design of building shapes. The form of the building based on climatic conditions helps to reduce energy needs in the building and environmental damages. Ken Yeang echoes Olgyay's classic book Design with Climate, with his contribution. He studied building configuration in terms of the plan length to width ratio and vertical cores for HRBs in climates such as cool, temperate, arid, and tropical climates (Yeang, 1994).

Generally, the 1:2 to and 1:3 length ratios are suggested for building forms near the equator with a tropical climate (figure 21). In arid regions, the orientation of longer side of the buildings should be twice as long as the sides. It creates an opportunity to decrease the shading impact of buildings placed on South, if the building is located below the equator. Moreover, to have maximum sun penetration inside the building, the window placements should be on the North façade, if the building is located in the equator. The long axis of the structure should be oriented east/west to maximize sun penetration from north/south (Yeang, 1999; Yeang, 1994).

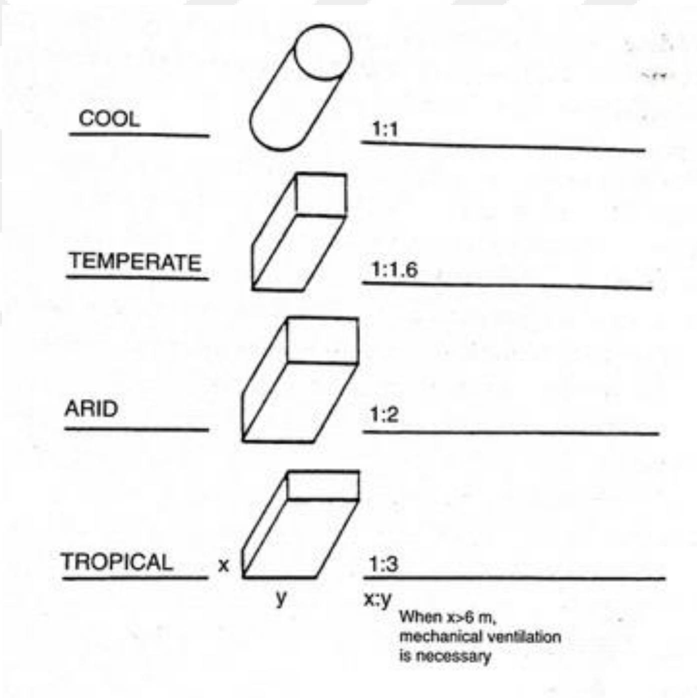


Figure 21. Optimum aspect ratios of sustainable high-rise buildings. (Source: Yeang, 1999)

4.3.2. Building Location-Orientation

In any building project, the site organization is the first important thing that affects the whole design and is an essential factor in building green or efficient high-rise buildings. A designer should consider the relationship between the environment or surroundings and the building design, including the way people access the building, the façade design that is crucial for achieving harmony with the urban skyline, the circulation in the building, and its relation between the interior and exterior. The orientation is important for any kind of building design. Some of the necessary considerations can be summarized as follows;

- The connection between the buildings and the surroundings should be considered.
- The transportation should be easy for people. The building should be designed considering access from public transportation spots, pedestrian ways, and streets.
- Visual impact of the tall building on the surroundings should be studied in terms of height, materials, and form. A building should be designed as a contribution to the urban skyline.
- Natural façade materials usage and the pattern between the inside and the shell should be harmonious.
- To make a building as part of nature, the green areas are essential. Green spots should be located near the entrances, and they should continue inside the building.
- The building orientation is also critical to utilize the effects of the sunlight and the wind inside the building. If the building is located accordingly, it is easier to take daily sunlight and wind inside the building (Tohumcu and Zeytun Çakmaklı, 2017).

4.3.3. Façade Design

"The building is like 'our third skin' after our physical skin covering and our clothes…" (Yeang, 1999)

Thus, the building should be naturally in harmony with our bodies and the natural surroundings, and it should be able to breathe. The building envelope must be controlled and modified to adapt to changing local climatic conditions. The external envelope must be designed to act as an environmentally responsive filter to have a better living environment inside the building. The way to have an environmental façade design is to have adjustable openings on the facades – acting as a sieve-like filter to get maximum natural ventilation, to control cross-ventilation, and to provide solar protection (Yeang, 1999). The green façade helps to decrease solar heat gain with external shading devices, creating fresh air ventilation (can also act as an acoustic barrier) and maintaining access. Also, double-skin facades can help to get natural ventilation and heat balance inside the building.

- ***Double-skin Façade (DSF)***

Generally, high-rise buildings have seen different façade design systems such as glass curtain walls, or metal cladding, and stone panels. However, the most effective skin design to build environmental buildings is the double-skin façade (Lago, Trabucco and Wood, 2018). DSF eases the air flow for ventilation this way. It makes buildings more energy-efficient, and it diminishes the noise and high-wind pressures in buildings. Even though there is a possibility of creating greenhouse effects in the building, it moderates the outside air and creates a heat trap in summer. It also facilitates solar shading that is not exposed to wind forces. That enables glazed high-rise buildings with less risk for solar gain (Yeang, 1999; El-Shorbagy, 2009).

- ***Green Wall***

A green wall, also known as a vegetated façade, is a system where the plants can grow on vertical surfaces of buildings by providing regular maintenance. The selection, irrigation system and maintenance of the plants is important factors for the success of a green wall. There are two systems to achieve a green façade in design.

- The first system is **the Façade-Integrated Living Walls** (figure 23) where the plants are attached and integrated with the façade structures. The plant mediums and plants are on a vertical surface of the external skin. The plants are separated from the structure with a waterproof membrane layer to protect the façade from unwanted moisture. The water sensors can provide a sustainable and efficient irrigating system (see case 2 at chapter 5) (Wood, Bahrami and Safarik, 2015).

- The second system is **the Façade-Supported Green Wall** system (figure 24). The façade supports it, but the planting equipment is not connected to the skin of the building. Instead, the planting medium is carried in horizontal pots, combined with steel, wood, or plastic trellises that are fixed on the building façade. Typically, a steel mesh supports plants at some distance from the wall, with their rooting system in pots at the bottom (*see case 1 at chapter 5*).

A green façade will generally have climbing plants weaving themselves in and around a framework of mesh, wires or cables. Living walls usually contain potted plants rather than climbers.

Figure 22. The D-block of Izmir University of Economics in Izmir is an example for façade integrated green wall that failed due to poor maintenance. Left, general view; right, detail of the soil pockets. (Photo taken by author on September 2022)

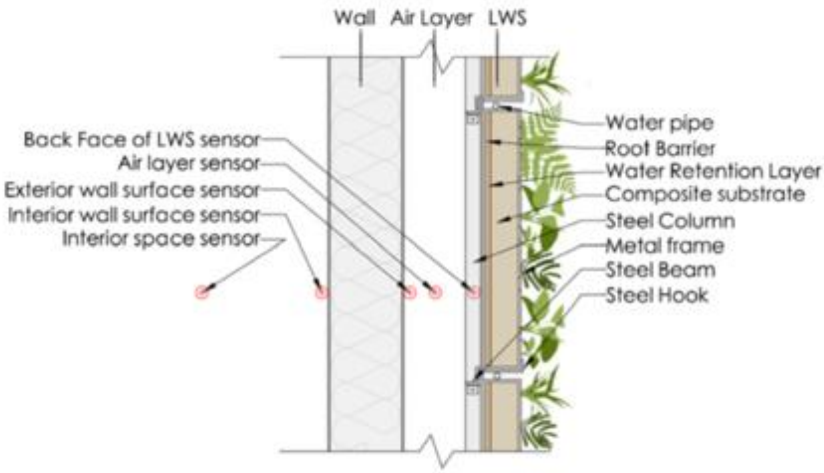


Figure 23. Living wall system [LWS] details. (Source: Chen, Li and Liu, 2013)

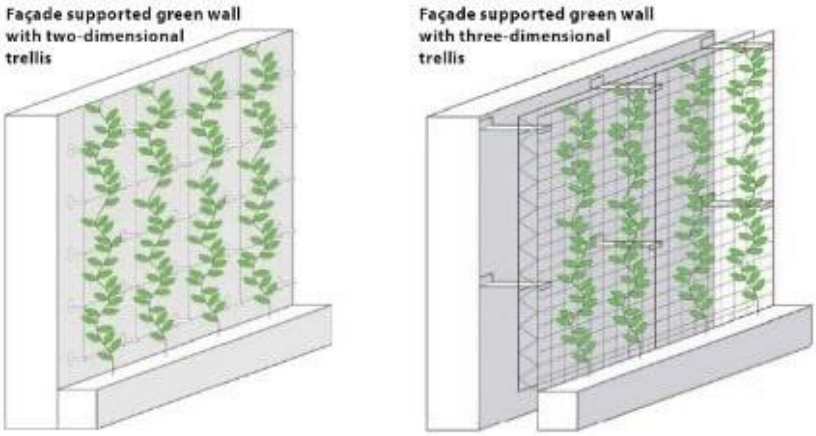


Figure 24. Façade supported green wall. (Source: The Constructor Building ideas, 2022)

Green Walls reduce the Urban Heat Island phenomenon and dampen outside noise before entering the building, improve building energy efficiency and air quality in the surrounding, increase property value, and provide biodiversity and natural animal habitats. The indirect green walls include modular trellises and pots filled with substrate and individual support structures. That allows the suspension of the elements along the wall at various heights (Manso and Castro-Gomes, 2015). At the same time, they prevent possible damage to the envelope of the buildings and create internal air quality, air filtration, and oxygenation, which affects dwellers' health (Yeang, 1999).

4.3.4. Energy Efficiency

The energy consumption of HRBs is a crucial factor that the designers should minimize to design an eco-friendly environment for the human future. Some solutions include solar radiation usage, double-layer structures (double-skin façade), and computer controlled mechanical systems to reduce energy needs. The main aim of energy-efficient buildings is to decrease the negative impact of building on the environment. The reduction of energy consumption in construction is succeeded by covering structures with optimal thermal qualities, using maximum natural lights from big openings to reduce the indoor temperature, which can also be supported with automated climate control systems. Moreover, the alternative way to achieve energy-efficient buildings is to exploit renewable energy sources like wind power, the thermal energy of the earth, and photovoltaic solar cells (Zhigulina and Ponomarenko, 2018). However, Oldfield (2019) states that, on-site energy generation can contribute only a low proportion of energy needs -often less than 15%. The possible energy generating methods are *combined heat and power (CHP), photovoltaic collectors, wind energy, and fuel cells.*

- ***Combined Heat and Power (CHP)***

CHP is accepted as an efficient energy source for densely built-up areas. It is known as co- or tri-generation, producing power, heat, and chilled water for air conditioning. CHP systems prevent transmission losses since the electricity is produced closer to its consumption. . Thanks to the CHP, up to 80% of thermal efficiency can be achieved because it produces heat and electricity at the same time. (El-Shorbagy, 2009). Also, it needs less fuel to work, reducing CO_2 more than 30% compared to coal-fired power station and more than 10% of gas fired combined cycle gas turbines. Therefore, the CHP systems can be an attractive solution to have minimum carbon release and also can be applied in tall buildings or groups of tall buildings if the need for electricity load and annual cooling is similar. *The case 1* - One Central Park building in Sydney is an example of how CHP works in energy efficiency for high-rise buildings (Ali and Armstrong, 2008).

- ***Photovoltaic Collectors***

Photovoltaic collectors are used as a solution for sustainable energy production in buildings. The PV cells are more efficient when they are placed above the building or on top of the buildings for unobstructed direct insolation **(see case 1 at chapter 5)**. They can also be positioned on walls as a cladding system om concrete or steel framed buildings providing rain cover, and hosting a light show on the facade. However, being vertical are less efficient in terms of energy output, especially if they are not located on the side facing the equator. ***(****See case 1 - One Central Park).* Also, the use of PV panels for tall buildings can help energy collection in diffused light and, provide a clear path for direct sunlight above the other structures (El-Shorbagy, 2009).

- ***Wind Energy***

Wind has some advantages in HRBs because of their height, that designers can use positively overcoming the disadvantages (Lotfabadi, 2014). Wind is commonly used as an energy source with turbines that can be integrated with buildings on their top. The wind turbines take advantages from the different pressure between the windward and leeward sides and increase the wind flow (Oldfield, 2019). Burj al-Taqa (Energy Tower) in Dubai is a non-materialized example having 61m wind turbines on its top (figure 25). However, there is lack of information about how the vibrations caused by the wind turbines effect the building and the surroundings (El-Shorbagy, 2009). On the other hand, there are applicable versions of wind turbines on buildings. Pearl River Tower is a one of the examples of how wind turbines can be applied not only at the top of the building. A different version of wind turbines is applied at the top of the Strata SE1 tower (figures 26, 27).


