TÉCNICO LISBOA

Sustainable High-rise Construction in Shanghai

Case study – Shanghai Tower

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Thesis to obtain the Master of Science Degree in

Civil Engineering

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In Memoriam

“Godfather” Conny van Rietschoten

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Resumo

De acordo com as estimativas e projeções de população das Nações Unidas, em 2050 a população urbana mundial irá aumentar significativamente e, estima que a população urbana Chinesa irá aumentar mais 292 milhões, esta estimativa terá um enorme impacto sobre a maior cidade da China – Shanghai. Shanghai é uma megacidade com uma população de mais de 24 milhões, devido à sua densa morfologia urbana e recursos terrestres limitados, construções em altura são suscetíveis a serem a primeira escolha para minimizar o impacto sobre o uso do solo.

Embora os edifícios proporcionem inúmeros benefícios à sociedade, os edifícios também são um dos principais consumidores de energia, bem como as principais fontes de poluição ambiental. A fim de dar um futuro melhor à próxima geração, deve-se começar a investir na construção sustentável que com base nas melhores práticas enfatizam a acessibilidade a longo prazo, qualidade e eficiência.

Esta dissertação tem como objetivo obter uma melhor compreensão de avaliação padrão para Edifícios Verdes na China e do respetivo sistema de avaliação – Green Building Evaluation Label (GBEL), também conhecido como “Three-Star”, por identificar regulamentos e orientações para construção sustentável em Shanghai, e comparar GBEL ao sistema de classificação americano LEED, que é reconhecido e utilizado na China.

Além disso, um caso de estudo será analisado, o segundo edifício mais alto do mundo, recentemente construído - Shanghai Tower. Não é o mais alto, mas é o mais alto arranha-céus sustentável dos dias de hoje. Shanghai Tower obteve o certificado LEED Gold e a classificação máxima de GBEL. Shanghai Tower incorpora inúmeros elementos de arquitetura verde e práticas sustentáveis, incluindo a fachada dupla de vidro, ar condicionado com armazenamento de gelo, sistema de tri-geração etc. Essas estratégias permitirão um melhor desempenho ao longo do ciclo de vida do edifício.

Palavras-chave: Shanghai; Construção sustentável; Edifício verde; Edifícios altos; Avaliação GBEL; Shanghai Tower.

Abstract

According to the United Nations population estimates and projections, by 2050 world´s urban population will increase significantly and, China is projected to add 292 million urban dwellers, this estimate will definitely affect the largest city of China – Shanghai. Shanghai is a mega-city with a population over 24 million people, due to its high dense urban morphology and limited land resources, high-rise buildings are likely the first choice to minimize the impact on land use.

Although buildings provided amount benefits to society, but they are one of the main consumers of energy, as well as the main sources of environmental pollution. In order to give a better future to next generation, must start investing in sustainable construction, based on best practices that emphasize long-term affordability, quality and efficiency.

This thesis aims to get a better understanding of Evaluation Standard for Green Building in China and the respective assessment system – Green Building Evaluation Label (GBEL), also known as "Three-Star", by identify regulations and orientations to sustainable construction in Shanghai, and comparing GBEL to American LEED rating system, which is recognized and commonly used in China.

In addition, a case study will be analysed, the recently built world´s second tallest building – Shanghai Tower. It is not the tallest, but it is the tallest sustainable high-rise building of nowadays. Shanghai Tower earned both LEED Gold certificate and the highest score of GBEL. Shanghai Tower incorporates numerous green architecture elements and sustainable practices, including double skin façade, ice storage air-conditioning, tri-generation system etc. These strategies will allow better performance over building´s life cycle.

Keywords: Shanghai; Sustainable construction; Green building; High-rise; GBEL assessment; Shanghai Tower.

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Acronyms and Abbreviations

Notation	Description
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
B	Basement Floor
BIM	Building Information Modelling
CAI	Chicago Architecture Info
CAPC	Chicago Architectural Photographing Company
CCAP	Centre for Clean Air Policy
CCHP	Combined Cooling, Heat and Power
CMF	Chinese Ministry of Finance
CSS	China Statistical Society
CSUS	Chinese Society for Urban Studies
CWSS	Curtain Wall Support System
CTBUH	Council on Tall Buildings and Urban Habitat
ECADI	East China Architectural Design & Research Institute
ESEC	The Encyclopedia of Shanghai Editorial Committee
ESGB	Evaluation Standard for Green Building
F	Floor
FCU	Fan Coil Unit
GAQSIQ	General Administration of Quality Supervision, Inspection and Quarantine
GBDL	Green Building Design Label
GBEL	Green Building Evaluation Label
GBL	Operational Green Building Label
GDP	Gross Domestic Product

GHG	Greenhouse Gas Emissions
GSHP	Ground Source Heat Pump
ICBEST	International Conference on Building Envelope Systems and Technologies
IISD	International Institute for Sustainable Development
IOSM	Information Office of Shanghai Municipality
JKEC	Shanghai Jianke Engineering Consulting
JKPM	Shanghai Jianke Project Management
K	Thermal Conductivity
LEED	Leadership in Energy & Environmental Design
MC	Ministry of Construction
MEP	Mechanical, Electrical, and Plumbing
MOHURD	Ministry of Housing and Urban-Rural Development
RMB	Renminbi (Chinese yuan, CNY) – the official currency of the People's Republic of China
SAR	Special Administrative Region
SC	Shading Coefficient
SM	The Skyscraper Museum
SMB	Shanghai Meteorological Bureau
SRIBS	Shanghai Research Institute of Building Science
SSB	Shanghai Statistics Bureau
ASME	The American Society of Mechanical Engineers
UN DESA	United Nations Department of Economic and Social affairs
UNICEF	United Nations International Children's Emergency Fund
UNPFA	United Nations Population Fund
USEIA	U.S. Energy Information Administration
USGBC	U.S. Green Building Council
VT	Visual Transmittance

1 Introduction

High-rise buildings emerged in the late nineteenth century in the United States of America. Today, these buildings are a worldwide architectural phenomenon. Especially in Asian countries, such as China, Korea, Japan, and Malaysia. The construction of high-rises is currently an inevitable trend in the development of large urban centres, particularly the so-called megacities, to accommodate the continued growth of the world population. According to the United Nations population estimates and projections, duo to world´s urban population increasing, by 2050, about 66% of world's population will live in urban areas. And China is projected to add 292 million urban dwellers by then (UN DESA, 2014), this estimate will definitely affect the megacity – Shanghai, posing immense challenges for developing building, infrastructure and social services for new citizens.

High-rises are likely the first choice to minimize the impact on land use in city centres. Although buildings provided countless benefits to society, but they are also one of the main consumers of energy, as well as the main sources of environmental pollution. Building construction consumes 40% of the raw stone, gravel and sand used globally each year, and 25% of the raw timber. Buildings also account for 40% of global energy, 25% of global water, and they emit approximately one-third of global greenhouse gas (GHG) emissions. Residential and commercial buildings consume approximately 60% of the world’s electricity (UNEP) (Shams, et al., 2011). Buildings also produce 40% of waste that going to landfills and 40% of air emissions (Davies, 2007). Unfortunately the planet cannot support the current level of energy and resource consumption associated with buildings.

In China, the statistics data from the Ministry of Housing and Urban-Rural Development (MOHURD) of the People’s Republic of China shows that: two billions square metres of new buildings are constructed every year in China and 80% of them are high energy consumption buildings, also 95% of the existing 40 billions square metres of domestic buildings are high energy consumption buildings (Wang, et al., 2014). In order to give a better future to next generation, must improve environment by decreasing standard building practices, which are guided by short-term economic considerations. And start investing sustainable construction that based on best practices which emphasize long-term affordability, quality and efficiency.

In the scope of this thesis, field survey was conducted with several visits in Shanghai Tower during the construction phase. This paper aims to identify building regulations and orientations to High-rise sustainable constructions in Shanghai and analyse sustainability of the recently built world´s second tallest building – Shanghai Tower, amount sustainable strategies were applied on this phenomenon tower, including double skin façade, ice storage air conditioning system, energy efficient elevator, tri-generation system etc. These strategies will allow better performance over building´s life cycle.

For this purpose the methodology used involve: 1) Brief presentation about Shanghai and introduce basic concepts of high-rise building. 2) The impact of building industry on environment. And identify carbon emission, energy consumption and other environmental issues worldwide and in China, especially in Shanghai. Then review the State-of-the-art: Green building policies and respective assessment systems applied in mainland China. 3) Case study analysis: Shanghai Tower, the second tallest in the world. Understand how the building design itself can contribute for material saving, and analyse other examples of sustainable practices incorporated in the building, which lead to energy efficiency, water saving and reduce the building's carbon footprint. 4) Discussion and conclusion.

Chapter 2 is divided into two subchapters. The first one, presents a brief background of the megacity Shanghai, highlighting the geographic context, climate, population, history, social and economic development and construction type that characterize the city. In the second part, is made an approach to the subject of high-rise buildings, describing some basic concepts of a high-rise, what conceptually makes them differ from the current buildings, its evolution worldwide and in China.

In Chapter 3, firstly, addresses the impact of construction industry on the environment worldwide and defining sustainable construction and namely some main contributes to sustainable tall buildings. Secondly, analyse the current energy consumption and carbon emission situation in China and a series of relevant policies formulated by Chinese government to improve their sustainable construction sector, including a Green Building rating system – Green Building Evaluation Label (GBEL), also known as "Three-Star" assessment system created by Chinese government. Analyse GBEL, and comparing it to America´s Leadership in Energy & Environmental Design (LEED), which is also commonly used in China.

Afterwards, a case study will be analysed in Chapter 4. Shanghai Tower, the second tallest building in the world. This structure is a new generation of skyscraper that have been designed with energy conservation and sustainability as its principal criteria. Shanghai Tower is considered as the most sustainable skyscraper nowadays, earned both LEED Gold certificate and highest score of Chinese Green Building Evaluation Label. This chapter contains Shanghai Tower´s location, structure details, architecture design concept based on wind tunnel testing, curtain wall design analysis, and other numerous sustainable strategies incorporated in the building, such as reusing water, energy efficient elevator, ice storage air-conditioning and the installation of a tri-generation system, etc. Green design and all the sustainable practices incorporated in the building made Shanghai tower a megatall high-performance building.

In chapter 5 discussion, mainly if the approach could achieve to thesis objectives, discuss strategies presented in the case study and their limitations.

Finally, the main conclusions will be addressed. The thesis will finish with bibliography and appendices.

2 Shanghai and High-rise building

2.1 Shanghai Context

2.1.1 Country

China, officially the People's Republic of China (PRC) located in East Asia, founded on October 1, 1949. The PRC is a single-party state governed by the Communist Party, with its seat of government in the capital city of Beijing. China is a multi-ethnic, multi-lingual country. There is 56 ethnic groups and more than 80 languages and local dialects, the official language of the PRC is Mandarin (CSS, 2013).