Figure 25. Burj al-Taqa in Dubai. Right; the wind tribunes at top. (Source: Design Build Network, 2008)

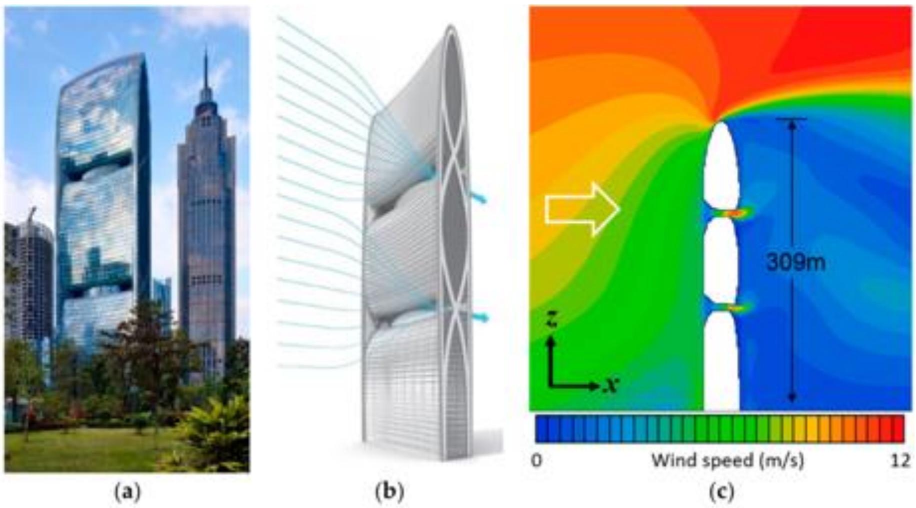


Figure 26. Pearl River tower: (a) photo of front view; (b) wind penetration structure; and (c) contour plot of wind speed on a horizontal cross-sectional plane (Source: Kim, Jeon, and Kim, 2016)

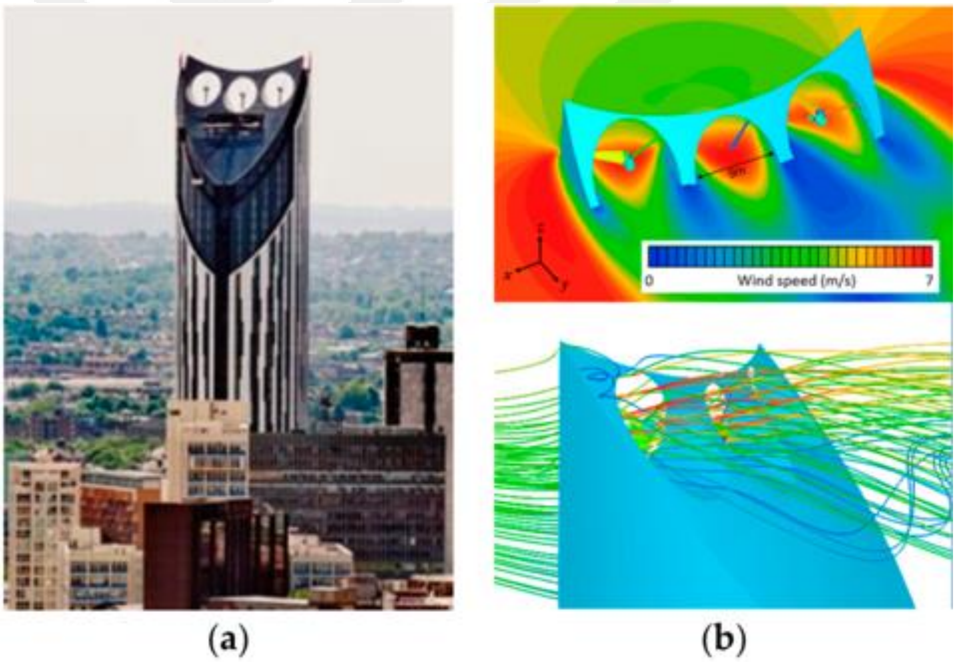


Figure 27. The Strata SE1 tower: (a) wind turbines at top, (b) the density contour of wind speed and directions at the top of the buildings. (Source: Kim, Jeon, and Kim, 2016)

- ***Fuel Cells***

Hydrogen can be converted to electricity by fuel cells, including electrolytes surrounded by two electrodes – one is for hydrogen and oxygen to pass over. Ultimately, it produces heat and water that are also used in the CHP system. The positive effects of fuel cells in terms of electricity and fewer emissions in silence. Many researchers aimed to investigate second-generation fuel systems with progressive technology, low cost, and durability adaptable with co/tri-generation. However, fuel cells are costly. That is why only significantly sized fuel systems are used worldwide (El-Shorbagy, 2009). Fuel cells are used in spacecraft and airplanes, but now they have been used in buildings like Conde Nast Building in New York to support the inhabitants' heat and electricity. The use of fuel cells also has benefits because they are flexible in installation and operations, reduce GHG emissions clean and quiet. Also, Ali and Armstrong (2008) believe that fuel cells will become the most common system in the future for using carbon-neutral energy sources in buildings. According to the U.S Department of Energy, 10 million households will use hydrogen and fuel cells by 2030 (Ali and Armstrong, 2008).

4.3.5. Building Material Selection

Architects should select the material of HRBs as other types of buildings by combining ecological and architectural criteria. The embodied energy of the material and its ecological impact, the effects of materials on human health, and possible reuse or recycling of materials would be the selection criteria for construction materials of buildings (Yeang, 1999). *Green materials* have a life-cycle sustainability from a 'cradle to grave' perspective and are not hazardous to human health. The materials should be chosen if they do not lead to any indoor pollution or uncomfortable indoor climatic condition.

The standards for green material selection can be listed as follows;

- The durability and maintenance are important as well as the recyclability and reusability
- Thermal performance to achieve satisfactory energy use during the operation,
- Acoustic qualities to provide indoor comfort
- Safe materials to mount as well as fireproof given the high importance of safety in HRBs
- Aesthetic outcome to be well related to the surrounding.
- Materials that are not hazardous for human health (Kumar, Aggarwal, and Gupta, 2021; Franzoni, 2011).

4.3.6. Water Management

Water is becoming important in the current world situation with increasing water stress in various parts of the world. The climatic changes related to global warming and increasing population should affect water use in the world. Ken Yeang (1999) and Graves (1998) state that the citizens in the US utilize 578 liters per person which equals three times more water than the Europeans who use 160 liters per person. Also, between 2001 and 2011, water consumption in China increased by around 33% because many people started living in buildings with more than seven floors (Smith et al., 2017). Thus, a pumping system in the buildings with more floors is needed. Thus, energy use for water supply became a concern in China.

Similarly, in Hong Kong the average number of floors in residential buildings is about 25.8 story. The annual water consumption in Hong Kong is about 1200 mm^3 which is equal to 408 L daily consumption per capita. So, the total electric usage for water supply in Hong Kong is about 1.6% of total electricity in city (Smith et al., 2017; Cheung, Mui and Wood, 2013). Thus, water management is an important environmental feature for high-rise buildings in the world. Also, it is significant in dry zones like the United Arab Emirates regardless of height. Mostly, potable water is generated with the desalination of seawater where there is a lack of natural water resources. Water desalination in Arabic cities generates between 1.3 and 3 kg CO2 per cubic meter of water (Oldfield, 2019).

There are some water management systems to minimize the water consumption and the energy needed for pumping in high-rise buildings. One of these systems is recycling the grey water which should be considered especially in HRBs in dry zones. The building needs a dual-sewage pipework, collecting black-water from the toilets to the sewer, while the greywater from the kitchen, sinks, and bath is reused inside the building via a filtration system. The filtration systems provide to remove solid materials, hair, and food particles. These can be achieved by the stocking or sock filter on the inlet pipe to the storage tanks or sand, stone, and gravel media filters (*see Case 2 - Bosco Verticale*) (Abd-Alaziz and Al-Saqer, 2014; Al-Kodmany, 2012).

On the other hand, rainwater can be collected on rooftops and then stored in tanks which can be sized depending on the amount of the average local rainfall and water consumption patterns. The surfaces on the façade of a building can also be used for rainwater harvesting. However, rooftop harvesting requires less treatment than other paved surfaces. Also, it has lower levels of total dissolved solids than gray water or scheme water *(see Case 1- One Central Park and Case 5 - Shanghai Tower)*. (Ali and Armstrong, 2008; Chanan et al., 2003)

CHAPTER 5 : CASE STUDIES

Among the many high-rise buildings in the world, this work focuses on selected eco-iconic high-rise buildings, with different design strategies, locations, and functions, by comparing their contribution to environmental sustainability based on the design criteria discussed in chapter 4.

5.1. Selection Criteria

The examples were chosen based on the following criteria:

- *the locations* to represent how climate affects HRB construction,
- *the function* to understand how the use of HRB also have influence on design objectives,
- *the environmental performance certifications* to know about their sustainability levels, and finally but most importantly
- *the sustainable design features* which are having energy efficient or energy saving systems, green wall and glazed wall façade, building orientation and location to minimize the transportation usage, and water management systems

Table 7 lists the selected schemes with some general data.

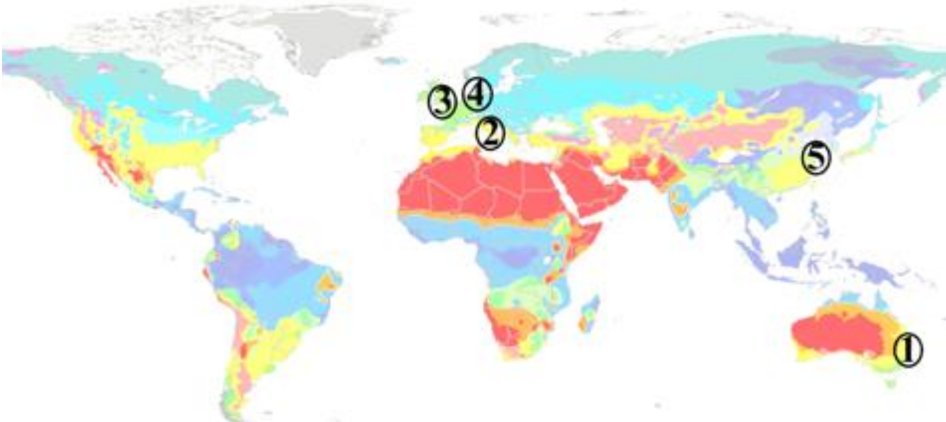


Figure 28. Köppen climate map and the location of the case studies represented by author. 1-One Central Park, 2-Bosco Verticale, 3-30st Mary Axe, 4-Commerzbank Tower, 5-Shanghai Tower

Table 8. Main features of selected examples of HRB by author.

Case	**1**	**2**	**3**	**4**	**5**
	One Central Park	**Bosco Verticale D/E**	**30st Mary Axe**	**Commerzbank Tower**	**Shanghai Tower**
Architect	Jean Nouvel	Stefano Boeri	Norman Foster	Foster +Partners	Marshall Strabala, Arthur Gensler, Andy Cohen, Jun Xia
Height / Floor Area	117m / 255, 500m^2	D:83m - E:115m / 360, 000m^2	180m / 64,500m^2	259m / 120,000m^2	632m / 576, 000m^2
Date	Start: 2010 Completed: 2014	Start: 2010 Completed: 2014	Start: 2001 Completed: 2003	Start: 1994 Completed:1997 Recladding: 2010	Start: 2009 Completed: 2015
Function	Residential	Residential	Office	Office	Mixed-use
Location / Climate	Sydney/Sub-tropical	Milan/Sub-tropical	London/Temperate	Frankfurt/Temperate	Shanghai/Sub-tropical
Certification	- 5 Green Star	LEED	LEED	LEED	LEED / 3 Green Star
Sustainable features	-Green wall -Glass façade - Energy generating - Water management - Building orientation and location - Material Selection	- Green wall - Water management - Building orientation and location	-Built form configuration (double-core) -Double-skin glass façade and twisted floor plan (natural ventilation) (energy saving)	-Built form configuration (V shaped central core) -Natural ventilation (Double skin façade and sky gardens) -Solar gain (from sky garden and glassed façade and 16degree South-West orientation)	-Double-skin façade -Energy generating (CCHP, Geothermal Energy, Wind turbine

There were more cases to choose from like, One World Trade Center in New York, Pearl River Tower in Guangzhou, the Taipei 101 in Taipei, the Shard in London, Ocean Height in Dubai, Lotte Tower in Seoul etc. However, these buildings were not chosen because of difficulties in finding sufficient information, climatic conditions and function, deficiency of sustainable certifications or/and locating in same cities with case studies listed above.

5.2. *Case 1 – One Central Park (Sydney)*

Table 9. One Central Park information

One Central Park	Height	Primary function	Date	Gross floor Area	Location Climate	Certification
	117m	Residential	2010-2014	255,500 m^2	Sydney Sub-tropical	5 Green Star

Figure 29. The One Central Park in Sydney. (Source: ArchDaily, 2014)

The One Central Park in Sydney, also known as Frasers Broadway (figure 29 and table 9), was designed by Ateliers Jean Nouvel –as principal architecture firm, and PTW Architects – as architect of record. The complex consists of 2 separate towers including 34-storey and 12-storey residential tower and, each tower includes a common retail podium below. One Central Park is a response to the rising population in downtown Sydney. Nouvel and Beissel stated 'The Central Park challenges the Modernist resistance to surface accretion, both with a planted veil that cleans the air, provides shade and speaks for naturally-integrated urban vitality (Nouvel and Beissel, 2014).

The building itself demonstrates how energy and water flows can be blended in the environmental design. (McLean and Roggema, 2019). The master plan of the building was designed by considering and giving importance to Sydney's population growth. The building is located in a place where the traffic nodes and the residential towers are near the inner city to waste less energy for transport, consume less farmland, and minimize the cost of infrastructure and transportation (Nouvel and Beissel, 2014).

5.2.1. Sustainability strategies

The building consists of two residential towers: one 116m high, and another 64.5m high. One Central Park or Frasers Broadway includes several sustainable design strategies to become one of the eco-friendliest residential towers in Sydney. It was designed by using environment-conscious technology such as hydroponic walls and heliostats. Due to the hydroponic green walls at the façade, the building has a water flow system to manage and minimize the water usage. Moreover, the building includes energy generating system to produce its own energy. Based on these features – green wall, energy generating system, water flow systems and solar energy uses, the building was awarded with 5 Green Stars (ASPECTStudios Oculus, 2020).

The building includes environmentally sustainable features that were defined in chapter 4.2 above. It includes green façade energy generating systems in tri-generation as well as heliostats *which transfer daylight inside the building,* durable materials, and reusing water system for water management (table 10). Patrick Blanc, a French botanist, developed the irrigation system to provide plants growing without soil for a vertical garden. He designed a connection between a plant's root and wetted felt. The collected rain water is re-used as gray water to use in laundry, wet spaces, and irrigation of green spaces by innovative Flow Systems. The building also reduces greenhouse gas emissions by trigeneration system (Yesilodak, 2019). The building was designed to be graded as the highest project of Green Building Council of Australia (GBCA) under the Green Star rating system in Sydney.

Table 10. The core sustainable features of One Central Park with how they were applied. See the text below for details.

Sustainable features	Design solutions
- Green wall	The vertical gardens that appeared in the skyline
- Material Selection	The plants on the façades are placed in recyclable Polyethylene planter boxes with proper drainage
-Heliostats	Having heliostats on the upper part of the subtracted volume that acts like solar energy storage for transmitting direct sunlight to shaded areas and inner gardens and providing solar heat inside the building.
-Energy Generating by Glass façade and Combined heat and power (CHP)	Designing to minimize thermal exposure with transparent façade and including horizontal shelves placed on the north façade to reduce heat gains by 20% as well as the effects of cantilevered reflectors at sky garden "baseball cap" to provide shaded and heated area. Also, the tri-generation systems near the building supported with underground infrastructure.
-Water management	Uses the gray water recycling from the toilet flushes to irrigate the plants

- ***Green Wall***

The Hydroponic walls, (figure 30) provides organic shade and direct sunlight that also creates a vertical landscape by Blanc. Also, it makes the building a powerful green icon on the Sydney skyline, using recycled water to grow plants. (AJN, 2014). The vegetation up to the roof all over the tower façade was the best way to create a big park in the neighborhood as the architects wanted. These green wall systems also can be changeable or removable according to habitant needs or wishes (Manincor, 2014). According to Mike Home - a resident and a landscape designer in One Central Park, living in such a building brings him joy. He states that, when he looks up, he sees a garden in the sky. The green in every window reminds him of living in the jungle which is great for him. Also, the site design of the building is important for him because he can walk with his dog in pedestrian ways surrounded by specious trees (Fullen and Painter, 2015).

Figure 30. One Central Park façade. Hydroponics Wall –Vertical Gardens by Jason A. Dibbs. Right; Polyethylene planter boxes on the façade to provide organic shade. (Source: AJN, 2010)

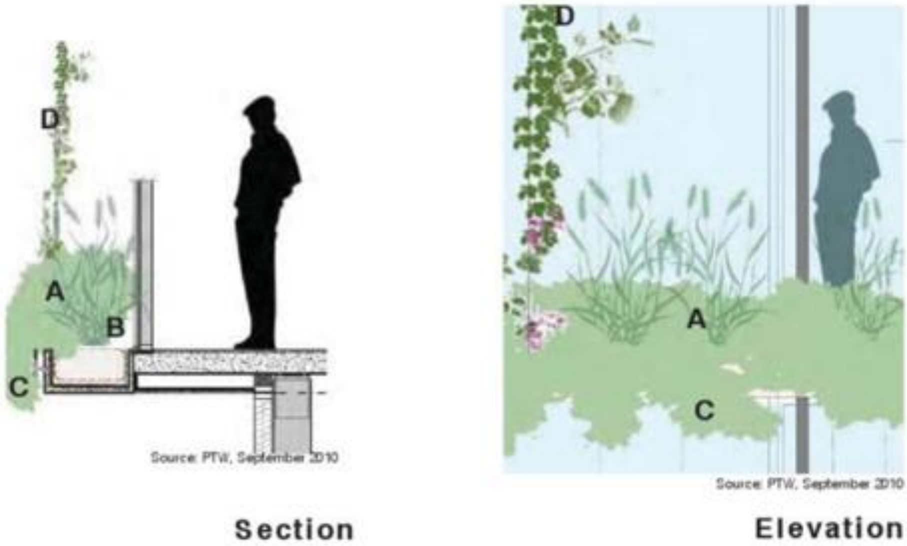


Figure 31. Plant Podiums and Green Wall design of One Central Park; A-Primary Planting, B- ground cover, C- Cascade Plant, D- Climbing (Source: PTW, 2010)

- ***Heliostats – Mirror Panels***

Heliostats (figure 32) can get direct light into inner gardens and shaded areas for light and heat by using mirrors. To achieve this, the sunlight is reflected up to cantilever reflectors placed under the big green cantilevered terrace of the luxurious penthouse, with the help of 40 sun-tracking heliostats on the roof of the lower tower.

- ***Combined Heat and Power***

The building produces thermal energy itself by low-carbon natural gas power plants. The 2-megawatt (MW) trigeneration energy plant supplies energy, heating, and cooling for residents, podiums, and 14 commercial spaces located in Central Park by providing low-corban thermal energy (figure 33). Figure represents how the heliostats work. The mirror heliostats at the top of the west tower absorb the sun light an reflect to other heliostats at the top of the east tower. Thus, the mirror heliostats provide to get sun light directly inside the buildings which is a way to provide solar energy. The heliostats are also uses for night lightening. In addition, the Brewery Yard building and County Clare Hotel consume the low-corban electricity from the trigeneration energy plants. According to the environmental consultant, these 2-megawatt energy plants can minimize greenhouse gas emissions by as much as 190.000 tones over 25 years of the design life of the plant, thus representing the tri-generation is double the coal-fired power by its energy-efficient qualities.

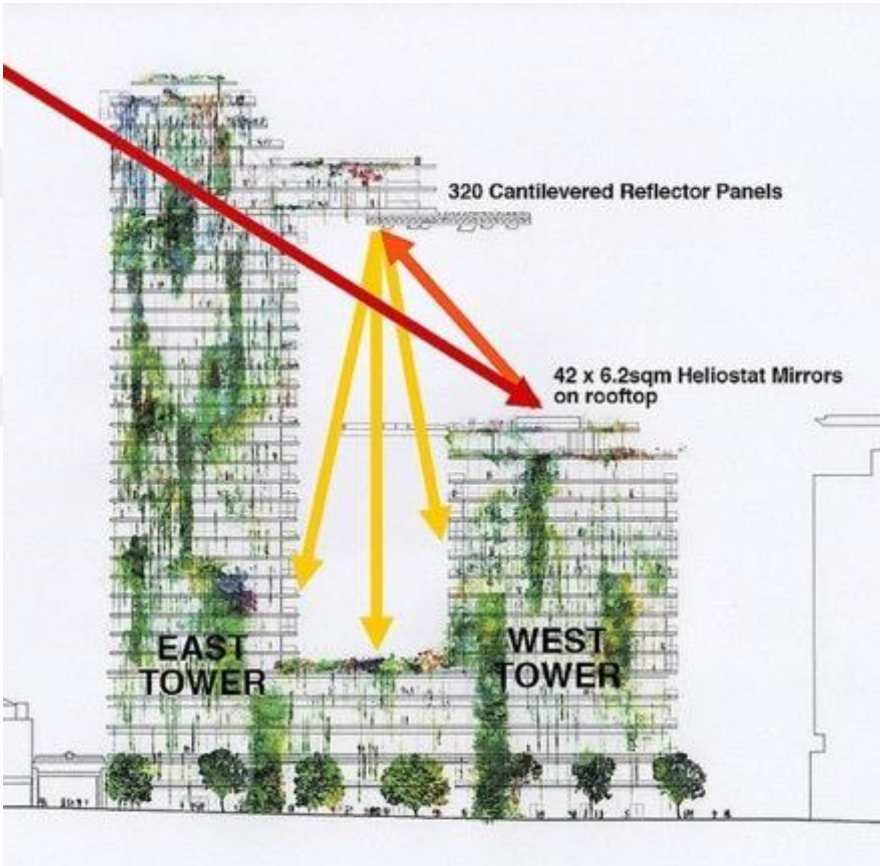


Figure 32. Top: Heliostats - Mirror Reflectors by Murray Fredericks. Bottom: Long Section of One Central Park. (Source: top; YeşilOdak, 2022 bottom; Modernist Architecture, 2013)

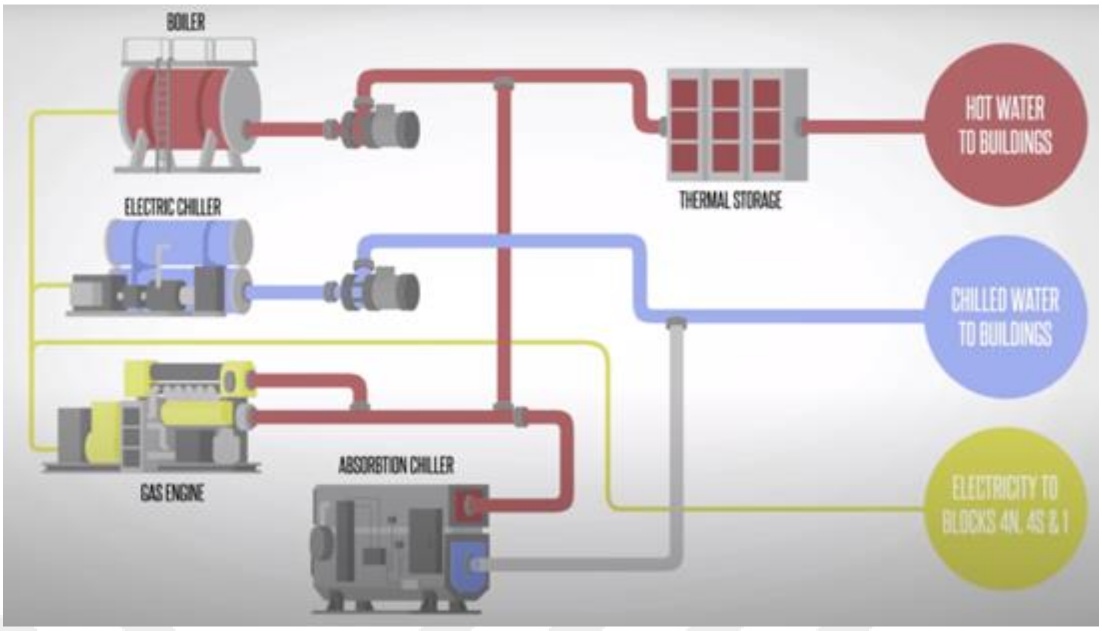


Figure 33. Green Energy System of One Central Park. (Source: YouTube, 2021)

- ***Water Management***

The One Central Park has become the first representative of combining living walls and green facades (see chapter 4.2.3). A significant element of its green infrastructure is the reused water network which can manage and sustain the water of the complex. To use reclaimed and treated sewerage, or graywater, an automated irrigation system (figure 34) that can be controlled from a distant laptop, was developed and placed over four basement levels by using Membrane Bioreactor[3] (MBR) and Reverse Osmosis[4] (RO). The water flow system takes all management of the water cycle in the neighborhood to save money and decrease the amount of wasted water by 50% or 40%. The eco-friendly pipelines procure the delivery of different water qualities. It also limits the total water use by households and businesses, of which 10 to 20% is for drinking or cooling, 20-30% for cleaning, and 50 to 70% for other activities like toilet flushing, laundry irrigation, and air cooling or green wall watering.

As a result of this innovation, the building has water purification steps as shown in figure 33. The components of the water management system are;

- Rainwater that comes from the roof,
- Storm water from planter box drainage and waterproof surfaces,

[3] It is a wastewater treatment process.
[4] It is a system where the water can be deionized by the pressure of the semi-permeable membrane.

- Groundwater that comes from the drainage system in the basement,
- Irrigation water from hydroponic walls,
- Drinking water that comes from the main public water pipe,
- Wastewater – black-water from the Once Central Park community (sewage, bathroom)
- Sewage from Sydney's ancient public sewer (McLean and Roggema, 2019)

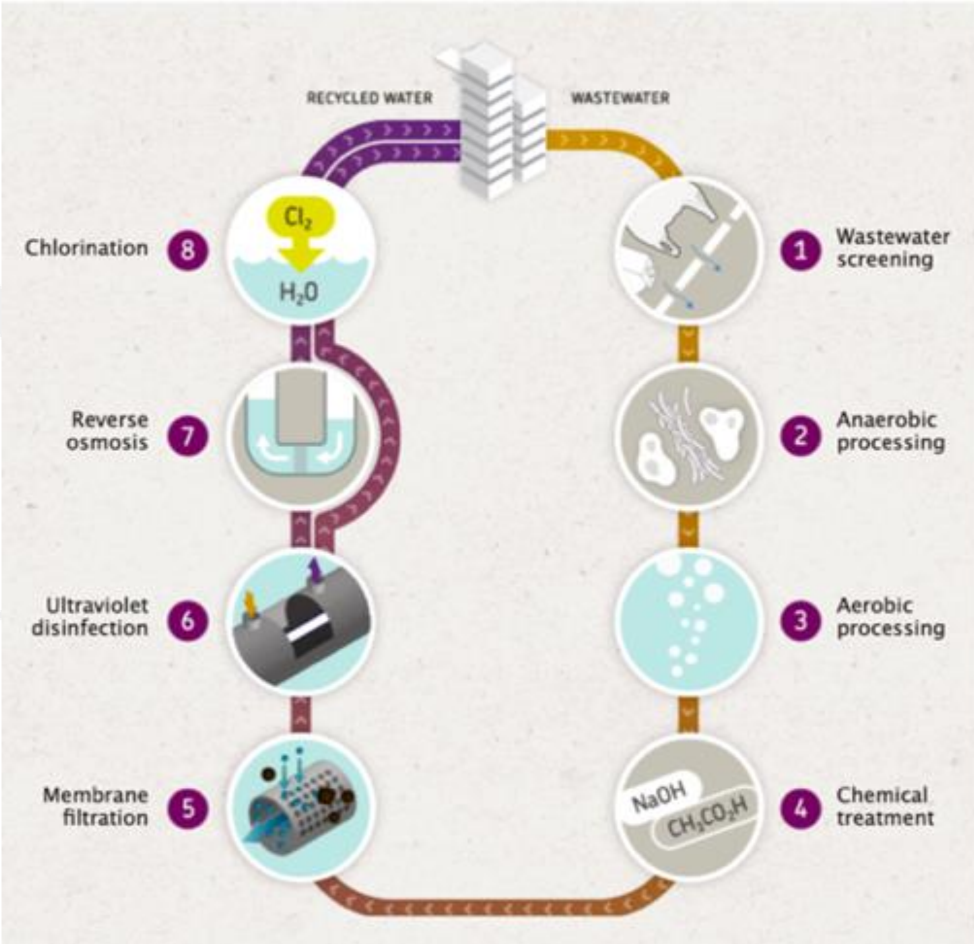


Figure 34. 8-step Purification process of One Central Park. (Source: McLean and Roggema, 2019).