China is the world's second largest country by land area and its total area (land and water area) is approximately 9.6 million square kilometres. China's coastline along the Pacific Ocean is 14,500 kilometres long, and is bounded by the Bohai, Yellow, East and South China Seas (CSS, 2013). There are 23 provinces, 5 autonomous regions, 4 direct-controlled municipalities (Beijing, Tianjin, Shanghai and Chongqing) and two special administrative regions (Hong Kong and Macau).

2.1.2 Geographic Context

Shanghai, which means the "Upon the Sea", is one of four municipalities directly under the Central Government. Shanghai is undoubtedly the largest city in China. Nicknamed the “Oriental Pearl”, Shanghai serves as the economic, financial, trade and shipping centre of China.

Figure 2.1 - Map of China (Fudan, 2010)

Shanghai is situated on the Yangtze River Delta (Chang Jiang) in East China, is located at 120°51’~122°12’ East and 30°40’~31°53’ North (ESEC, 2010). The municipality sits at the mouth of the Yangtze in the middle portion of the Chinese coast providing it great maritime trade potential.

Shanghai borders the provinces of Jiangsu and Zhejiang to the north, south and west, and is bounded to the east by the East China Sea, can be seen in Figure 2.1.

In 1949, Shanghai's land area was only 636 square kilometres. Today, Shanghai is about 120 kilometres long from south to north, and about 100 kilometres wide from west to east. With a total area of 8,239 square kilometres, Shanghai has 6,241 square kilometres of land, and 1,998 square kilometres non-terrestrial waters and tidal flats, etc. Of the mainland, the urban area occupies about 289 square kilometres, and suburban and countryside about 5,952 square kilometres (ESEC, 2010).

According to ESEC (2010) the altitude of the city lies between three and five metres. With comparatively soft and loose earth, the city has a slightly higher coastal area in the east and a lower hinterland to the west.

The Yangtze Delta region is a compound alluvial plain, the accumulation of sediment soil laid down by rivers during long ages. There are a few isolated hills, but for the most part, the land in this region is flat. The lower reaches of the Yangtze River running through the city bring lots of mud and sand to its estuary (Shanghai, 2014).

Shanghai is known for its rich water resources, with the water area accounting for 11% of its total territory (Shanghai, 2014). Most of the rivers are tributaries of the Huangpu River. The water network inside the city is the densest and the most developed in China. A lot of rivers and lakes in the city provide sufficient water to facilitate the transportation and irrigation. And its coastal area abounds in resources of fish and salt.

However other natural resources are not abundant in the region. Shanghai also lacks mineral resources and energy sources. Only crude oil and natural gas are found in the offing of East China Sea and south Yellow Sea nearby (Shanghai, 2014).

Shanghai has no conventional energy reserves such as coal, petroleum or waterpower. It has to rely on energies imported from other provinces. But Shanghai turns out a certain amount of high-quality second-energy products, including electric power, oil products, coal and gas (including liquefied petroleum gas). Potential energy resources to be tapped include methane, wind power, tidal power and solar energy.

2.1.3 Weather and Climate

Shanghai's climate is influenced alternately by cold dry air from inner Asia and Siberia from the north and north-west, and by warm moist air from the Pacific Ocean from the south and south-east.

This city experiences a subtropical maritime monsoon climate and so the weather is generally mild and fairly moist and experiences four distinct seasons: a warm spring, hot summer, cool autumn and cold winter. The city gets a moderate level of rainfall throughout the year, and relatively high humidity.

According to Shanghai Meteorological Bureau (SMB), annual average temperature is 17.6ºC. The summers are subtropical, July and August are the two hottest months (see Figure 2.2). During this period temperatures frequently rise to 38 degrees Celsius for prolong periods of time, the highest temperature in 2013 was 39.9 degrees Celsius (see Table 2.1). Contrary winters are cold, especially in late January to early February winter (usually during the Spring Festival) is the coldest period in Shanghai (see Figure 2.2), but the temperatures seldom drop to below zero, hence Shanghai is the only port city that is free from ice at all seasons among all ports in northern half of China.

Although Shanghai is frequently hit by typhoons and rainstorms during the rainy season but they rarely cause much damage to the city.

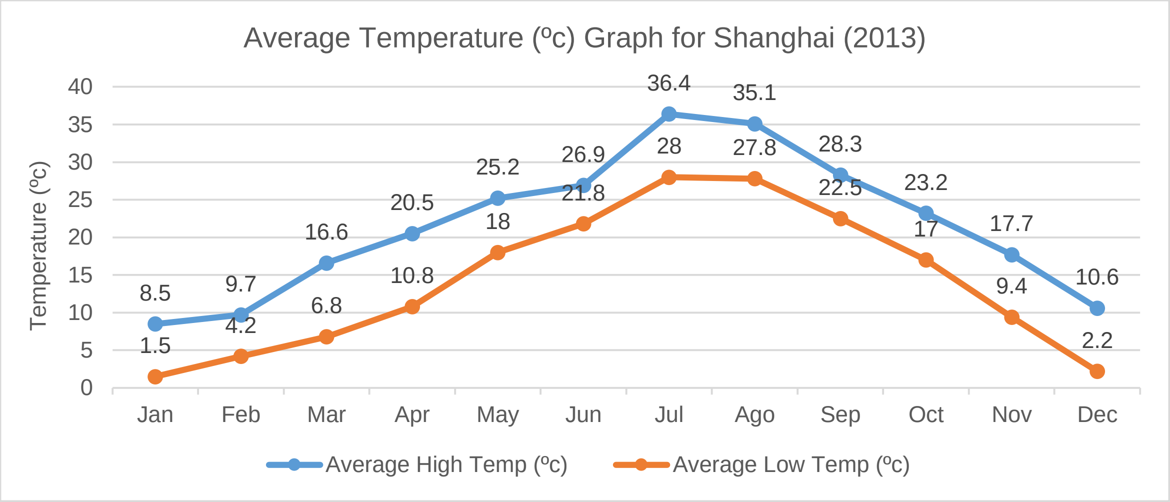

Figure 2.2 - Average Temperature (ºc) Graph for Shanghai (SSB, 2014)

Table 2.1 - Highest and lowest air temperature in 2013 (SSB, 2014)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Highest air temperature (ºC)	18	17.8	30.9	32.3	31.3	36.6	39	39.9	35	28.7	27.8	19.7
Lowest air temperature (ºC)	-3.1	-2.3	0.1	3.2	9.4	15.8	23.7	24.2	16	8.9	-1.7	-4.2

Figure 2.3 indicates annual precipitation in 2013 was 1,173.4 mm and it was 111 rainy days. More than 60% of the annual rainfall concentrated in the flood season from May to September. June produces the highest level of rainfall.

As for annual sunshine time, the average over the year 2013 was 1,885.9 hours, Figure 2.4 shows the monthly sunshine hours in Shanghai. The highest temperature is in July and August, as well as hours of sunlight, normally 7 to 8 hours per day.

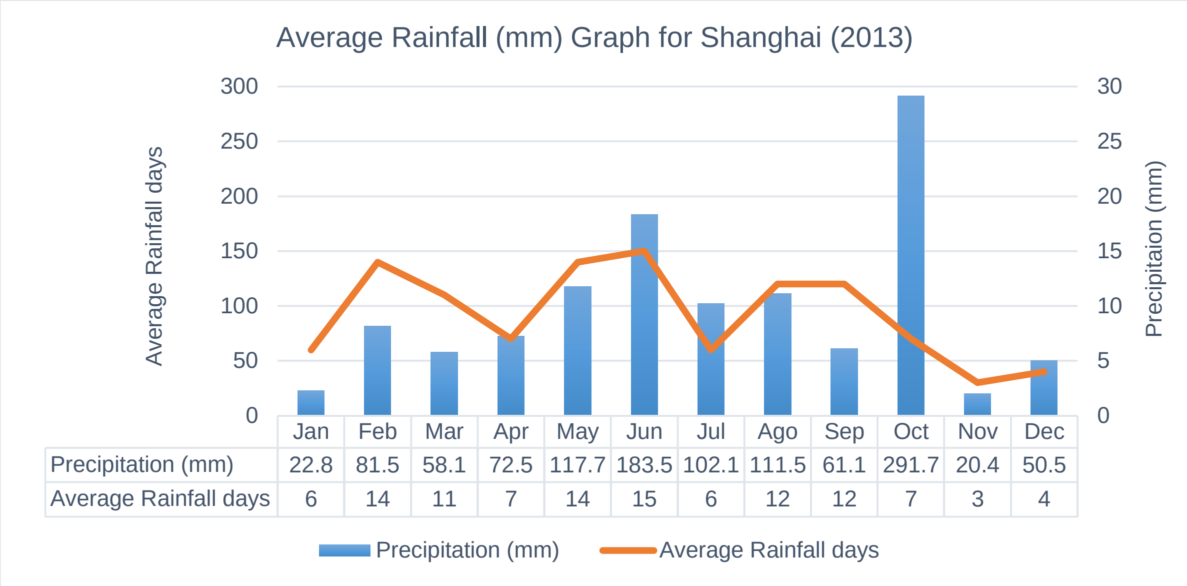

Figure 2.3 - Average Rainfall (mm) Graph for Shanghai (SSB, 2014)

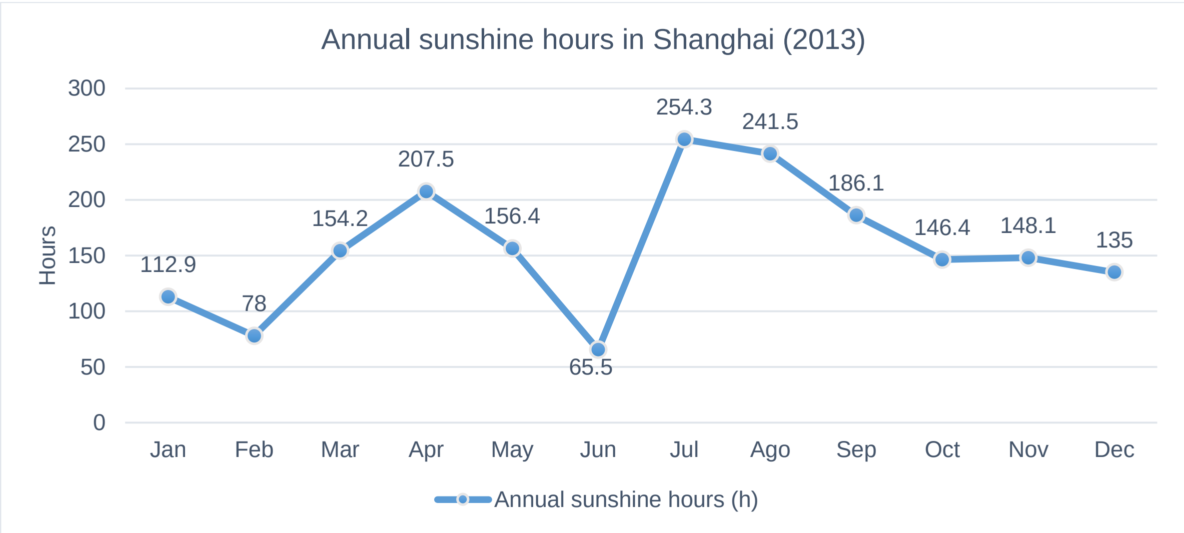

Figure 2.4 - Average monthly sun-hours in Shanghai (SSB, 2014)

2.1.4 History

The name "Shanghai" actually came during the Song Dynasty (960-1279), when Shanghai became a new rising trade port. The mother river Huangpu River, which runs through Shanghai and empties into the Yangtze River, has 18 creeks and one of the creeks was called "Shanghai Creek" -- near the Bund, thus the town nearby was called Shanghai Town. Later this whole area is named "Shanghai". By the Ming Dynasty (1368-1644), Shanghai became China's largest textile centre and business was developing fast (Cultural link, 2011).