5.2.2. Summary

The One Central Park in Sydney is an eco-iconic high-rise building, with several features of sustainable architecture. It shows how to minimize environmental damage and to tackle such possible damages aesthetically through its design concept. The concept of heliostats at the upper part of the tower provides solar energy directly inside the building where the sun cannot reach normally. It is an innovative way of utilizing solar energy by using the mirror's reflection. Also, trigeneration is another innovative way of sustainable architecture. It helps decentralize local energy solutions, local wastewater recycling, and green walls - the main reasons why One Central Park is awarded the Green Star certificate (McLean and Roggema, 2019). The environmental benefits like; use of 93% demolition recycled materials, about 80% decrease in greenhouse gas emission, 90% carbon neutrality, and most importantly, recycled water supplies in 100% were the main configuration of the design. For this reason, it was ranked as 5 Green Star designs for the East and West Towers – used for residential purposes, and Podium – used for retail. Therefore, it is called the greenest and most self-sufficient urban development where eco-design is represented as a way of life in Australia (ASPECTStudios Oculus, 2020). Sustainable architecture will become a critical trend worldwide to reduce green gas emissions, ecological footprints, wastewater, and energy usage, even in high-rise buildings.

The One Central Park represents how a HRBs can be environmentally friendly and how the recycled material and water can be adopted into the mixed-use design. The scheme is an example of understanding that sustainability can not only be achieved by using recycled material as a construction element. It is also about solving infrastructural problems using technological developments and nature in design. However, even though one resident and worker of One Central Park (Mike Home, as mentioned above) claims there are no negative aspects to him, some of the sustainable features in the building were not very successful in practice. For example, the mirror reflectors (heliostats) at the top of the building were designed to create a better life on the lower floors, but it would not be so good for the people who live right under the heliostat platform. The reflection of heliostats and LED shows at night makes people uncomfortable living right below the platform. Besides the reflections of heliostats and LED show at night, the cantilever on the top is huge and it might make people worried under the cantilever because it has 120-ton weight (see figure 32).

5.3. Case 2 – Bosco Verticale (Milan)

Table 11. Bosco Verticale information

Bosco Verticale D/E	Height	Primary function	Date	Gross floor Area	Location Climate	Certification
	D:83m E:115m	Residential	2010-2014	360,000 m^2	Milan Sub-tropical	LEED

Figure 35. Bosco Verticale in Milan. (Source: Stefano Boeri Architetti)

Bosco Verticale – *Vertical Forest* consists of two residential high-rise buildings (Giacomello, 2015). Tower D has an 83-meter height with 19 floors, while tower E has a 115-meter height and 27 floors. Both towers were constructed in 2014 in Milan in Italy (figure 35). It includes the most intensive green facades in the world. It is called the most innovative high-rise building built recently in Milan with its sophisticated plants, the location and covering of green, and its structural design in terms of containing plants (Tokuç and İnan, 2017).

Stefano Boeri, the architect of Bosco Verticale and founder of Stefano Boeri Architetti, developed an idea consisting of six modules for transitional states between city, nature, and agriculture. These six modules are, Expo2015 (global kitchen garden), Metrobosco (a forest surrounding Milan), Wood House, Urban Agriculture, Courtyard Farms, and Vertical Forest – a tower with 1500 trees (Tokuç and İnan, 2017). The scheme stands on an 18,717 square meter land. The structural engineer is Arup Italia, and the project's owner is Fondo Porta Nuova Isola. Overall, both buildings have 480 large and medium-size trees, 250 small-size trees, 11.000 smaller plants in containers, 5.000 shrubs, and cantilever terraces (Flannery and Smith, 2015).

The building got awards like – the International Highrise Award in 2014 from the Deutschen Architekturmuseums in Frankfurt and the CTBUH Award for being the best tall building in the world at Chicago's IIT in 2015, of many features as the green walls, adjusting humidity, producing oxygen and absorbing CO_2 and microparticles. As Boeri states, the Vertical Forest idea become a trend in Milan. The existing and new buildings in the city started to be covered with flora and ivy by mimicking Bosco Verticale (Boeri, 2014).

5.3.1. Sustainability strategies

The aim of Bosco Verticale is to bring a new level of biodiversity into Milan for addressing sustainable challenges. Stefano Boeri claims that the Bosco Verticale represents a different perspective on sustainability and he thinks that the concept behind the vertical forest, which is a "home for trees that also houses humans and birds," also explains architectural qualities and technological and urban features (Giacomello, 2015; Boeri, 2014). The green walls are not only built as an ornament on facades but also as a combination of vegetation, creating rich biodiversity. It represents natural life with trees, seeds, herbs, bushes, and flowers.

"A home for flora is inevitably a home for fauna including beetles, spiders, butterflies [...] even kestrels." (Flannery and Smith, 2015).

Thus, the project's primary purpose was to create a vertical forest equivalent to 1 hectare as a solution to noise, pollution, and temperatures (Giacomello and Valagussa, 2015). Bosco Verticale has a few sustainable design features (table 12) of those discussed in detail at chapter 4 that led to receiving a LEED Gold Certification.

Table 12. The core sustainable design features of Bosco Verticale and how they were applied.

Sustainable features	Design solution
-Green Façade	The vegetation covers around 40% of the facades, while the green areas cover around 50% of the plan. It absorbs the CO_2 and improve air quality, controlling weather inside the building.
- Water management	The green wall utilizes an irrigation system consuming more water than residential towers without green façade. The system only includes the use of groundwater for irrigation of plants.

- ***Green Façade***

The green wall concept has many benefits, depending on geographic location, climate, building geometry, orientation, green wall components, and systems. It contributes to reducing air temperature, offers improved air quality, creates and supports biodiversity, and becomes a home for fauna (animals that live with vegetation like beetles, spiders, birds, bees, and more).

The vegetated exterior walls, plays a significant role as an example of sustainable development by reducing electrical energy needs by around 7.5% with plants on the exterior shell. They are not only for reducing the smog, absorbing CO2, and recovering the air quality but also turning into a thermal barrier to control the weather inside the building. The diversity of plants also reduces CO2, produces O2, and amends the poor air quality in Milan (Oldfield, 2019).

Furthermore, the greenery walls provide shading that minimizes the internal cooling load. Also, since trees are the lungs of the cities, both towers of Bosco Verticale act as a green lung for Milan. As said, green walls support healthy environments and energy-efficient buildings, reduce noise, increase indoor air quality, provide air filtration and oxygenation, protect vegetation, and supply agricultural opportunities for inhabitants (figure 37). Plants use solar energy for transpiration and photosynthesis which helps cooling the interior. -act as a windscreen by reducing convective heat transfer. Moreover, the plants on the façade reduce noise inside the building, thus increasing the indoor quality. (Giacomello and Valagussa, 2015).

Elena Giacomello states that concrete was chosen for the structure of the tower in order to support multiple structural load types such as; the gravity loads - which are increased because of trees and soil; 3.3-meter cantilevered terraces; unsupported seven meters spanned corners; and the dynamic loads that might affect the structure in terms of stability and security by wind forces (figure 36). Figure represents that plant containers at terraces located outside of the balconies opposite the exterior wall. Also, the plan containers are the part of the façade system unlikely the OCP. Dynamic load is important because, the trees generate significant amount of load not only due to their weight but also due to the wind. On the contrary of Case 1, the vegetation on the façade were not interfered by the inhabitants or owner of the apartment, they were only controlled by the management of the buildings.

The most important feature of green facades is the selection of the plants and planting media, irrigation system, and building structure for placing plants on the facade. They were selected based on their tolerance to urban conditions, high wind speeds, diseases, and fungus to live for long times, as well as the seasonal changes, heights and orientations. Also, designers give importance to choosing species that can live mutually in the same environment. The placement of the trees is considered based on factors such as their access to light, air, and moisture. The olive trees (species of Common Mediterranean evergreen trees) were located on the south and west sides. In contrast, the spring cherry-like trees are adaptable to cool and shade areas located in the east and north (Tokuç and İnan, 2017).

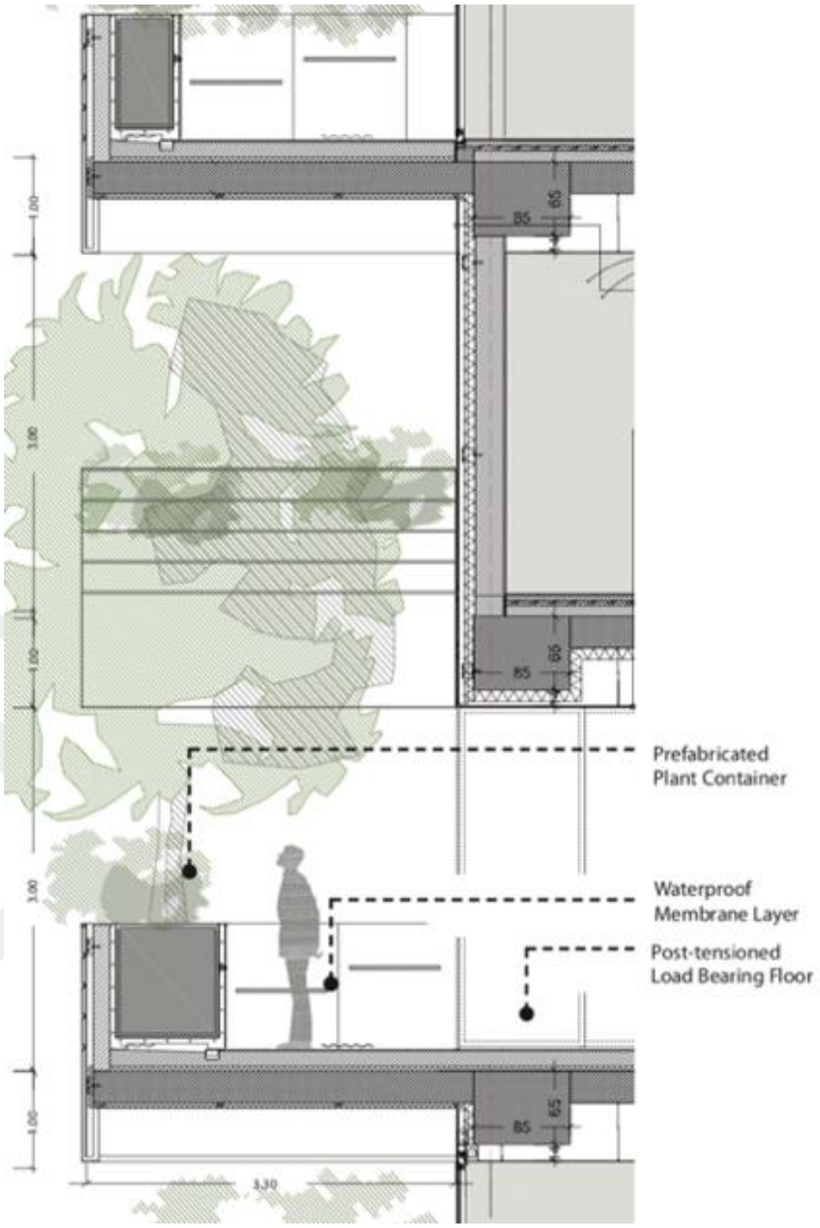


Figure 36. The green wall system of Bosco Verticale. (Source: Flannery and Smith, 2015)

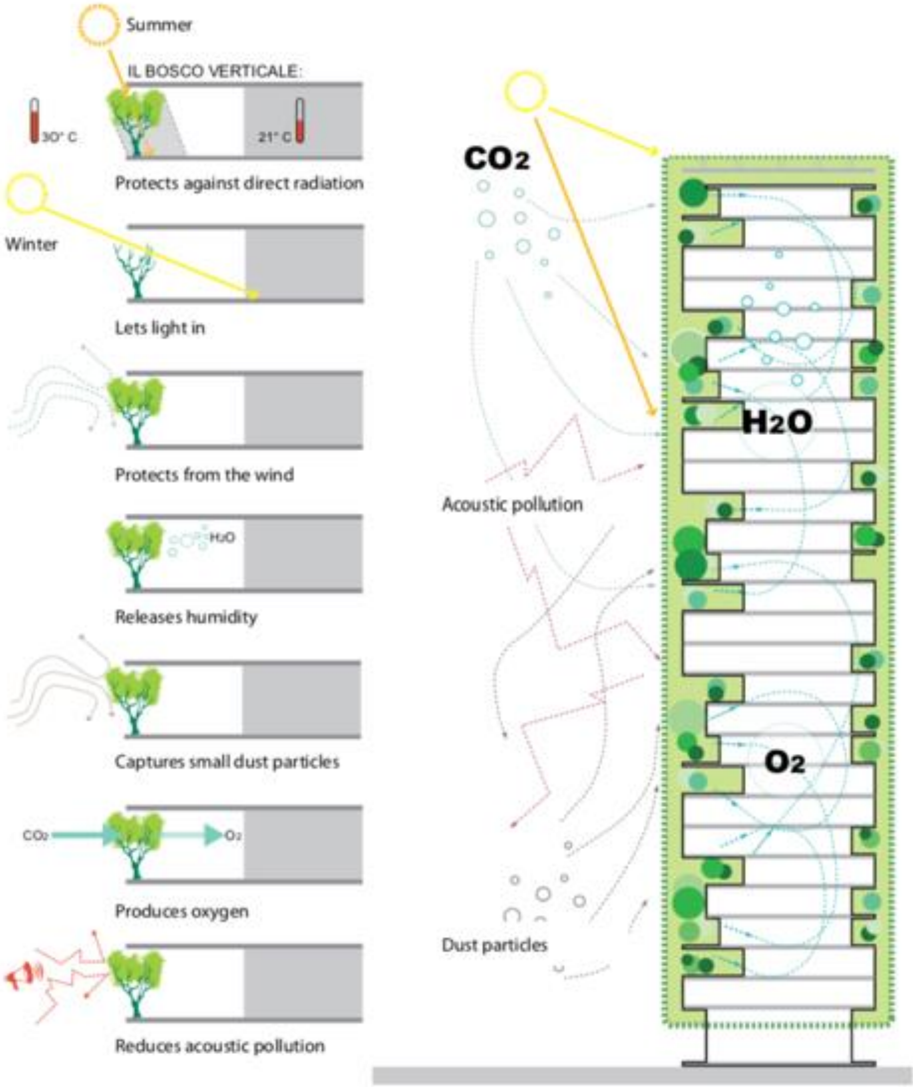


Figure 37. Schematic section of green wall system for Bosco Verticale. (Source: Giacomello, 2015)

- ***Water supply***

The irrigation system has a significant role in the design of the green wall to keep plants alive. Here the irrigation is supported by groundwater. The tubes for irrigation are located on the facades with innovative technology to avoid use in freezing temperatures. The system automatically drains away from the water inside the irrigation pipes in cold air conditions and fills when the temperature rises to 5 or 6 C° (Flannery and Smith, 2015). Moreover, the irrigation tubing and drainage pipes also maintain the plant roots, and tree trunks are stabilized with wire for extreme weather conditions (Tokuç and İnan, 2017; Coffman, 2018). The irrigation system consists of four main elements: the principal network, the control group in each plant box, the distribution elements in plant containers, and the humidity control system. It represents the gray water usage. The water for irrigation transforms through the houses for flush use (figure 38).