The geographical location of Shanghai, combined with its navigable inland water-ways network, at the time was the first foreign treaties with China. Given to the Chinese town, an outstanding position in the coastal, inland, as well as overseas trades. After the Opium War in 1843, the British named Shanghai a treaty port, opening the city to foreign involvement. Shanghai was soon turned into a city that carved up to autonomous concessions administered concurrently by the British, French, and Americans, all independent of Chinese law. Till 1863 the American Concession officially joined the British Settlement to become the Shanghai International Settlement (see Figure 2.5 and Figure 2.6). The French Concession remained independent and the Chinese retained control over the original walled city and the area surrounding the foreign enclaves. Each colonial presence brought with it its particular culture, architecture, and society.

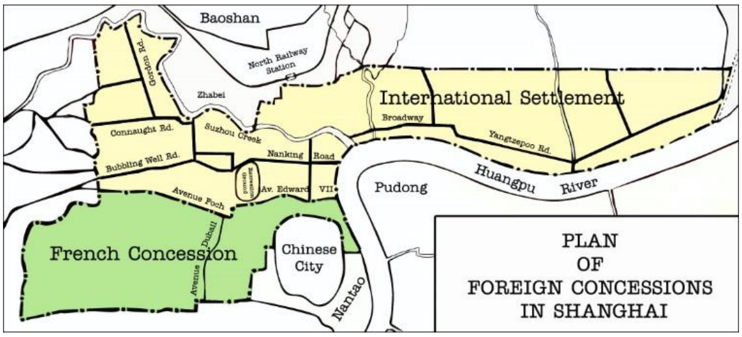

Figure 2.5 - Foreign Concessions in Shanghai (White China, 1920)

Figure 2.6 - Nanjing Road, Shanghai, within the International Settlement (Unknown, before 1946)

Although Shanghai had its own walled Chinese city, many native residents still chose to live in the foreign settlements. This city attracted not only foreign business people, but also Chinese migrants from other parts of the country. Thereby began a mixing of cultures that shaped Shanghai's openness to Western influence. Shanghai became an important industrial centre and trading port and the largest base of imperialist aggression in China. Shanghai even got a nick named as "Paris of the East".

In the past 30 years, Shanghai has achieved an incredible rapid and sustained economic, industrial, and population growth. While it has long been a large and important seaport, it wasn't until the 1990s that urbanization and expansion really exploded in Shanghai, turning it into a modern mecca.

Nowadays, Shanghai, the megacity on the eastern coast of China, the largest commercial and financial centre in China. This municipality is an important hub of communications with an easy access to the outside world by all means of transport: ocean, offshore and inland water shipping, highway and railroad transport, air flights etc. Via the Yangtze River and the Huhang (Shanghai to Hangzhou) and Jingguang (Beijing to Shanghai) Railways, it becomes the communication hinge connecting all parts of China. As the biggest seaport in China as well as one of the ten largest seaports in China, the port of Shanghai has trade links with ports of over 100 countries and regions. It also has over 40 inland and international airlines, connecting it with inland big cities as well as international cities like Dubai, Tokyo, Paris, London, Frankfurt, Sydney and New York.

2.1.5 Population and Urban Development

Shanghai's complexity came not from the foreign presence alone. Its rapid growth meant that even its Chinese population made it a city of immigrants. The political disturbances in neighbouring provinces since 1853 had caused a great influx of Chinese into Shanghai to seek life protection available in the International Settlements and the French Concession. Between 1855 and 1865, the initial stage of open trade, the population of the International Settlement and French concession had gained about 110,000 people.

Presently, Shanghai became the most populous city in China (see Table 2.2) with 16 districts and 1 county can be seen in Figure 2.7 (CSS, 2013) (Shanghai, 2014). As the population continues with a tendency to migrate to the big cities, which led to a dramatic urban dwell growth. Shanghai Statistical Bureau (SSB, 2014) shows the latest official estimate for the population of Shanghai in the end of 2013 was 24.15 million. This number is 4.6 times more than what the population was in 1949 (5.2 million).

Table 2.2 - Statistics on City Construction by Municipalities (2012) (CSS, 2013)

Municipalities	Urban area (sq.km)	Used for Urban Construction (sq.km)	Urban Population Density (persons/sq.km)
Beijing	12187.0	1445.0	1464
Tianjin	2334.5	722.1	2782
Shanghai	6340.5	2904.3	3754
Chongqing	6105.7	859.5	1832

Figure 2.7 - Municipality of Shanghai (Joowwww, 2008)

China is known for its enormous number of inhabitants, unfortunately the land resources are relatively scarce for high dense population, especially in the cities. Blindly expand the scale of the cities is not sufficient to fully solve the city's population pressure. On the other hand, urban sprawl may cause the reduction of arable land, forests and other resources, this will make China even more vulnerable to ecological environment.

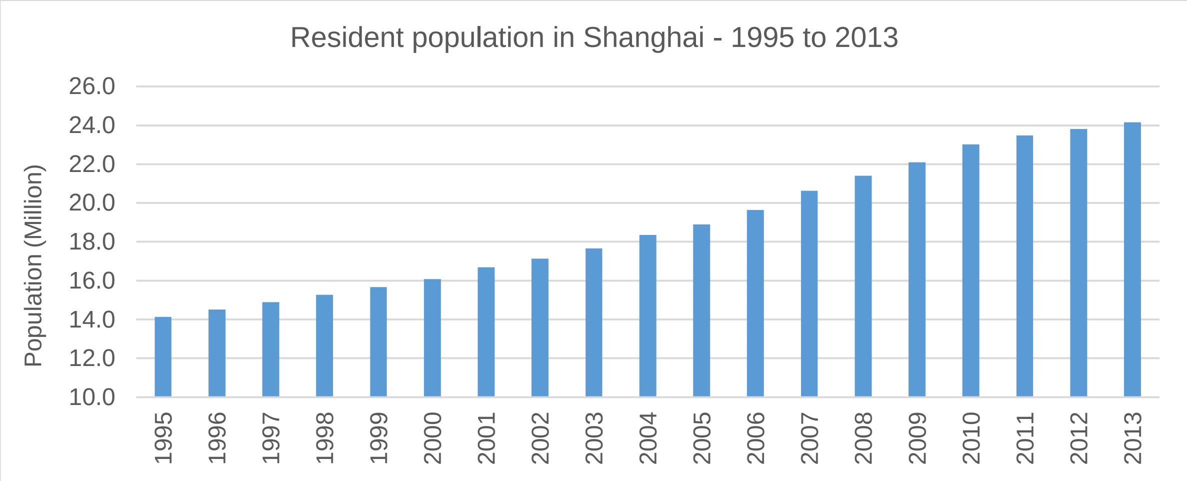

Figure 2.8 - Resident population in Shanghai – 1995 to 2005 (SSB, 2014)

As shown in Figure 2.8, the number of urban dwells in Shanghai since 1995. Just in two decades, the city's population increased 10 million and infrastructure has grown accordingly. So far the population continues to grow, thereby the city becomes denser and denser. As to the demand for housing increases every year. What is the answer for a city with intense demand for housing in property hot spots and at the same time, shortage of affordable land? This question leads to a need for buildings that rise rather than spread, build taller buildings to meet the needs of businesses and residents. For instance, Jin Mao Tower in Shanghai achieved access of nearly 200,000 square metres floor area on a less than 300 square metres land. Development of high-rise buildings in medium and big cities in China is a trend, but more importantly it is also a necessity.

Shanghai has focused on vertical urbanism since early 1990s. When someone refers Shanghai, the first thing comes to their mind is a modern city with amount of high-rise and skyscraper. Is very obvious these high-rise buildings are already an image of this city.

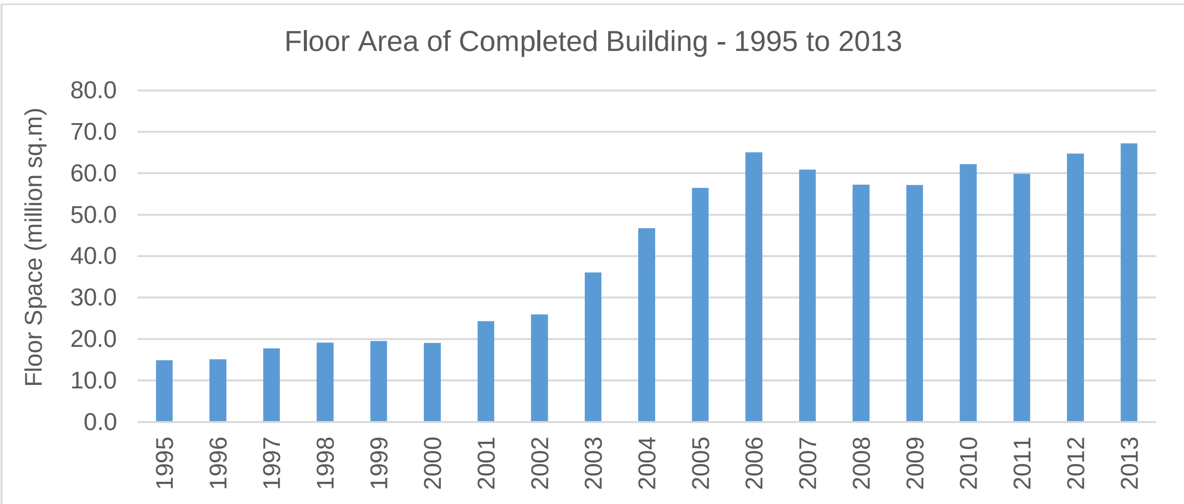

Figure 2.9 - Floor area of completed building – 1995 to 2005 (SSB, 2014)

SSB (2014) represents the floor area of completed building in Shanghai of each year, from 1995 to 2013, as shown in Figure 2.9. Since 2005, the city has built at least 56.5 million square metres floor area each year. This means more and more high-rises like Jin Mao Tower have arose in Shanghai.

2.1.6 Social and Economic Development

According to Yan Jun, chief economist of the Shanghai Municipal Statistics Bureau, the employment situation remained stable. Shanghai created more than 600,000 jobs in 2013, including 111,500 non-agricultural jobs for rural labourers. The registered urban unemployment rate was 4.2% of 24.15 million of resident population, can be seen in Table 2.3.

Table 2.3 - Population and Employment (SSB, 2014)

Population	**1990**	**2000**	**2010**	**2012**	**2013**
Resident Population (million persons)	13.34	16.09	23.03	23.80	24.15
Employment					
Staff and Workers (million persons)	5.08	3.90	6.48	9.44	10.15
Registered Unemployment Rate in Urban Areas (%)	1.5	3.5	4.2	4.2	4.2

In 2013 GDP of the city grew by 7% from the previous year to 2.16 trillion RMB (see Table 2.4), ranking first among all the cities on the mainland China. And per capita GDP of Shanghai was close to 90,092 RMB. Which was really good for Shanghai, considering the grim and complicated global economic situation and the city's daunting task for industrial transformation. For instance, 68.4% of Shanghai's GDP of 2013 came from added value of the tertiary industries. Finance and insurance, retail and distribution and real estate contributed about half of the growth in the tertiary sector.

Table 2.4 - Macro Economy (SSB, 2014)

Domestic Economic Accounts	**1990**	**2000**	**2010**	**2012**	**2013**
Gross Domestic Product (100 million yuan)	781.66	4771.17	17165.98	20181.72	21602.12
Primary Industry	34.24	76.68	114.15	127.80	129.28
Secondary Industry	505.70	2207.63	7218.32	7854.77	8 027.77
Tertiary Industry	241.82	2486.86	9833.51	12199.15	13445.07
Per Capita Gross Domestic Product (yuan) (Calculated by Resident Population)	5911	30047	76074	85373	90092
Contribution Rate of Economic Growth (%)					
Primary Industry	2.5	0.6	- 0.4	-	- 0.2
Secondary Industry	62.6	55.7	69.2	17.3	31.8
Tertiary Industry	37.2	43.7	31.2	82.7	68.4

The urban infrastructure construction investment of 2013 was 104.331 billion RMB, it has increased 0.5% over the previous year. Among them, the transportation and telecommunications investment was

55.042 billion RMB; municipal construction investment was 33.497 billion RMB; utilities invest was 4.757 billion yuan. Further the city's highway length has achieved 815 kilometres.

Yan Jun (2014) said “Total investment in real estate development in Shanghai reached 281.96 billion RMB in 2013, 18.4% more than in 2012. New homes sold in 2013 totalled 23.82 million square metres, 25.5% more than in 2012. Shanghai is following the central government policy to control runaway home prices. Last year it renovated 110,000 state-owned houses, built 104,000 affordable apartments, constructed public facilities for 40 new residential communities, and demolished 746,000 square metres of rundown houses.”

In Yan Jun´s opinion the surge in home prices has three factors. First, the shortage of land which drove up land prices by 27% in 2013. Second, the ever-growing population and influx of migrants fuelled demand for housing. Third, the new round of price hikes started from a relatively lower base as a result of market control in 2012. (IOSM, 2014)

2.1.7 Construction Types

Modern Shanghai is very much the product of the Western invasion of China in the nineteenth century. Due to its profound history background, Shanghai is rich with many different architectural styles. The Bund features a strip of European-style buildings (see Figure 2.10 and Figure 2.11), and the city shows the clear influence of British, American, German, French and Italian architecture. The city also has some buildings in Japanese and Islamic styles. Many imported styles are modified or incorporated with traditional Chinese design, though traditional Chinese architecture also survives independently. Shanghai is a multicultural city, with Structures range from unique Shikumen, Buddhist temple, Chinese pagoda, French Concession building, Roman church to modern high-rise.

Figure 2.10 - The Bund at night (Tickle, 2005)

Figure 2.11 - The Bund

Shikumen

Shikumen, translated as “stone gate” (see Figure 2.12, Figure 2.13 and Figure 2.14), is a style of housing unique to Shanghai that blends Chinese and Western structural styles. It´s named due to the stone door frame. Shikumen houses are two or three-story townhouses, with the front yard protected by a high brick wall. The entrance to each alley is usually surmounted by a stylistic stone arch. The influences could be found in everything from intricate carvings in wooden doors, stone archways to door steps (Tay, 2010).

Figure 2.12 – Shikumen stone gate (Etripchina, 2012)

Figure 2.13 -Museum of the First National Congress of the Chinese Communist Party (Pyzhou, 2004)

Figure 2.14 - First National Congress of the Chinese Communist Party alley (Mclarenshen, 2006)

Buddhist temple and Chinese pagoda

Most Chinese people are Buddhists, thus Buddhist temple and pagoda are part of traditional Chinese architecture. The Buddhist temple was adapted to Chinese architecture when it arrived in China. Generally, follows the imperial style. A large Buddhist monastery normally has a front hall, housing the statue of a Bodhisattva, followed by a great hall, housing the statues of the Buddhas. Accommodations for the monks and the nuns are located at the two sides. Sometimes Buddhist monasteries also have pagodas. Pagodas can be made of stone, wood, coloured glaze or metal. Most seen are seven-layer or nine-layer pagodas. The older ones tend to be four-sided, while later pagodas usually have eight sides or even circular.

Longhua Temple (see Figure 2.15 and Figure 2.16) is the oldest temple in Shanghai for its long history of over 1700 years. Because of the several destructions by the wars, later was reconstructed.

Figure 2.15 - Longhua Temple (Cultural China, 2005)

Figure 2.16 - Longhua Temple and Pagoda (Shanghai Residencial, 2014)

French Concession building

Due to the old French Concession, is common to find houses and buildings influenced by French architecture on Shanghai streets, especially at Xuhui district and former Luwan district. The Shikumen which was referred before is one of Shanghainese architecture influenced by the French. For much of the 20th century, the area covered by the former French Concession remained the premier residential and retail district of Shanghai. The figures below show some examples of former French Concession buildings that remained

Figure 2.17 - A house in the former French Concession (Unknown, 2004)

Figure 2.18 - French concession building (Unknown, 2005)

Figure 2.19 - Normandie Apartment (Wang, 2013)

Roman church

Located in one of the city's most prosperous commercial centres, the first Western church in China, the St Ignatius Cathedral or the Xujiahui Cathedral (see Figure 2.20 and Figure 2.21) has been standing for more than a century. It is now the headquarters for the Shanghai Catholic diocese. The Gothic-style cathedral was designed by English architect William Doyle, and erected in 1910 by French Jesuit missionaries (Liu, 2012).

Figure 2.20 - The Gothic-style Xujiahui Cathedral (Schneider, et al., 2013)

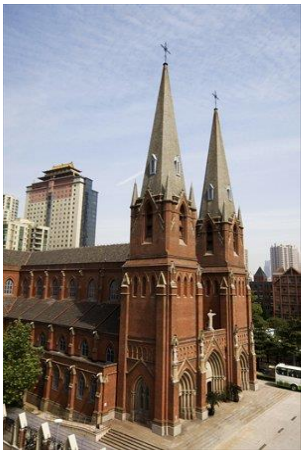

Figure 2.21 - St Ignatius Cathedral (CFP, 2012)

Modern High-rise

Although Shanghai has many different architectural styles, but thanks to the new constructions materials and technologies, made possible to go higher and higher. Modern Shanghai has countless high-rises and skyscrapers (see Figure 2.22). These are normally slender structures with steel frame, a majority of commercial high-rises in Shanghai has glass façade. The following subchapter describes some of the concepts of this kind of construction.

Figure 2.22 - Pudong Shanghai (Unknown, 2014)

2.2 High-rise Building

2.2.1 Defining and Measuring of High-rise

High-rise building, also called high-rise, multistore building tall enough to require the use of a system of mechanical vertical transportation (see Figure 2.23) such as elevators. (Encyclopaedia Britannica, 2013). In some country high-rise can be considered as a multi-story structure above 60 metres tall, or a building of unknown height with more than 20 floors. In other countries the definition could be a little different, classify a structure above 100 metres as tall building.

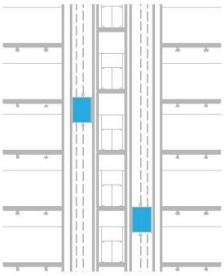

Figure 2.23- Vertical transportation (CTBUH, 2014)

Figure 2.24 - Height Relative to Context (CTBUH, 2014)

However, the high-rise concept is really defined with respect to the height of the surrounding buildings, the context in which it exists. If the majority of the buildings in a city are 3 or 4 stories, then a 12-floor building would be considered tall (see Figure 2.24). If this same 12-floor building locates in cities such as New York, Hongkong or Shanghai, that structure will no longer be considered as high-rise.

According to China's "Civil Design Principles" GB50352-2005: building height which exceeds 100 metres, regardless of residential and public buildings are considered high-rise buildings. Therefore this definition will be used in this dissertation.

Note the number of floors is a poor indicator of defining a high-rise due to the changing floor to floor height between differing buildings and functions (e.g., office versus residential usage).

The term *skyscraper* originally applied to buildings of 10 to 20 stories, but by the late 20th Century the term was used to describe high-rise buildings of unusual height, generally greater than 40 or 50 stories. (Encyclopaedia Britannica, 2014). However there is no official definition or height above which a building may be classified as a skyscraper and at which height may not be considered a high-rise anymore. Can be understood as a very tall multi-storeyed building, or a very tall high-rise building.

Currently, there is an international organization called the Council on Tall Buildings and Urban Habitat (CTBUH) that studies and reports on all aspects of planning, design, construction and operation of tall buildings. This entity also announces who is the representative of the title tallest building in the world and is the authority that establishes the official height of tall buildings.

The CTBUH (2014) defines “supertall” as a building over 300 metres in height, and a high-rise that reaches beyond 600 metres is classified as a “megatall”, can be seen in Figure 2.25.

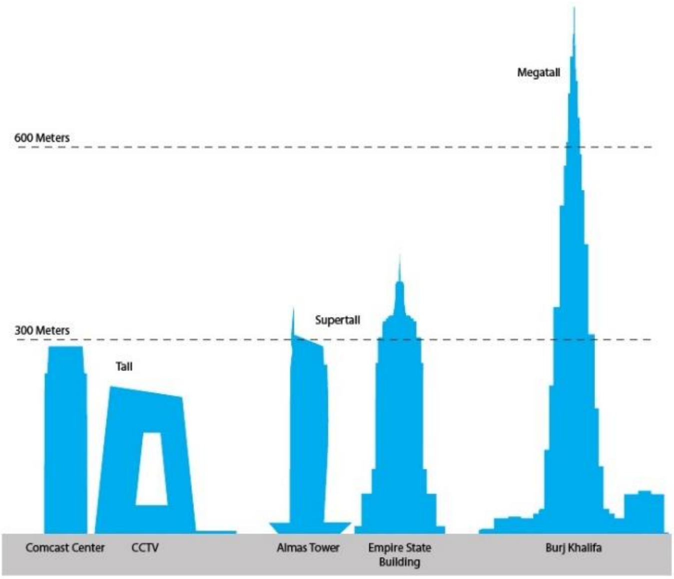

Figure 2.25 - Supertall and Megatall (CTBUH, 2014)

Actually, there are three categories for building measurement: height to architectural; highest occupied floor; height to Tip. And the first category measurement, height to architectural prevails in CTBUH rankings.