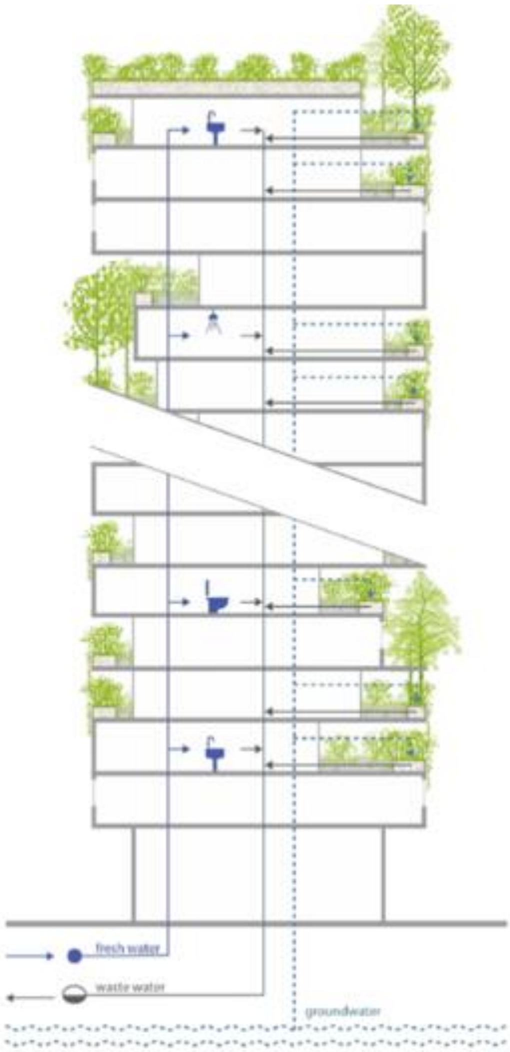


Figure 38. Right; Groundwater system of Bosco Verticale. (Source: Well and Ludwig, 2020).

The images at left in figure 38 presents the piping system. - **The principal tower network provides** to bring groundwater to the terraces. The control group in the plant boxes obtained water from the leading network and adjusted the water inside the vegetation boxes. - **The control group** comprises three elements, which are the buried substrate of boxes as a solenoid valve, a filtration unit, and a pressure regulator. That creates an opportunity to irrigate according to the needs of different plants. - **The distribution of plant containers** has the hardened drip line against root penetrations and siphoning by a chemical barrier. In addition, there is two humidity control system under the all-plantation boxes to save the humidity level of the bottom layer of the boxes (Giacomello, 2015).

5.3.2. Summary

Bosco Verticale is a famous example of the possible way to use greenery in high-rise buildings. The vertical forest aimed to reduce summer energy needs and mitigate the heat island effect. CO2 absorption is an essential sustainability feature in Bosco Verticale with a green façade design, which also produces O2 production and improves urban biodiversity. CTBUH chose the Bosco Verticale for research study in International Seed Funding Program because of the green wall and its implementation. In addition, the garden-balconies create a 'second skin' cover for the building, creating shaded areas and privacy for the occupants.

Another environmental advantage of Bosco Verticale is that its green façade system reduces electrical energy needs of the building by about 7.5%. Moreover, greenery on the façade improves the city and the apartments by absorbing noise, retaining carbon, and improving air quality. Sustainability is also achieved with the water supply system that provides grey water usage. The central system automatically provides irrigation for the plant on the façade using groundwater. The groundwater pumps have advantages, including heat pumps to obtain hot water from the ground as an energy source. In addition, water tanks were attached to pumps that serve water needs, and the water demands were controlled with sensors that calculated the humidity in the pots using innovative technology in the building.

According to the green features of Bosco Verticale, we cannot entirely say that Bosco Verticale is sustainable due to its overall building operational performance. As stated above, the building includes invariable green façade systems which are designed with pre-stressed concrete cantilevered to control the load caused by the weight and wind resistance of the plants. Thus, the use of additional building materials creates more embodied energy and requires additional natural resources which must be kept minimum in environmentally sustainable HRB. Moreover, the green façade might create a problem for occupant's life. They might not be comfortable with insects and deciduous plants under seasonal changes. As for energy, no special provisions are implemented in the scheme.

5.4. Case 3 – 30st Mary Axe (London)

Table 13. 30st Mary Axe information

Gherkin / 30st Mary Axe	**Height**	**Primary function**	**Date**	**Gross floor Area**	**Location Climate**	**Certification**
	180m	Office	2001-2003	64,469 m^2	London Temperate	LEED

Figure 39. 30St Mary Axe, London. (Source: ArchDaily, 2022)

30 St Mary Axe – also known as The Gherkin by the locals, is designed by Foster & Partners. It is located in the center of the 56-hectare site in the heart of London. Built in 2004, it had cost £138 million. The building has 40 floors, and according to CTBUH, the overall height of the Gherkin is 180 meters. It was built up of a circular steel core with integrated steel members, which go up spiral skyward around the external edge of the tower and meet at its apex (figure 41). The shape was designed to have smooth wind flow around the building and minimize the wind effects. It has a diagrid structure. The tower has some sustainable features like, double-skinned glazed, energy saving. (Fenske, 2013). It is built on the site of a significant commercial building, Baltic Exchange, damaged by an Irish Republican Army bomb in 1992. After that, the site owner Trafalgar House planned to build Millennium Tower 88-storey in 1996, but the

decision was revoked (Küçük and Arslan, 2020). After this back down, Norman Foster designed the 30st Mary Axe - also known as Swiss Re because it was designed for Swiss Reinsurance Company, with the aim to bring all personnel working in London for Swiss-Re, under one roof in a single headquarters. The building has over 64,469 square meters of floor area, including office spaces, kitchen facilities, private dining rooms, a bar, and a restaurant. Its height weakens the effects of the surrounding traditional box-like office buildings with its tapered circular plan, giving the building the maximum amount of natural light at height (Richards, 2006).

5.4.1. Sustainability strategies

Norman Foster paid attention to environmental conditions of London and its surroundings. The placement of the Gherkin and its shape within the center of the insurance district of London, provides natural ventilation and reduce wind downdraft. Norman Foster got inspired by biomimicry while designing, having the hexagonal skin of Venus Basket Sponge (figure 40) as an inspiration source and he used a diagrid structure made of aluminum-coated steel for biomimicking sponge (Nkandu and Alibaba, 2018).

The engineering company Arup, constructed the diagrid steel structure, which is based on a triangular form covered with glass. The skin of the building consists of triangular diamond-shaped curtain walls which narrow at the upper part of the building, and a lens-like dome is located at the top, which is used as an observation deck. The nodes are used to intersect the structural elements and transform the load through other elements. The nodes include three steel plates at different angles (figure 40) (Küçük and Arslan, 2020). The outer body of the building permits the absence of any traditional load-bearing elements like columns in the interior.

Figure 40. Left ;Venus Basket Sponge Right; A structural node on the façade of 30st Mary Axe.(Source: Nkandu and Alibaba, 2018)

Table 14. The core sustainable design features of 30st Mary Axe with how it implemented.

Sustainable Features	**Design solution**
-Built Form Configuration	The shape of the tower minimizes the wind load.
-Energy Efficiency	The openable windows and twisted floor plans provide natural ventilation with the twisted floor plan.
-Double Skin Façade	The façade includes solar control blinds inside the cavity between the inner and outer skin of the building. It provides cooling and heating. Thus, the use of air conditioning is minimized.

These formal and structural features play an important role in achieving sustainability. Table 14 presents the sustainable features of the tower. The cucumber-like form of the building has a reduced footprint to increase public uses and provides natural ventilation and minimum wind turbulence. The spiral plan, which is twisted on upper floors, provides natural ventilation and allows wind to circulate through the building (figure 39) (Al-Kodmany, 2018). The building consists of double-skinned glass in the outer layer and a single glazed inner layer, including solar control blinds in the cavity between the inner and outer skin of the building. These gaps behave like a buffer zone to diminish mechanical cooling and heating. The curved form of the building is a result of the shift of 5 degrees of each floor from the next one continuously to the top-most level. Also, the rotated plans contain six shafts to take sunlight, ensuring friendly working spaces and minimizing light costs. The shafts pull warm air out of the building during the summer and warm the building in the winter using passive solar heating (M.Ibrahim and Aziz, 2018). Moreover, the tower has a core structure. The building includes a central core configuration with openings in north-south and cores on the east and west can achieve substantial savings for air-conditioning and create natural ventilation in both temperate and cold climatic zones (figure 41).

- ***Built form and configuration***

As mentioned in the previous section, the form of the building makes it environmentally friendly. The building produces natural ventilation with different air pressure levels through the external skeleton (M.Ibrahim and Aziz, 2018). The ventilation is provided firstly through a diagrid structure. The opening and closing qualities of a double-skin triangular glass façade are significant for air circulation. It contributes to indoor air quality, one of the objectives of designing a sustainable building. Also, the openings at the atria were designed to create ventilation inside. The air can spread around the interior with the help of 5 degrees rotation of the floor (figure 41) (Nkandu and Alibaba, 2018). The open shafts on each floor support airflow and ventilation inside the building and help air move up and down. During the summer, the shafts take warm air out and keep the interior of the building neither warm nor cold, while they use the sun to bring warm air through the building in winter (figure 42) (Singh and Nayyar, 2015).

The second feature of the building for providing ventilation is its aerodynamic form. The conical shape makes it possible to reduce using air conditioning and have an economically sustainable contribution. The unique ventilation systems are also achieved by the building shaped and 792 openable mechanical windows, which differentiate the external pressure of twisted winds (figure 43). All structural qualities decrease the need for heating and cooling energy, and the double-skinned façade has blinds which are computer controlled, programmed to change the tilt according to the temperature of the interior and exterior, providing 85% solar protection. The gaps on the façade that provide ventilation inside the buildings. Solar control blind- inside the cavity between the inner and outer skin of the building- and the gaps-between the inner and outer layer- behave like buffer zone to diminish mechanical cooling and heating (figure 42). If the external temperature is between 20 and 26 C° and the wind speed is lower than ten mph, the blinders will be opened (Küçük and Arslan, 2020).

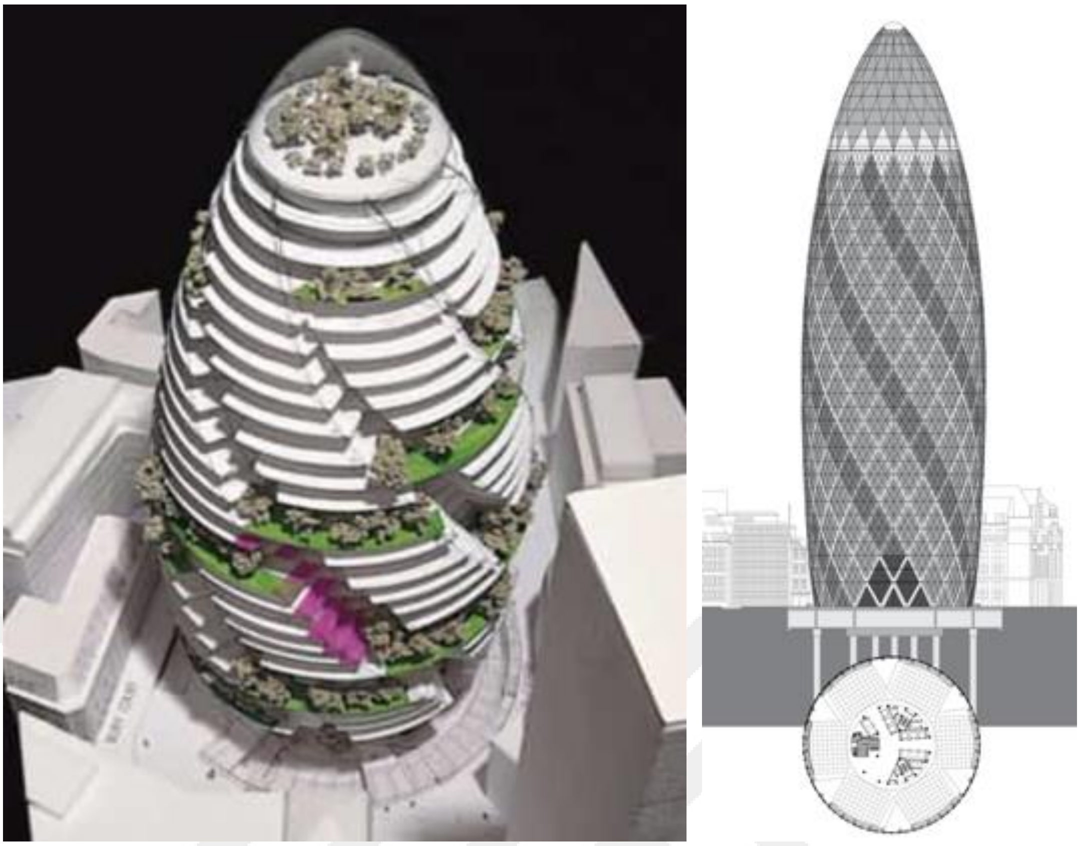


Figure 41. Left; Interior view of the twisted-floors. Right; 30st Mary Axe plan and elevation (Source: Archute, 2022)