Height to Architectural Top:

Height is measured from the level of the lowest, significant, open-air, pedestrian entrance to the architectural top of the building, including spires, but not including antennae, signage, flagpoles or other functional-technical equipment. This measurement is the most widely utilized and is employed to define the Council on Tall Buildings and Urban Habitat (CTBUH) rankings of the “World’s Tallest Buildings.” (CTBUH, 2014)

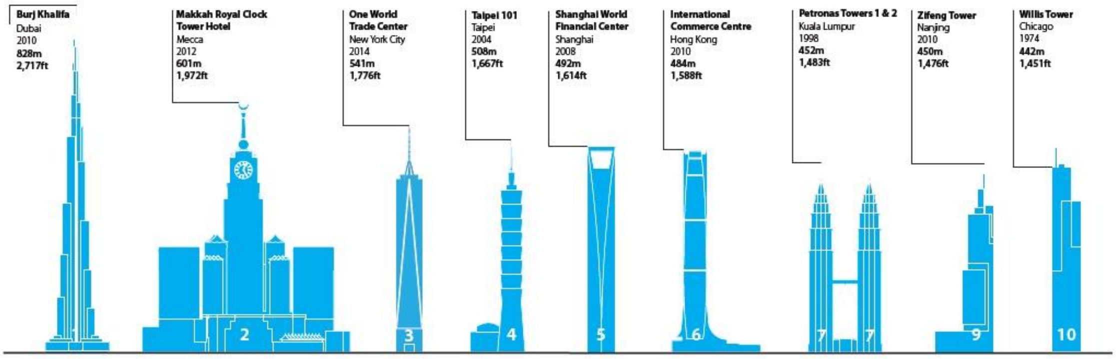

Figure 2.26 - World's ten tallest buildings according to Height to Architectural Top, by November 2014 (CTBUH, 2014)

Highest Occupied Floor:

Height is measured from the level of the lowest, significant, open-air, pedestrian entrance to the finished floor level of the highest occupied floor within the building. (CTBUH, 2014)

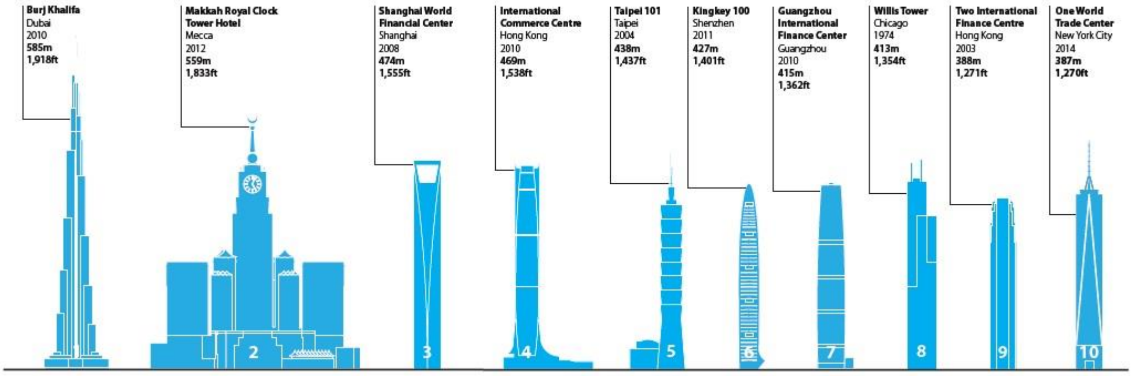

Figure 2.27 - World's ten tallest buildings according to Highest Occupied Floor, by November 2014 (CTBUH, 2014)

Height to Tip:

Height is measured from the level of the lowest, significant, open-air, pedestrian entrance to the highest point of the building, irrespective of material or function of the highest element (i.e., including antennae, flagpoles, signage and other functional technical equipment). (CTBUH, 2014)

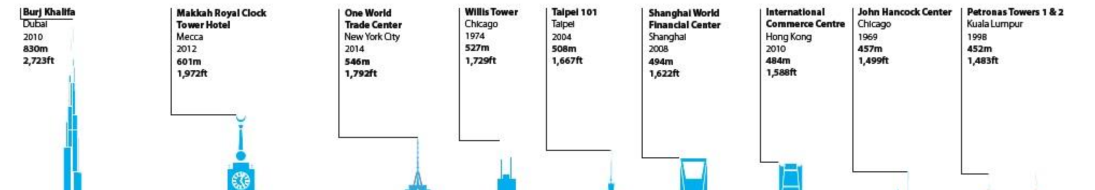

Figure 2.28 - World's ten tallest buildings according to Height to Tip, by November 2014 (CTBUH, 2014)

2.2.2 Building Usage

The difference between a tall building and a telecommunications/observation tower is a tall "building" can be classed as such and is eligible for the "Tallest" lists if at least 50% of its height is occupied by usable floor area (see Figure 2.29). (CTBUH, 2014)

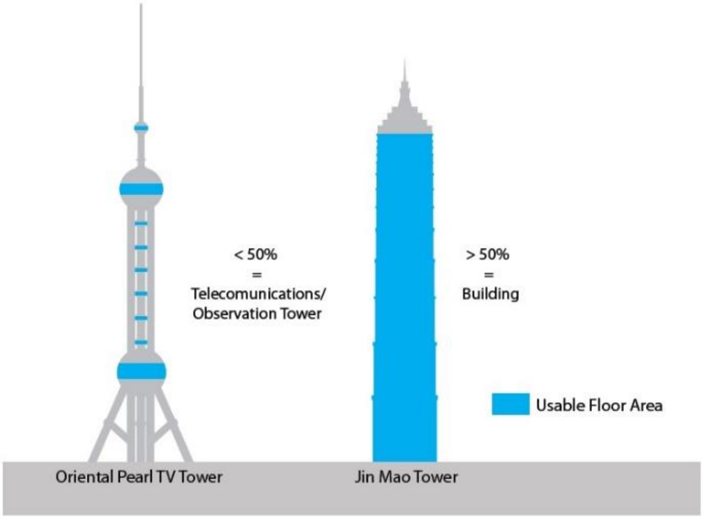

Figure 2.29 - Tall building or telecommunications/observation tower (CTBUH, 2014)

According to CTBUH (2014), a single-function tall building is defined as one where 85% or more of its total floor area is dedicated to a single usage (see Figure 2.30).

A mixed use tall building contains two or more functions (or uses), where each of the functions occupy a significant proportion of the tower's total space. Support areas such as car parks and mechanical plant space do not constitute mixed use functions. (CTBUH, 2014)

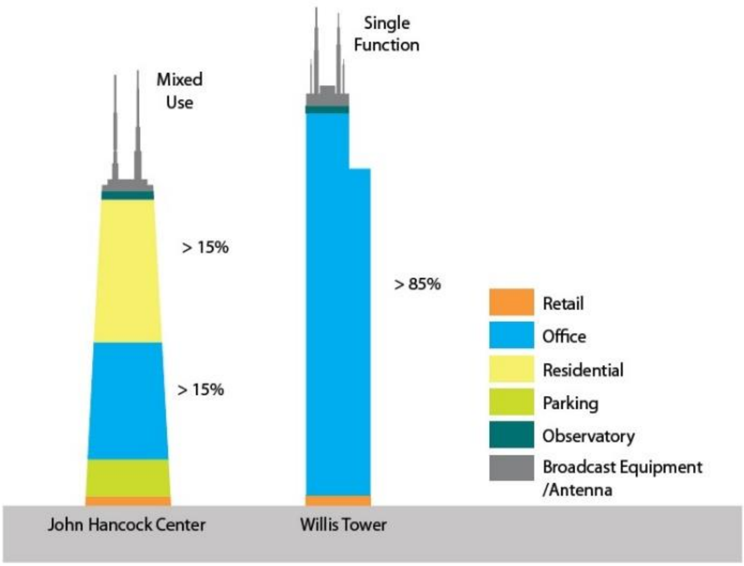

Figure 2.30 - Single-function and mixed-use tall building (CTBUH, 2014)

2.2.3 Evolution of Skyscrapers

More than 150 years ago, cities looked very different from the way they look today. The buildings that housed people and their businesses were rarely over the height of a flagpole. Urban landscapes tended to be flat and uniform in pattern, apart from monuments, temples, and town halls.

“Historically, the word tower usually designated the church and the town hall until the birth of the skyscraper. The main evolutionary change has been in function, from a Campanile watchtower of the Renaissance or minaret of Islamic architecture to the office building.” (Beedle, et al., 2007)

Two major developments led to skyscrapers that dominate major city skylines throughout the modern world (Craighead, 2009):

1. In 1853, an American, Elisha Graves Otis, invented the world’s first safety lift or elevator. This new form of vertical transportation enabled people to travel safely upward at a much greater speed and with considerably less effort than by walking (see Figure 2.31).
2. In the 1870s, steel frames became available, gradually replacing the weaker combination of cast iron and wood previously used in construction. Until then, the walls had to be very thick to carry the weight of each floor.

Figure 2.31 - Otis Publicly Demonstrates the World’s First Safety Elevator, in 1854 (Everett, 2011)

Figure 2.32 - Home Insurance Building in Chicago (CAPC, after 1884)

The very first tall building with elevator was built in Chicago in 1885, the ten-story Home Insurance Building (see Figure 2.32), 42 metres tall, designed by William Le Baron Jenney. In 1890, two additional floors were added to Home Insurance Building´s original structure (final height was 55 metres). While its height is not considered very impressive today, but it was at that time.

According to Chicago Architecture Info (CAI), William Jenney figured out a structure with a skeleton of iron could have stability, rigidity, and height without the thickness of structural stone. In fact, the frame of the building would be so strong that it could support a stone skin. And he was right, it provided the blueprint for hundreds of thousands of skyscrapers that would follow it.

The Home Insurance Building, is generally considered to be the world's first skyscraper. As stated in the *Architectural Record*, before the Home Insurance Building was demolished to allow construction of the New Field Building, "a committee of architects and others was appointed by the Marshall Field Estate to decide if it was entitled to the distinction of being the world's first skyscraper. This committee, after a thorough investigation, handed down a verdict that it was unquestionably the first building of skeletal construction." (Shepherd, 2003) Today, the Home Insurance Building is considered as "father of the skyscraper."

During late nineteen and early twenty century some other tall buildings also marketed their footprint in the skyscraper history.

Since 1885, 17 buildings have staked claim to the title "The World's Tallest Building." According to information obtained from *Skyscraper*, these buildings are as follows (Table 2.5):

Table 2.5 - World´s tallest towers: all Skyscrapers holding the title of Tallest Building in the world from 1885 to the present (Craighead, 2009) (SM, 2010)

Date	**Building**	**Location**
1885	Home Insurance Building	Chicago, Illinois
1890	World Building	New York City
1892	Masonic Temple Building	Chicago, Illinois
1894	Manhattan Life Insurance Building	New York City
1898	St. Paul Building	New York City
1899	Park Row Building	New York City
1908	Singer Building	New York City
1909	Metropolitan Life Tower	New York City
1913	Woolworth Building	New York City
1930	Manhattan Company	New York City
1930	Chrysler Building	New York City
1931	Empire State Building	New York City
1971 - 1973	World Trade Centre - North Tower	New York City
1974	Sears Tower	Chicago, Illinois
1998	Petronas Towers	Kuala Lumpur, Malaysia
2004	Taipei 101	Taipei, Taiwan
2009	Burj Dubai	Dubai, United Arab Emirates

High-rises and skyscrapers may have started in United States, but this trend quickly speared to other countries. Jared Diamond (2007) once wrote in History of Skyscrapers "Skyscrapers began to appear in Shanghai, Hong Kong, São Paulo, and other major Asian and Latin American cities in the 1930s, with Europe and Australia joining in by mid-century."

2.2.4 High-rise Development in Mainland China

Modern high-rise buildings originated in the early 20th century in Shanghai. Oldest extant historic high-rise was built in 1913 and located in Yanan East Road, former Shanghai Premises and Land Resources Administration Bureau and Shanghai Civil Design Institute office building (see Figure 2.33). In 1934, completed the tallest building in Asia - Park Hotel Shanghai (see Figure 2.34), 83.8 metres tall with 24 floors. This proved in a short period of time Shanghai reached the advanced level in tall building construction technology in Asia.

Figure 2.33 - Former Shanghai Premises and Land Resources Administration Bureau and Shanghai Civil Design Institute office building (Wang, 2013)

Figure 2.34 - Park Hotel Shanghai (Wing, 2007)

After the founding of the People's Republic of China. In the 1950s, China began to design and build their own high-rise building. In 1976, the 115 metres Guangzhou Bai Yun Hotel was built. Marking China's own design and construction of high-rise buildings (which exceeds 100 metres). This means the beginning to the super-tall building development stage (see Table 2.6). 1980s were a prosperous period for the development of High-rise buildings. Built in 1985, Shenzhen International Trade Centre (160 metres tall) was the highest in the 1980s building. Then in 1990, Guangdong International Trade Building completed with 198.4 metres, and became the country's tallest building. The Beijing Jing Guang Centre (208 metres) was built in 1990 in mainland, the first building to exceed 200 metres in China. 1996 was the beginning of 300 metres height, both Shenzhen King Building (325 metres) and Guangzhou Transit Plaza (now CITIC Plaza, 322 metres) were completed (SRIBS, 2014).

Table 2.6 - Significant High-rise in China tall building construction history

Date	Building	Location	Height (m)	Floors
1976	Guangzhou Bai Yun Hotel	Guangzhou	115	33
1985	Shenzhen International Trade Center	Shenzhen	160	50
1990	Guangdong International Trade Building	Guangdong	198.4	63
1990	Beijing Jing Guang Centre	Beijing	208	57
1996	Shenzhen King Building	Shenzhen	325	81
1996	Guangzhou CITIC Plaza	Guangzhou	322	80

Recent years, Shanghai achieved a very remarkable supertall development. Firstly in 1998, the 88-story Jin Mao Tower (420.5 metres) completed in Shanghai (see Figure 2.35). This supertall building opened a new door to China, a country which dominates high-rise building construction technology, ranks among the advanced countries in this field. Secondly in 2008, the 101-story Shanghai World Financial Centre was built, 492 metres tall (see Figure 2.36), and it was the world´s third tallest building at the time of completion.

Finally, the Shanghai Tower (see Figure 2.37), a megatall with a height of 632 metres and opens to the public in the summer of 2015. This 127-floor mixed use building with office, retail and hotel space functions as a vertical city. Shanghai Tower is the second tallest building of the world, after Burj Khalifa in Dubai.

Figure 2.35 - Jin Mao Tower (SOM, 2000)

Figure 2.36 - Shanghai World Financial Centre (Mori, 2008)

Figure 2.37 - Shanghai Tower (Unknown, 2014)

2.2.5 Near future – The Era of the “Megatall”

Since the first appearance of high-rise buildings, there has been a transformation in their design and construction. This has culminated in glass, steel, and concrete structures in the international and postmodernist styles of architecture prevalent today. Due to lighter materials, construction technology continuous evolution and a lot of past experience, high-rise has become much more common today than the past.

As the 21st century started, just 14 years ago, the Petronas Towers held the title of “The World’s Tallest” at 452 metres in height. Taipei 101 took the title in 2004, at 508 metres. Then, at the end of the decade, the Burj Khalifa set new standards at 828 metres (CTBUH, 2011).

According to CTBUH (2011) world is witnessing the completion of a significant number of buildings over 600 metres – that’s twice the height of the Eiffel Tower (301 metres). By 2020, will be expected at least eight buildings such as Burj Khalifa to exist internationally. The term “Supertall” is no longer adequate to describe these buildings. It is a beginning of the era of the “Megatall” (see Figure 2.38).

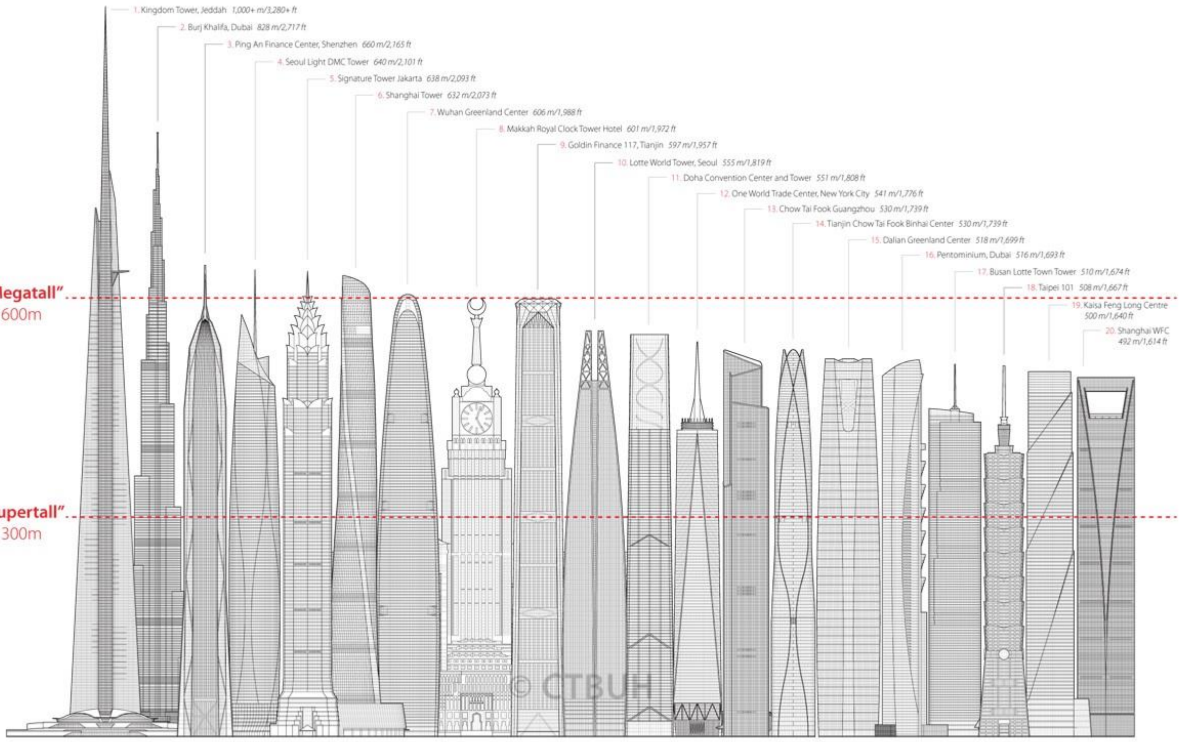

Figure 2.38 - The projected 20 tallest buildings in 2020 (CTBUH, 2011)

High-rise building could be an option to assure larger number of users with low soil occupation and if could assure a good balance with environmental, social and economic could be an option to search and support an important objective that is sustainable development (Chapter 3).

3 Sustainable development

Sustainable development, or sustainability for short. The term began to gain wide acceptance in the late 1980s, after its appearance in Our Common Future, also known as The Brundtland Report. Which defined Sustainable development as "Meeting the needs of the present without compromising the ability of future generations to meet their own needs." Implicit in this definition is the idea that in order to meet the social and economic needs of people today and in the future, there must be continued efforts towards poverty eradication, human rights, and equity, as well as sustainable consumption and protection of natural resources (see Figure 3.1) (UNFPA, 2010) (UNICEF, 2013).

Sustainable development requires to see the world as a system, a system which connects space; and a system that connects time. Think of the world as a system over space, start to understand that air pollution from North America affects air quality in Asia, and that pesticides sprayed in Argentina could harm fish stocks off the coast of Australia. And think of the world as a system over time, begin to realize that the decisions our ancestors made about how to farm the land continue to affect agricultural practice today; and the today´s economic policies will have an impact on future generations. (IISD, 2013)

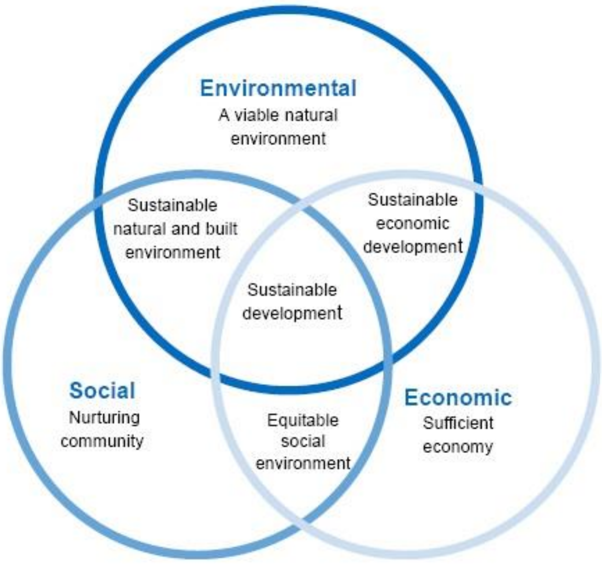

Figure 3.1 - Sustainable development (Eco-friendly house, 2014)

3.1 Sustainable Construction

3.1.1 World's Urban Population Growth and its Influence to Society

According to the 2012 Revision of the official United Nations population estimates and projections, the world population of 7.2 billion in mid-2013 is projected to increase by almost one billion people within the next twelve years, reaching 8.1 billion in 2025, and to further increase to 9.6 billion in 2050 and 10.9 billion by 2100.