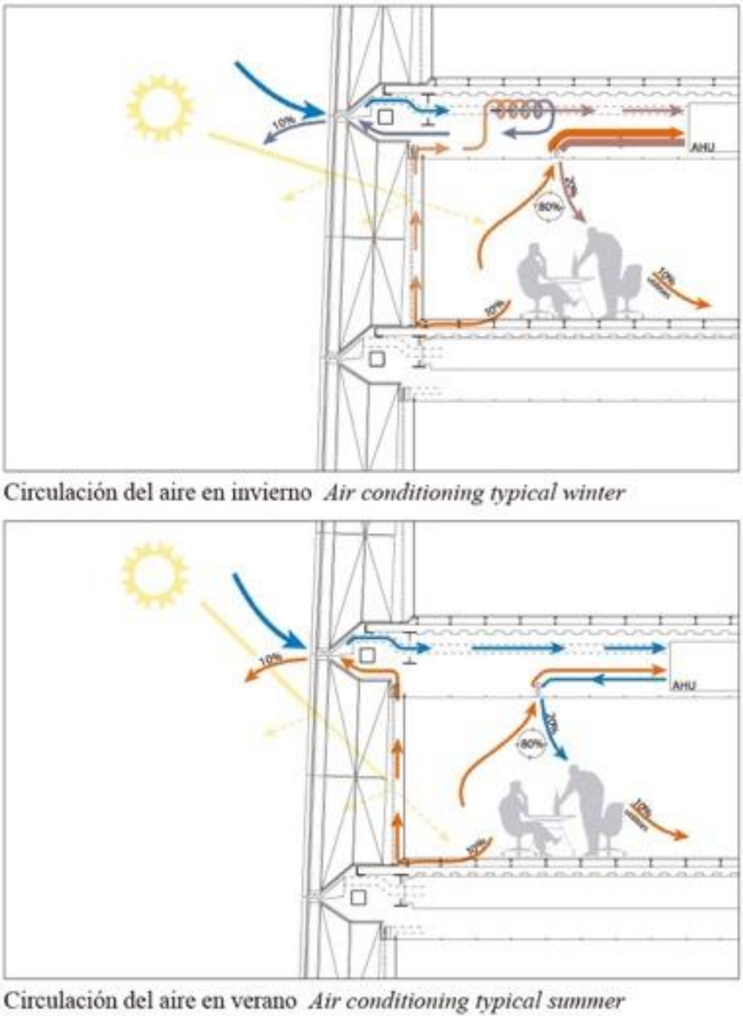


Figure 42. The double skin glass section of 30st Mary Axe (Source:Fernández-Galiano, 2013)

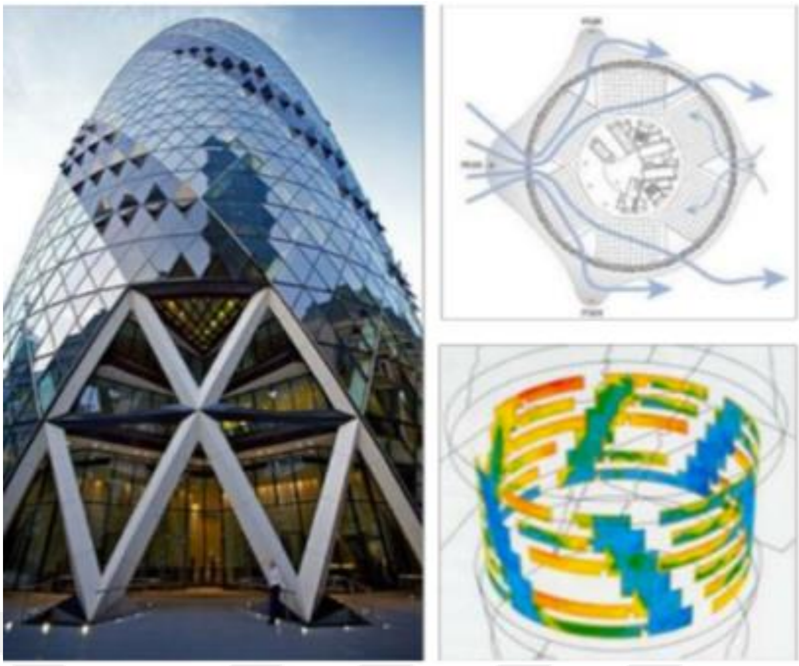


Figure 43. 30st Mary Axe ventilation strategies. Left: the blinds on the facades intercept solar energy by a 15% solar transmission rate. Right-top: the natural ventilation. Right-bottom: The wind flow. (Source: Küçük and Arslan, 2020)

- ***Energy Efficiency***

30 St, Mary Axe building uses 50% less energy than other traditional office buildings in the vicinity due to its structural and architectural form. The natural ventilation and the light shafts reduce the energy usually needed for office buildings. The airflow and wind circulation inside the buildings are controlled by the double-skin glass façade and the triangular gallery spaces on every six floors (M.Ibrahim and Aziz, 2018). The exterior design of the building provides 85% solar protection, which helps to control the heat and cooling system inside by reducing the use of air conditioning by half. Also, the building includes 23 elevators to provide vertical circulation for a maximum of 379 passengers simultaneously who can travel at a speed of six meters per second (Küçük and Arslan, 2020). Moreover, the cucumber shaped form reduces cladding with wind flow across the building and minimizes the total amount of wind compared with other high-rise buildings of similar shape and size (figure 44) (M. Ibrahim and Aziz, 2018). Last but not least, the circular plan provides optimum exposed surface to interior volume of each floor.

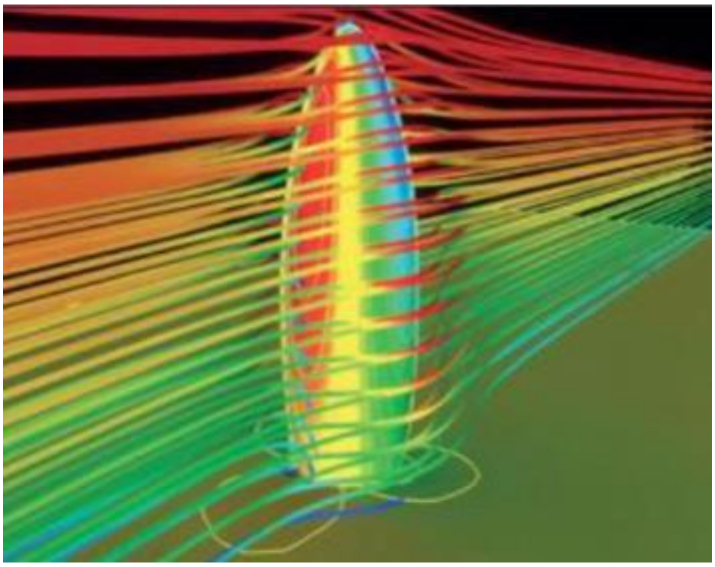


Figure 44. The wind flow around the Gherkin. (Source: Archute, 2022)

- ***Lighting***

The circular plan has six large shafts on each floor that provide sunlight, ensuring friendly working spaces and minimizing lighting costs (Giedrowicz, 2015). The Gherkin tower makes it possible to receive daylight from the top level to the whole building. The six triangle openings at floor plans and the five degreed rotation of floors create the light wells, which promote the distribution of light inside the buildings. These light wells create a brighter environment for the workers and assist their relaxation during the day (Küçük and Arslan, 2020).

5.4.2. Summary

The Swiss Re (30st Mary Axe) is designed with aerodynamic properties achieving a high-performance building form. The form of the building prevents the powerful winds from going through the surrounding buildings and street levels with a tapering profile from bottom to top. In addition, the tower's form provides natural ventilation, minimizes its footprint, and creates more space for public use. Thus, the tower got LEED Platinum certification by U.S. Green Building Council.

Moreover, the case 3 have a double core configuration which - Yeang (1999) defines- is stated as one of the design principles of sustainable HRBs. The openings on the facades and building's ore also create natural ventilation and airflow. The tower has a twisted spiral plan. The upper floor also helps to get natural ventilation and airflow inside the building openings on the floor plate. The double-skinned glazed façade acts as a human's third skin and helps the building breathe with solar control blinds inside the gap between inner and outer skins. These gaps and solar control blinds reduce the need for mechanical cooling and heating because they act as a buffer zone.

The 30st Mary Axe is designed to focus on achieving energy efficiency. The aim was to create natural ventilation with the buildings' openings, standard features, and twisted floor plans. However, it is not enough to be called a green HRB by only adapting a few criteria of sustainable HRB.

5.5. *Case 4 – Commerzbank (Frankfurt)*

Table 15. Commerzbank information

Commerzbank	Height	Primary function	Date	Gross floor Area	Location Climate	Certification
	259m	Office	1994-1997 Recladding in 2010	120, 000 m^2	Frankfurt Temperate	LEED

Figure 45. Commerzbank Tower in Frankfurt. (Source: Wigginton and Harris, 2002)

Commerzbank Tower is a commercial (office) tower built in 1997 in Frankfurt with a 259-meter height. It was a project designed by Foster and Partners after an international design competition (figure 45). The brief of the competition was to embrace environmental design and energy efficiency. The German building regulation require that office spaces must have visual contact with the outside world. This means in practice that the workspaces must be located less than six meters from the façades. For deep plan forms like Commerzbank, that means placing the workstation 12-14 meters away from the façade which is prohibited. Also, such placement causes problems for occupants in terms of accessing light and ventilation. Thus, designers decided to locate a ‘V-shaped’ plan around an atrium (figure 46), thus diminishing the plan depth and locating workstations near the façade or the atrium. This design strategy brings light and natural ventilation from the shafts for people with energy efficiency inside the building (Oldfield, 2019).

The structural way to achieve this design was to place columns, staircases, elevators, and utilities at the corners of the building. Moreover, the V-shaped plans are surrounded by four-story internal garden creating a view of greenery for occupants and, eliminates large, continuous office space. This design creates an ideal indoor quality for working spaces. The garden at the right of the plan serves as a place to relax and socialize in addition to bringing natural lights and green visuality (figure 46) (Pank, Girardet and Cox, 2002).

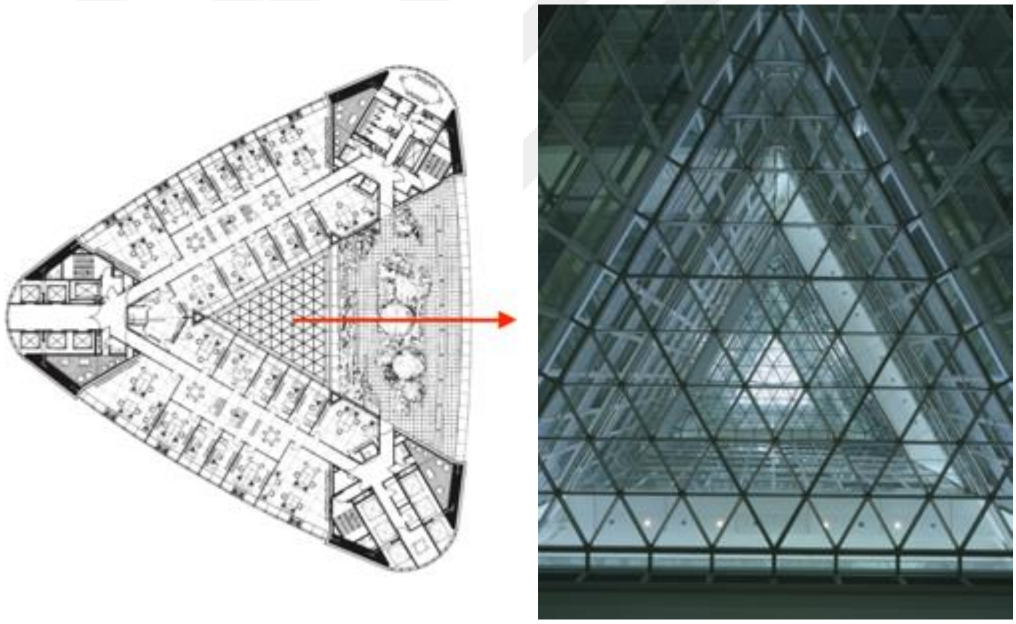


Figure 46. Left: Plan of Commerzbank - V shaped atrium and core. Right; The working spaces were located around the atrium which is covered with glass ceiling. (Source: Wigginton and Harris, 2002)

5.5.1. Sustainability strategies

The Commerzbank tower was planned to maximize energy efficiency through natural ventilation. To provide natural ventilation in high-rise buildings, the variable nature of wind speed at different heights must be controlled. Here, the architect uses the double-skin façade to control the wind speed and provide natural ventilation. Also, the tower provides mobility and connectivity by its location. It is close to public transportation stops which lessens the car caused environmental damage (the importance of location near the transportation was discussed in chapter 2.4.1 under the environmental effects of HRB.) Table 15 presents some of the sustainable features of the building that were covered in chapter 4.2 and the ways to achieve them. The building orientation is around 16 degrees through South-West with a triangle shape that provides maximum solar radiation as well as wind in all directions. The sky gardens are a great place to gain solar energy directly. Figure 48 and 49 represent that, the location of the sky gardens also helps air flow via the V-shaped atrium which works as a natural ventilation chimney, to take fresh air and light inside the working spaces.

Table 16. The core sustainable design features of Commerzbank and their implementation.

Sustainability Features	**Design solution**
-Building Form Configuration	The v shaped and central atrium provides negative pressure zone that comes by natural ventilation through the building.
-Glass Façade	Acts as buffer zone and provides minimum use of energy by creating natural ventilation inside the building.
-Water and Waste Management	The timber from the existing Forestry Stewardship Council was used in buildings. The water from chillers was recycled to use for flushing at WC.
-Energy Efficiency	Solar radiation by Sky Gardens and orientation of 16° through South-West. Natural ventilation by DSF and Sky Garden.