The 2014 revision of the *World Urbanization Prospects* launched by UN DESA indicates the urban population of the world has grown rapidly from 746 million in 1950 to 3.9 billion in 2014. Asia is home to 53% of the world’s urban population, followed by Europe with 14% and Latin America and the Caribbean with 13%. And China currently has the largest urban population of 758 million.

About 54% of the world's population currently lives in urban areas and this proportion is expected to increase to 66% by 2050, i.e., the world's urban population is now close to 3.9 billion and is expected to reach 6.3 billion in 2050, according to the UN report (2014). Projections show that urbanization combined with the overall growth of the world’s population could add another 2.5 billion people to urban populations by 2050, a total of 9.8 billion people, with close to 90% of the increase concentrated in Asia and Africa.

The report (UN DESA, 2014) also said that the largest urban growth will take place in India, China and Nigeria between 2014 and 2050, with the three countries accounting for 37 per cent of the projected growth of the world's urban population. By 2050, India is projected to add 404 million urban dwellers, China 292 million and Nigeria 212 million.

World Urbanization Prospects notes in 1990, there were ten “mega-cities” with 10 million inhabitants or more, which were home to 153 million people or slightly less than seven per cent of the global urban population at that time. This has increased to 28 mega-cities worldwide in 2014, home to 453 million people or about 12% of the world’s urban dwellers. Of these 28 mega-cities, sixteen are located in Asia, four in Latin America, three each in Africa and Europe, and two in Northern America. Tokyo remains the world’s largest city with 38 million inhabitants, followed by Delhi with 25 million, Shanghai with 24 million. By 2030, the world is projected to have 41 mega-cities with 10 million inhabitants or more.

A city centre site is often a brownfield site and therefore regarded as more sustainable than using a Greenfield site. One of the main drivers for high-rise is to minimize the use of land. If a developer wants to minimize the impact on land use, the only way to expand in city centre is upwards. That is why high-rise buildings are likely the first choice in dense urban areas.

3.1.2 Impact of the Construction Industry on the Environment

City is an inhabited place of greater size with high density of population, where generally has complex systems for sanitation, utilities, land usage, housing and transportation

Are compact cities sustainable? By theory, providing public transportation, as well as housing, electricity, water and sanitation for a densely settled urban population is typically cheaper and less environmentally damaging than providing a similar level of services to a dispersed rural population. Besides, higher density inner city living would help ease the road traffic and reduce the automobile dependence by housing people closer to work. This way results to less energy use and less carbon dioxide emission. However in practice, as society grows, more and more people move to cities for different reasons, posing immense challenges for developing building, infrastructure and social services for new citizens. That means a lot of constructions. Here comes the problem: the construction industry dominates worldwide materials consumption, causes major carbon emission, air pollution, land contamination, noise pollution and waste pollution. Around half of all non-renewable resources mankind consumes are used in construction, making it one of the least sustainable industries in the world.

The truth is: cities are the main arena of human activity, they are also the greatest consumers of energy and natural resources. Though cities account for only 2% of global land area, however they are responsible for more than 70% of global greenhouse gas (GHG) emissions and 60 to 80% of global energy consumption (Sang, et al., 2014).

Although building and infrastructure developments provide countless benefits to society, especially in cites, but they cause significant environmental and health impacts. However, contemporary human civilization depends on buildings and infrastructures, people live in houses, travel on road, work and socialize in buildings of all kinds.

Table 3.1 - Resources used by buildings (UNEP) (Shams, et al., 2011)

Resources	%
Energy	40
Water	25
Raw stone, gravel and sand	40
Raw Timber	25

Buildings are significantly altering the environment. Building construction consumes 40% of the raw stone, gravel and sand used globally each year, and 25% of the raw timber. Buildings also account for 40% of global energy, 25% of global water, and they emit approximately one-third of global greenhouse gas (GHG) emission (see Table 3.1). Residential and commercial buildings consume approximately 60% of the world's electricity (UNEP) (Shams, et al., 2011). Buildings also produce 40% of waste going to landfills and 40% of air pollution (Davies, 2007). This industry became one of the least sustainable industries in the world, unfortunately the planet cannot support the current level of energy and resource consumption associated with buildings.

Although some types of development may be regarded as more sustainable than others. For example, the benefits of converting existing buildings rather than demolishing and rebuilding them in terms of reduced materials use and waste, but these will need to be balanced against the opportunities for designing a new building with low energy requirements, and which can utilize renewable energy.

In order to give a better future to next generation, it is essential that the construction industry focus more on minimizing waste production, maximizing the use of recycling. And also must improve environment by decreasing standard building practices, which are guided by short-term economic considerations. And start investing in sustainable construction that based on best practices which emphasize long-term affordability, quality and efficiency.

3.1.3 Definition of Sustainable Construction

According to Kibert (2003), the term sustainable construction seems to be the most comprehensive description of all the activities involved in trying to better integrate the built environment with its natural counterpart. Began as an international movement in 1993, sustainable construction can be defined as "creating a healthy built environment based on ecologically sound principles."

Sustainable construction depends on the entire life cycle of the built environment: planning, design, construction, operation, renovation and retrofit, and the end-of-life fate of its materials. Sustainable construction considers the resources of construction to be materials, land, energy, and water and has an established a set of principles to guide this new direction. (Kibert, 2003)

In 1994 the principles of Sustainable Construction (Kibert, 1994) that are highlight are:

- Reduce resource consumption, include soil occupation;
- Reuse resources to the maximum extent possible;
- Recycle built environment end-of-life resources and use recyclable resources;
- Protect natural systems and their function in all activities;
- Eliminate toxic materials and by-products in all phases of the built environment

Over the last decade, sustainable construction market gained significant strength and momentum, much more demands for ecological designs, green buildings, bioclimatic houses, sustainable construction methods, renewable energy, water and waste treatments, etc. Because at each stage of the life cycle of the building, sustainable construction increases comfort and quality of life, while decreasing negative environmental impacts and increasing the economic sustainability of the project. A building designed and constructed in a sustainable way minimizes the use of water, raw materials, energy and land, i.e., green buildings are designed to reduce the overall impact of the built environment on human health and the natural environment. But ecological solutions are not always very economic, that in way governments should work closely with business leaders and other stakeholders to implement appropriate strategies for improved efficiency in this sector and encourage sustainable building project by providing financial incentives. The search for green and sustainable challenges leads to better performance in several dimensions, such as air quality, energy, raw material, soil, water, carbon emission, greenhouse gas and waste.

3.1.4 What Contributes Most to Sustainability in Tall Buildings?

Based on CTBUH 2013 London Conference, the next generation of tall buildings will be judged on more than sheer height or aesthetic appearance. In the context of sustainability, they will also be judged on more than just their energy consumption. They will be judged on their contribution to the well-being of their occupants, as well as the wider community.

Embodied energy is the total primary energy consumed from direct and indirect process associated with a product or service (CTBUH 2013 Internacional Conference, 2013).

Figure 3.2 shows that façade and structure initial embodied energy represents almost 50% of the built project, and according to Poon (2013) these two components represents more than 20% of the total embodied energy for the life of the building. Therefore sustainable façade design, architectural form and efficient structure system are fundamental to achieve green and sustainable goals.

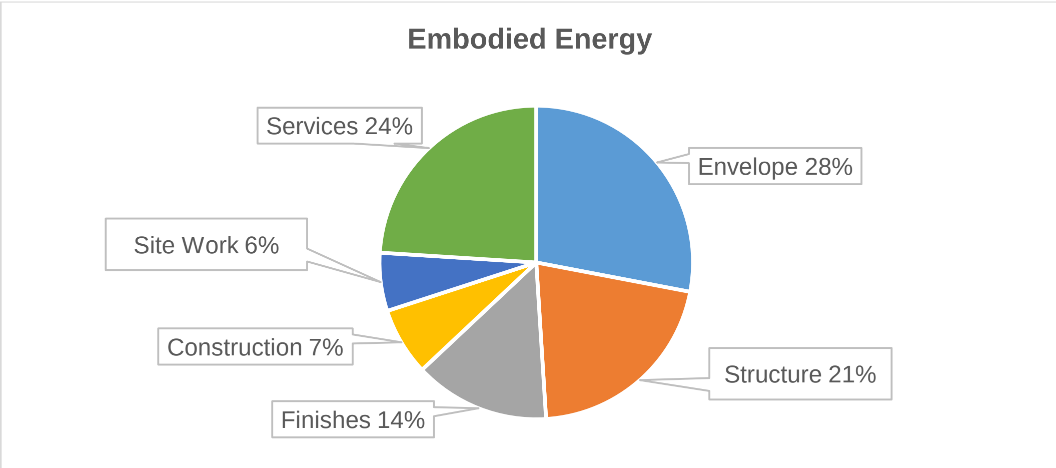

Figure 3.2 - Embodied energy distribution of built project (CTBUH 2013 Internacional Conference, 2013)

In order to build green, must set few key considerations (CTBUH 2013 Internacional Conference, 2013):

- Reduction of
    - ➢ Embodied energy
    - ➢ Energy consumption of heating
    - ➢ Energy consumption for electricity
    - ➢ Fresh water consumption
    - ➢ Carbon dioxide emissions
    - ➢ Waste and pollution
    - ➢ Operation costs
- Recycling of materials
- Natural ventilation and user comfort
- Durability
- Certification

And in order to achieve mentioned targets, should take into account the following points (CTBUH 2013 Internacional Conference, 2013):

✓ Efficient architectural forms

- ✓ Efficient structural system
- ✓ Selection of building materials
- ✓ Advance design process to optimize building designs and minimize construction delays/field modifications
- ✓ Efficient building envelope/façade system
- ✓ Sustainable design to reduce building operation energy/cost

The design, construction and operation of green buildings nowadays is regulated by international guidelines, codes and standards, which is essential to global sustainable construction growth. And by adopting green building strategies, allow maximize both economic and environment performance in high-rises. Last but not least, building rating tools are playing a key role in shaping sustainable built environment. These are used to provide a measure of a building´s environmental performance (Davies, 2007).

Currently, buildings in China are certified mainly by two rating systems: Green Building Evaluation Label (GBEL) and Leadership in Energy & Environmental Design (LEED) that are explained in the following sections.

3.2 Chinese Evaluation Standard for Green Building

3.2.1 Carbon Emission, Energy Consumption and Outdoor Air Quality in China

China became one of the largest developing and the world's most populous country, has a rapidly growing economy (industrialization and urbanization), which has driven the country's high overall energy demand and the quest for securing energy resources.