- ***Glass Façade***

Commerzbank is enclosed by a double-skin façade that minimizes the effects of the wind speed. The inner layer includes double-glazed windows, the outer layer includes fixed glass and the third later has the slot at the top of the window. It represents the air flow through the operable window. The air moves into the cavity between openable inner skin and fixed external skin by a slot (figure 47). The second skin of the façade acts as a shield like in Case 3 Mary Axe. The slots at the floor levels take air between the inner and outer skin of the façade and the openable windows at the inner skin take the air to the interior. These windows can be opened in any weather conditions windy or rainy thus, the building uses an air conditioning system only in extreme conditions. Also, the DSF helps to get daylight inside the building which increase indoor air conditions for people in workspaces. The tower has a central computer system to manage indoor quality in terms of ventilation and lighting.

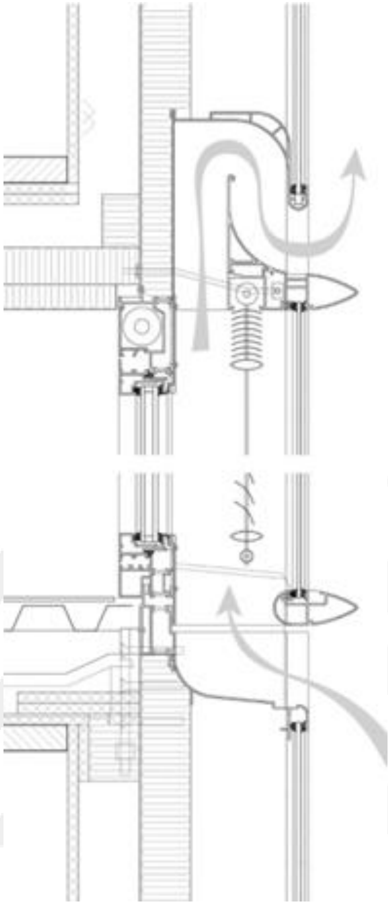


Figure 47. Three layered façade system detail of Commerzbank. (Source: Sev and Aslan, 2014)

- ***Sky-garden***

The structural system consists of Vierendeel trusses supported by vertical columns at the three corners of the plan. The trusses are removed at certain heights to provide three-story spaces for sky gardens. The sky gardens and the double-skin façades help to provide natural ventilation during certain seasons. It reduces energy usage by up to 50% compared with air-conditioned offices (Foster+Partners, 2022). The fresh air comes in through the top of the gardens at various levels, and then moves up through the central atrium. The cross ventilation from the gardens in all three directions enhances the indoor air quality (figure 48). The sky gardens act as solar collectors and thermal buffers. Also, the working spaces are naturally ventilated by the spacious sky gardens which were warmed by the underfloor heating (Lotfabadi, 2015). The garden takes natural day-light through the building and spread it to working place. The gardens are located at different levels and directions. Both façade system and gardens make the building to be naturally ventilated for approximately 60% of the year. Right represents the natural chimney (figure 49).

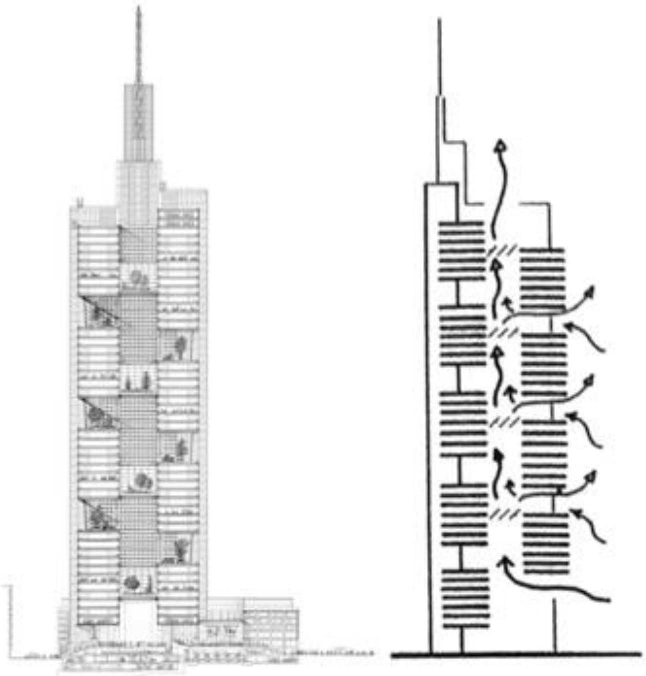


Figure 48. The section of Commerzbank presenting sky-lobbies and natural ventilation. (Source: Sev and Aslan, 2014)

Figure 49. Commerzbank sky garden and atrium acting as ventilation chimney. (Source: Lotfabadi, 2015)

5.5.2. Summary

The Commerzbank tower was built 25 years ago, being the first environmentally sustainable high-rise building in Europe. The tower uses green energy gained from renewable energy sources. It is naturally ventilated. Also, it uses recycled or reused materials such as timber (taken from the Forestry Stewardship Council) and an operational waste segregation facility. Thus, the tower had LEED Certification in 2017. Table 15 present that, the tower achieves sustainability with the top grade of energy & atmosphere (related to renewable energy and energy efficiency), a sustainable site (meeting the needs of alternative transportation), and water efficiency (by providing water performance measurements, water-efficient landscaping, and efficient plumbing fitting).

The building uses solar energy to reduce energy demands. Solar energy is affected by design features such as the form and orientation of the building, the size and the location of the windows, the shading conditions, and the ventilation conditions of buildings by sky-gardens. The triangular form and 16-degree orientation at South-West orientation provide gain maximum solar radiations and winds in all direction and more than 20% energy saving. The three-layered façade system creates around 25-30% energy savings (figure 46) (Sev and Aslan, 2014). Finally, the natural ventilation chimney (figure 48) provides cooling and ventilation through the heat of sun radiations and a solar chimney. Thus, around 45% energy saving is achieved. However, Lotfabadi (2015) states, the post-occupancy studies show that energy consumption of the tower is 20% less than the predicted amount due to natural ventilation and ,it continued to decrease every year since 2000. Designers are calculated that the occupants inside the buildings can get benefit from natural ventilation around 60% of the year, whereas, the building provide natural ventilation around 85% of the year.

Table 17. LEED Platinum O+M: Existing Building, 2017

1000066188, Frankfurt

Commerzbanktower Frankfurt am Main

LEED O+M: Existing Buildings (v2009) — **PLATINUM, AWARDED JUL 2017**

SUSTAINABLE SITES		AWARDED: 19 / 26
SSc1	LEED certified design and construction	0 / 4
SSc2	Building exterior and hardscape Mgmt plan	1 / 1
SSc3	Integrated pest Mgmt, erosion control, and landscape management ...	1 / 1
SSc4	Alternative commuting transportation	15 / 15
SSc5	Site development - protect or restore open habitat	0 / 1
SSc6	Stormwater quantity control	1 / 1
SSc7.1	Heat island effect - nonroof	1 / 1
SSc7.2	Heat island effect - roof	0 / 1
SSc8	Light pollution reduction	0 / 1

WATER EFFICIENCY		AWARDED: 13 / 14
WEp1	Minimum indoor plumbing fixture and fitting efficiency	REQUIRED
WEc1	Water performance measurement	2 / 2
WEc2	Additional indoor plumbing fixture and fitting efficiency	5 / 5
WEc3	Water efficient landscaping	5 / 5
WEc4	Cooling tower water Mgmt	1 / 2

ENERGY & ATMOSPHERE		AWARDED: 29 / 35
EAp1	Energy efficiency best Mgmt practices - planning, documentation ...	REQUIRED
EAp2	Minimum energy efficiency performance	REQUIRED
EAp3	Fundamental refrigerant Mgmt	REQUIRED
EAc1	Optimize energy efficiency performance	18 / 18
EAc2.1	Existing building commissioning - investigation and analysis	2 / 2
EAc2.2	Existing building commissioning - implementation	2 / 2
EAc2.3	Existing building commissioning - ongoing commissioning	0 / 2
EAc3.1	Performance measurement - building automation system	0 / 1
EAc3.2	Performance measurement - system-level metering	0 / 2
EAc4	On-site and off-site renewable energy	6 / 6
EAc5	Enhanced refrigerant Mgmt	0 / 1
EAc6	Emissions reduction reporting	1 / 1

MATERIAL & RESOURCES		AWARDED: 3 / 10
MRp1	Sustainable purchasing policy	REQUIRED
MRp2	Solid waste Mgmt policy	REQUIRED
MRc1	Sustainable purchasing - ongoing consumables	0 / 1
MRc2.1	Sustainable purchasing - electric-powered equipment	1 / 1
MRc2.2	Sustainable purchasing - furniture	0 / 1
MRc3	Sustainable purchasing - facility alterations and additions	0 / 1
MRc4	Sustainable purchasing - reduced mercury in lamps	0 / 1
MRc5	Sustainable purchasing - food	0 / 1
MRc6	Solid waste Mgmt - waste stream audit	0 / 1

MATERIAL & RESOURCES		CONTINUED
MRc7	Solid waste Mgmt - ongoing consumables	1 / 1
MRc8	Solid waste Mgmt - durable goods	1 / 1
MRc9	Solid waste Mgmt - facility alterations and additions	0 / 1

INDOOR ENVIRONMENTAL QUALITY		AWARDED: 10 / 15
EQp1	Minimum IAQ performance	REQUIRED
EQp2	Environmental Tobacco Smoke (ETS) control	REQUIRED
EQp3	Green cleaning policy	REQUIRED
EQc1.1	IAQ best Mgmt practices - IAQ mana...	1 / 1
EQc1.2	IAQ best Mgmt practices - outdoor air delivery mo...	0 / 1
EQc1.3	IAQ best Mgmt practices - increased ventilation	0 / 1
EQc1.4	IAQ best Mgmt practices - reduce particulates in ...	1 / 1
EQc1.5	IAQ best Mgmt practices - IAQ mana...	1 / 1
EQc2.1	Occupant comfort - occupant survey	0 / 1
EQc2.2	Controllability of systems - lighting	0 / 1
EQc2.3	Occupant comfort - thermal comfort monitoring	0 / 1
EQc2.4	Daylight and views	1 / 1
EQc3.1	Green cleaning - high performance green cleaning program	1 / 1
EQc3.2	Green cleaning - custodial effectiveness assessment	1 / 1
EQc3.3	Green cleaning - purchase of sustainable cleaning products and materia...	1 / 1
EQc3.4	Green cleaning - sustainable cleaning equipment	1 / 1
EQc3.5	Green cleaning - indoor chemical and pollutant source control	1 / 1
EQc3.6	Green cleaning - indoor integrated pest Mgmt	1 / 1

INNOVATION		AWARDED: 5 / 6
IOc1	Innovation in operations	1 / 1
IOc2	LEED Accredited Professional	1 / 1
IOc3	Documenting sustainable building cost impacts	1 / 1

REGIONAL PRIORITY CREDITS		AWARDED: 4 / 4
EAc1	Optimize energy efficiency performance	1 / 1
EAc3.2	Performance measurement - system-level metering	0 / 1
EAc4	On-site and off-site renewable energy	1 / 1
EQc3.1	Green cleaning - high performance green cleaning program	1 / 1
MRc6	Solid waste Mgmt - waste stream audit	0 / 1
WEc2	Additional indoor plumbing fixture and fitting efficiency	1 / 1

INTEGRATIVE PROCESS CREDITS		AWARDED: 0 / 2
IPpc89	Social equity within the community	REQUIRED
IPpc90	Social equity within the operations and maintenance staff	REQUIRED

TOTAL 83 / 110

40-49 Points	50-59 Points	60-79 Points	80+ Points
CERTIFIED	SILVER	GOLD	PLATINUM

5.6. *Case 5 – Shanghai Tower (Shanghai)*

Table 18. Shanghai Tower information

Shanghai Tower	Height	Primary function	Date	Gross floor Area	Location Climate	Certification
	632m	Mixed-use	2009 - 2015	576,000 m^2	Shanghai Sub-tropical	LEED China Tree Star

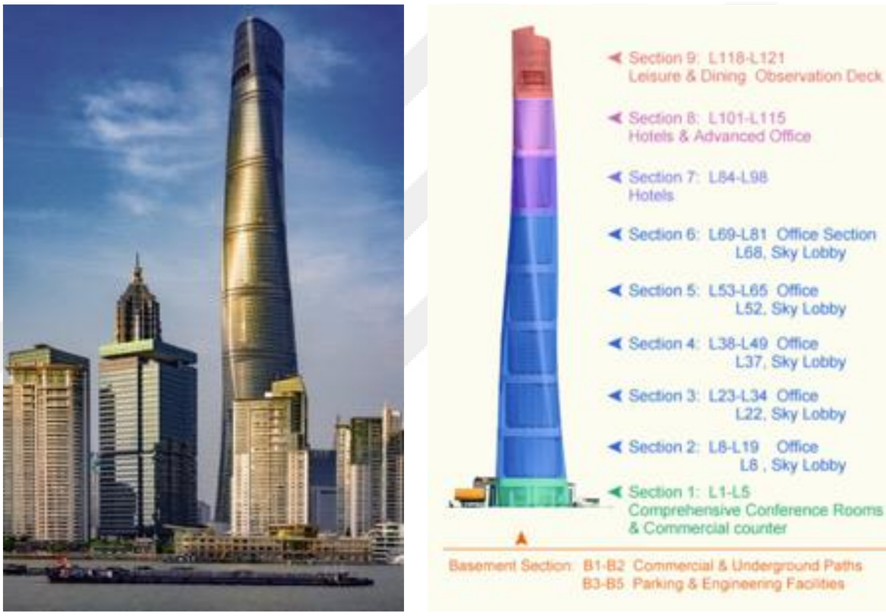


Figure 50. Left; View of Shanghai Tower in Shanghai, designed by Gensler. Right; the various functional sections of the building. (Source: left; Fotocommunity, 2018, right; TCT, 2022)

The Shanghai Tower (632m) was designed by Gensler. The construction started in 2009 and was completed in 2015. It was inspired by Shanghai's traditional old parks and neighborhoods. The twisted and curved façade represents the dynamic emergence of China. The tower has nine sections and each section includes its own 'sky-lobby' which is used as a hall for office floors and repeated every eleven floors until the function changes to represent the sense of community and daily life (figure 50) (Al-Kodmany, 2016). The upper floors are used as cultural venues and hotels including observation decks. The central floor is used for commercial purposes. The offices were located on the central floor, the six-story retail podium was used for shopping and dining near the ground floor and the base floor is used as an urban market (Parker and Wood, 2013).

5.6.1. Sustainability strategies

The tower was designed to achieve LEED certification and China Green Buildings Star. Architects focus on some environmental strategies to be an eco-iconic building (table 18). Firstly, the Shanghai tower uses a twisted form design to reduce wind loads. Gensler, -the architect of the Shanghai Tower- worked with structural engineer Thornton Tomasetti and wind engineers RWDI to develop the form of the tower. They conducted a series of wind tunnel tests with different building forms and twists ranging from 60° to 210° They came up with the optimal form which is a rounded corner twisted through 120°. This form decision decreases the wind loads by around 24% and structural materials by 32% (Oldfield, 2019). The saving of materials like 20.000 tons of steel decreases the CO2. Thus, the form of the tower saves 42,960 t CO2 through structural optimization. Secondly, the tower uses one of the renewable energy sources which is geothermal energy, which contributes to the energy needed for heating and cooling. Also, the tower includes Combined Cooling, Heat, and Power system (CCHP) with wind turbines (discussed below) (Parker and Wood, 2013).

Table 19. Sustainability features and applications of Shanghai Tower

Sustainable Features	**Design solution**
-Built From Configuration	The shape of the tower minimizes the wind load and possible effect that might come from the seaside. Also, it minimized the required structural steel by around 20.000 tons, thus reducing the CO_2 generating.
-Energy Efficiency	Wind turbines at the top of the building generate 54,000 kWh of electricity per year for the lighting of the building and of some of the adjacent park. Also, turbines produce 54,000kw/h per year. Cogeneration system creates electricity and energy for heating to the lower areas. Site generated system creates 640 tons of refrigeration at winter whether the weather is cold or hot.
-Double Skin Façade	Reduces the heat and cooling loads with inner and outer curtain walls. Fritted glass on the outer skin creates sun-shading by horizontal ledges at each floor to block summer sun.
-Water Management	Rainwater is collected via the building's spiraling parapet and is used for the tower's heating and air conditioning systems as well as flushing in the toilets.

- ***Energy Generating***

The tower includes three types of energy generating systems;

-Geothermal Energy -Ground Source Heat Pump System (GSHP) - Shanghai has a great climate to use geothermal energy because of its annually stable subsoil temperature which is around 18.8℃. The SGHP system of the tower decreases the heat emissions by reducing urban island effect. Also, geothermal energy uses the rainwater recycling system for wastewater management. It helps to reduce the energy need for conditioning the tower and greenhouse gas emissions (figure 51) (Chen and Li, 2022).

-Combined cooling, heat and power (CCHP) - the building has a CCHP system that works for 16 hours per day generating 11 million kWh per year (Lau, 2015).

-Wind Turbines - 270 horizontal wind turbines with 54 vertical axis wind turbines are located under the parapets, to generate power for the upper floors. They produce 157,500 kWh renewable energy covering 10% of the buildings' energy. The energy is used for common area lighting, elevators, air-conditioning and other power requirements (figure 52) (Hu, 2022).

Figure 51. Geothermal heat pump system. (Source: Chen and Li, 2022)

Figure 52. Wind Turbines of Shanghai Tower. (Source: left; Hu, 2022 right; The Architectural Review, 2015)

- ***Double-skin façade***

The tower has a circular core but it looks like it has a triangular plan layout (twisted around 120° through the height) from the outside. The floor plate of the tower has circular useable floor plan however; its external form is a rotating triangular prism. The void between the inner and outer skin of the façade is used for sky-lobbies. The number of elevators gives an idea of the electricity required for vertical transport (figure 53). The structure is covered with a double-skin façade - the inner layer is laminated glass while the outer layer is insulated glass. There is a green atrium where the gap of the double-skin façade has a large depth. Horizontal tubes were attached to the core structure to support the outer layer at a distance from the inner skin. The space between the two skins, allows air to move in and out without disturbing the inside. However, the atrium would not help to minimize "greenhouse" effect. Thus, there is minimal need for additional cooling and heating, which helps to reduce energy use in office spaces and the hotels (figure 54). This maximizes the natural airflow inside the building.

However, there is air conditioning because each atrium cannot be naturally ventilated by the height of the tower. That's why the air ventilation system must be split into different sections depending on the functions of the floors (Chen and Li, 2022). The atrium (sky-garden) inside the double-skin façade provides natural ventilation and energy saving similar to Commerzbank tower. They behave as a buffer zone by heating cool winter and distributing the accumulative summer heat inside the building.

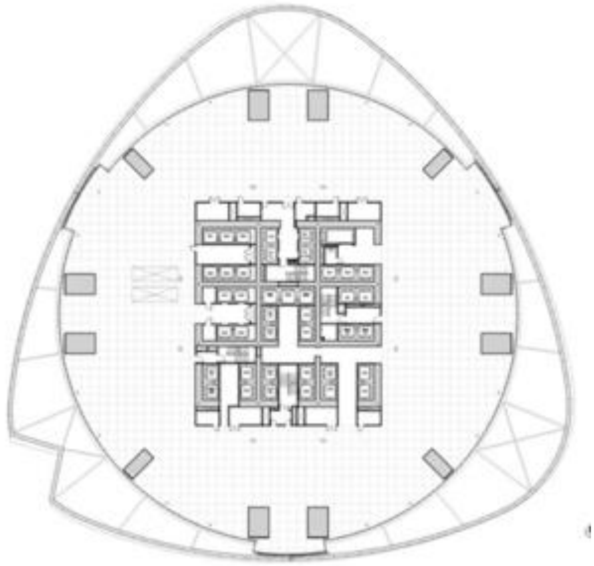


Figure 53. Floor plate of Shanghai Tower. (Source: The B1M, 2020)

Figure 54. Exterior curtain wall of Shanghai Tower (Curtain Wall A) and an interior curtain wall (Curtain Wall B)—with a tapering atrium in between. (Source: left; Gu, 2015 rigt; CTBUH)

5.6.2. Summary

Shanghai Tower has a carbon footprint about 34,000 metric tons of CO_2 equivalent per annum compared to more common buildings of similar size. Thus, the tower has received many certifications and awards. It has Leader in Energy and Environmental Design (LEED) Platinum and Gold certifications from the US Green Building Council for different aspects of the building. In September 2012, the tower was awarded the Certificate of Green Building Design, receiving a three-star rating in China.

The reduction of the building's carbon footprint by 34.000 metric tons per year is due to the applied sustainable strategies. The form includes multi strategies like asymmetry, tapering, round corners, and minimized floor plates as the tower rises. These strategies save 58 million dollars in building materials by reducing lateral loads by 24%. The transparent glass skin minimizes the energy needed for heating, cooling, and lighting. The tower reduces water consumption by around 38% through gray water recycling and rainwater harvesting. The rainwater is collected by a spiral parapet and used for heating and HVAC systems of the tower. The podium, basements, and shafts include water treatment plants to decrease the energy needed for pumping. The recycling of gray water and rainwater is used for the irrigation of plants and toilet flushing. The wind turbines at the top generate power for the upper floors while the natural gas-fired cogeneration system provides energy for the lower floors (Al-Kodmany, 2016).

However, Marshall Strabala – chief architect of Shanghai Tower indicates that, twisted and decreasing floor plan (figure 52) might be less efficient than square floor plan because of unadaptable spaces. However, Shanghai is a zone that might face with natural disasters like typhoon. Thus, the twisted floor plan minimizes the wind load by 24%. According to Gibson (2020), the useful floor area is about 50% of the total floor plan. Thus, residents are paying for large unusable floor spaces. Also, he indicates that the core and plan of Shanghai Tower makes building efficient in terms of office uses. Also, the floor plate and glassed façade minimizes the wind load. The major setback of the Shanghai tower is its low occupancy rate after it opened to use in 2016 which creates an economic failure. However, in 2018, the occupancy rate of the tower was over 70% (Gibson, 2020).

5.7. *Evaluation of Case Analyses*

This work aimed to assess the use of sustainability design features of high-rise buildings by two types of design priorities for sustainability that have to be balanced: (a) reducing the use of resources, and (b) providing better living environments. The environmental design perspectives of selected case studies were included in table 7 in chapter 4. The application of these design strategies can be different depending on the function and climatic conditions. Thus, table 20 has a separate column defining the function and climatic condition of selected case studies.

The use of green walls was only common in residential high-rise buildings design, yet we can see that the use of green areas in a high-rise building is not only attached to the exterior of the structure. Using inner gardens and sky lobbies in commercial and mixed-use high-rise buildings can create similar effects as green wall design. However, the use of energy-generating strategies was not covered in all case studies that are the main design priorities of sustainability in the research. Only case 1 and case 5 aimed to use energy-generating features for minimizing the use of resources. Since the energy needed for cooling and heating in commercial high-rise buildings is higher than residential high-rise buildings, the application of double skin façade is seen in cases 3, 4, and 5. The use of DSF is to provide airflow inside the building and heat control with openable windows and solar control blinds. Water management is another important design feature for sustainable high-rise architecture. Case 1 and 2 includes recycling greywater strategies due to the irrigation of plants on the façade. However, case 5 uses rainwater harvesting as water management by spiraling parapets at the top and is used for HVAC systems and heating via geothermal energy, and air conditioning systems.

On the other hand, the mass of the buildings is differed from each other based on their functions. Cases 1 and 2 were designed with two separate rectangular masses while the commercial and mixed-use towers are designed as single blocks with orientation and rounded surfaces. Natural ventilation was covered differently in each case except cases 1 and 2. Case 3 achieves minimum wind load with its shape and uses the twisted floor plan for both natural ventilation and indoor air quality, while case 4 uses a V-shaped configuration, a glass rooftop to get direct sunlight through the working spaces, and cross gardens to provide natural ventilation. Since case 5 is located in a typhoon zone, the tower is designed to have an optimal form -rounded and twisted at 120 degrees- for minimizing the wind load.

Based on the all information above, the function and climate are important key factors for designing environmentally sustainable HRBs as a manner of application. One Central Park is more successful in residential high-rise building examples because it produces its energy with renewable energy systems like photovoltaic and combined heat power. The commercial towers use similar strategies; double skin façade and double-core configuration to provide natural ventilation. The Shanghai tower includes the 4 of 5 sustainable features listed in table 20, only missing the green façade application. All case studies achieve the reduced use of resources somehow but the Bosco Verticale should cover more features such as generating its energy, having natural ventilation with a core design, or a double-skin façade system. It is designed for providing a good living environment mainly through vegetation, but not designed for reducing energy and material resources which is the major point of the quest for sustainability.

Table 20. The comparison of eco-iconic case studies - which sustainable features they include by author.

Case Studies	**1** 	**2** 	**3** 	**4** 	**5** 
Green Wall	façade supported	façade integrated			
Energy Generating	heliostats and combined heat power				wind tribunes, combined cooling, heat and power, geothermal energy
Double Skin Façade			includes solar control devices	triple layer façades include slots, openable window and sky garden	includes openable windows and sky lobbies
Water Management	graywater recycling	underground water			rainwater harvesting
Natural Ventilation			double skin façade, twisted floor plan, cucumber shape and double core design	double core design, V-shaped atrium and sky garden	sky-lobby/garden and orientation of 120 degree
Function / Climate	Residential Sub-tropical	Residential Sub-tropical	Commercial Temperate	Commercial Temperate	Mixed-use Sub-tropical

CHAPTER 6 : CONCLUSIONS

High-rise buildings are considered a solution to the needs of an increasing population. This thesis discusses the history of tall buildings and their developments over time in chapter 2, and surveys briefly the advantages and disadvantages of HRBs, including their environment-related design features for understanding the relationship between the environment and high-rise buildings. The advantages and disadvantages of high-rise buildings are clarified in Chapter 2.4. Tall buildings provide an opportunity to control urban sprawl by decreasing the building footprints and by increasing the occupancy of the available land. Also, back to the beginning of the International Style in the 1950s tall buildings were represented as a power symbol of cities. They increase the land values and make the city seem more powerful. Especially the multi-functional HRBs reduce travel time and minimize the transportation burden in the city. Also, their large volumes turn them into landmarks.

However, there are significant disadvantages, mainly from an environmental perspective. Higher buildings have a significant level of embodied energy and consume more energy during their operation and maintenance. They also require improvement of infrastructure and urban services. The height of clustered high-rise buildings creates wall effects that alter the natural ventilation in the surroundings. Moreover, the HRBs intensify the Urban Heat Island effect because of the disposal of a significant amount of Operational Energy. Overall, the disadvantages outweigh the advantages. In order to minimize the disadvantages of high-rise buildings, environmentally sustainable design features should be applied as much as possible, and adjusted to high-rise building requirements. A review of the term 'Sustainability' follows concerning architecture and the environmental performance certification systems in chapter 3. Chapter 4 outlined some sustainable design parameters for incorporating sustainable qualities into high-rise buildings, such as the building shape configuration, the building location and orientation, façade design, energy efficiency, material selection, and water management to minimize their environmental damage, which is the primary drawback of high-rise buildings.

Finally, selected five case studies were used to understand the degree of achieving the sustainable objectives described above. The location and form of the building, the renewable energy recourses for energy efficiency, double skin, and green façade are mostly applied in the case studies while the material selection was not a prime consideration. Based on table 20 in chapter 5 and the preceded research, it appears not possible to build HRBs with the current technology that offers a satisfactory level of sustainability. The sustainable strategies of the HRBs are shaped by the function and the climatic condition of the buildings. Using environment-friendly techniques like gray water recycling, rainwater harvesting, double skin façade, combined heat power, and geothermal energy helps to minimize environmental damage in general. However, the use of green façade and photovoltaic cells is good in design objectives but in practice, there might be different results. Thus, designing a completely sustainable HRBs seems not possible, but minimizing the environmental damages is possible as the paper aims to present.

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