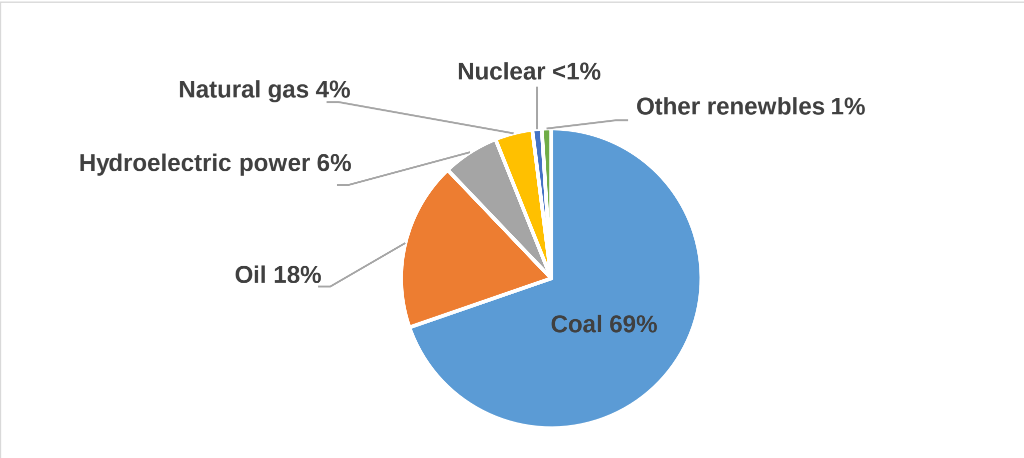

Figure 3.3 - Total energy consumption in China by type in 2011 (USEIA, 2014)

Figure 3.3 indicates, coal supplied the vast majority (69%) of China's total energy consumption in 2011. Oil was the second-largest source, accounting for 18% of the country's total energy consumption. While

China has made an effort to diversify its energy supplies, hydroelectric sources (6%), natural gas (4%), nuclear power (nearly 1%), and other renewables (1%) accounted for relatively small shares of China's energy consumption (USEIA, 2014).

Energy consummation is not the only issue of this nation, the environmental deterioration in China has increased significantly, such as air pollution, water shortages and pollution, desertification, and soil pollution. All these issues have become more pronounced and are subjecting Chinese residents to significant health risks, especially the outdoor air quality in Beijing and Shanghai. Some of these concerns can be seen in Table 3.2. The rate of good ambient air quality in 2013 is 66%, much lower than the previous year.

Table 3.2 - Outdoor Air Condition in main years – Shanghai (SSB, 2014)

Indicators	**2000**	**2010**	**2012**	**2013**
Annual Daily Mean Concentration of SO_2 in Urban Area (mg/m^3)	0.045	0.029	0.023	0.024
Annual Daily Mean Concentration of NO_2 in Urban Area (mg/m^3)	0.090	0.050	0.046	0.048
Mean Concentration of Inhalable Particulate in Urban Area (mg/m^3)	-	0.079	0.071	0.082
Rain PH Value	5.19	4.66	4.64	4.81
Frequency of Acid Rain (%)	26.0	73.9	80.0	75.1
Quantity of Days with Good Ambient Air Quality (day)	295	336	343	241
Rate of Good Ambient Air Quality (%)	80.8	92.1	93.7	66.0

Besides, global warming has been one of the most important environmental problems of our ages. Global emissions of carbon dioxide (CO2) – the dominant contributor to the greenhouse effect and the main cause of global warming, increased by 45% between 1990 and 2010, and reached an all-time high of 33 billion tonnes in 2010 (PBL, 2011). China has overtaken the United States and become the number one CO_2 emitter since 2006 (Greff, et al., 2008), due to its phenomenal economic growth, coal-dominated energy structure and the increasing exports (Wang, et al., 2007) (Weber, et al., 2008) (Greff, et al., 2008). From 2000 to 2008, China's GDP grew by 10.1% annually and over half of coal consumption was used for meeting electricity demand (Lin, et al., 2010).

Moreover, according to Wu and Xu (2012), China has become one of the largest energy consumers in the world, while buildings in China take up over 30% of the total energy consumptions and these are also the main sources of environmental pollution in this country.

For instance, Shanghai has the largest urban development, highest number of buildings in four municipalities, almost everything in building depends on electricity, consequently the electricity consumption in Shanghai is much higher than other municipalities, can be seen in Figure 3.4. Over 2013, 141 billion kWh electricity was consumed in Shanghai, it´s almost twice of Tianjin´s consumption. Although the electricity consumption per person (see Table 3.3) in Shanghai is not the highest in four municipalities, that´s because Shanghai is a financial centre. While Tianjin and Chongqing are municipalities with high percentage of industrial factories, therefore a larger proportion of the electricity consumption is connected to industrial and manufacturing sectors (CSS, 2014).

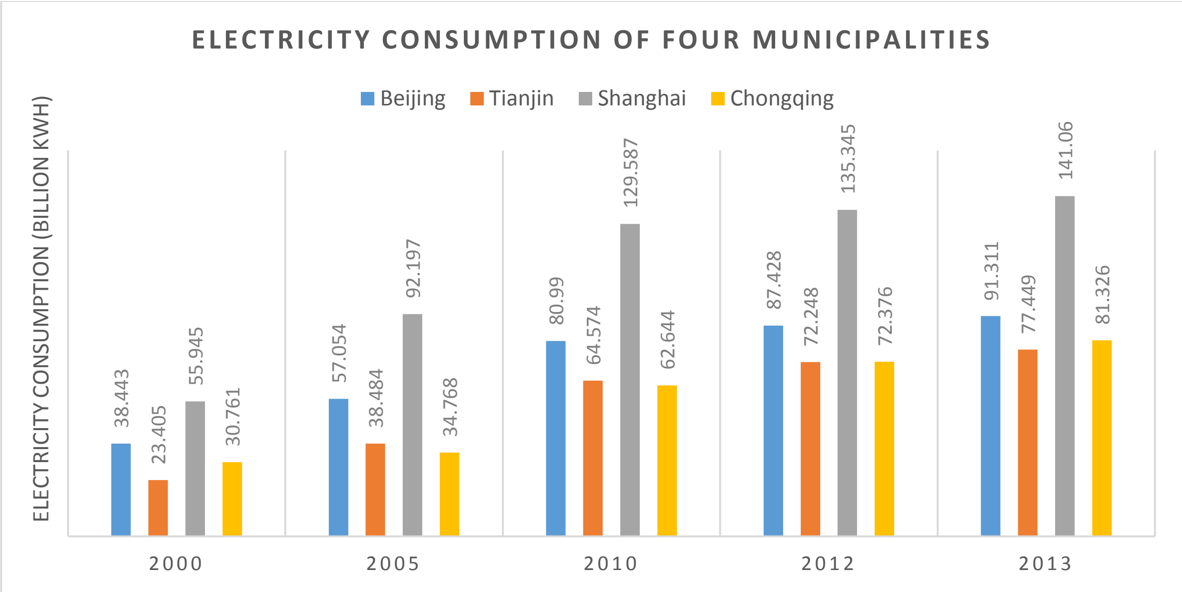

Figure 3.4 - Electricity Consumption in municipalities of PRC (CSS, 2014)

Table 3.3 - Electricity consumption per person in municipalities

kWh/person	Beijing	Tianjin	Shanghai	Chongqing
2000	2154.88	3604.1	2350.43	2749.96
2005	3198.09	5926.09	3873.5	3108.17
2010	4539.8	9943.64	5444.37	5600.21
2012	4900.67	11125.35	5686.29	6470.23
2013	5118.33	11926.24	5926.39	7270.34

The statistics data from the Ministry of Housing and Urban-Rural Development (MOHURD) of the People's Republic of China shows that: two billions square metres of new buildings are constructed every year in China and 80% of them are high energy consumption buildings, also 95% of the existing 40 billions square metres of domestic buildings are high energy consumption buildings (Wang, et al., 2014). The building energy consumption mainly consists of heating, air conditioning, hot water supply, lighting, cooking, household appliances and elevators, etc. Heating and air conditioning occupy the majority of entire building energy consumptions at a percentage of 60 to 70 (Wu, et al., 2013). In case of the high-rise buildings, elevator is also a big contributor to energy consumption.

In order to control and prevent more issues relating to building energy consumption and building energy efficiency due to the fast urbanization, the Chinese government must increase their green and sustainable building market in both private and public sectors. In the 2000s, the building energy saving in China has spread to all regions and all building types. Chinese government has been extensively promoting the development of green building since 2004.

3.2.2 Green Building Evaluation Label

In 2005, the Chinese Ministry of Housing and Urban-Rural Development promulgated the design standard of public green building, which required reducing 50% of building's annual overall energy consumptions such as heating, ventilation, air conditioning and lighting (MOHURD, 2005). It then issued the special plan for green building during China's twelfth five year plan in January 2012, stipulating that by the end of 2015 newly built green building will reach no less than 65% in towns and 95% of new buildings should meet the mandatory energy-saving requirements (Wu, et al., 2013).

To realize these green building goals, the Chinese government has formulated a series of relevant policies since 2006 to stimulate the development of green building technologies. The renewable energy law of China (2006) began its formal implementation on January 1 in 2006, in which the development and exploitation of geothermal and solar energy were officially listed and encouraged (Central Government, 2006). Then in August, the temporary management regulation of special fund for renewable energy development (2006) stipulated that major support should be concentrated on the promotion and application of geothermal and solar energy when planning green building projects (CMF, 2006). Also in the same year, the Chinese Ministry of Finance (CMF) along with the MOHURD introduced the temporary management regulation of special fund for renewable energy application in building (2006), which mentioned to provide financial subsidy for decreasing total energy consumption and retrofit and renewable energy integration demonstration projects in existing government office and large-scale commercial buildings, heating reform retrofits in Northern China residential buildings, and high efficiency and renewable energy technologies for all buildings. (CMF, et al., 2006) (Khanna, et al., 2014).

Initially the concept of green building in China was developed from "Energy-Saving and Land-Saving Residential Building" required by the central government in 2004. To be specific, the green building should be energy-saving, land-saving, water-saving and material-saving, environment-benign and pollution-reducing, summarized as "Four-Saving & One-Benign". That is defined in a Chinese national standard enacted in 2006, the Evaluation Standard for Green Building (ESGB) (MC, et al., 2006).

Evaluation Standard for Green Building (ESGB) is China's first attempt to create a local green building standard. As the introduction of the rating system notes, the purpose is to create a voluntary rating system that will encourage green development. In China, green buildings are distinguished by the Green Building Evaluation Labels (GBEL), also known as "Three-Star" system, which is charged by the governmental department MOHURD.

Under supervision of MOHURD, the Green building evaluation system is achieved all over China. This program is administered by the Building Energy Efficiency and Technology Division. Management responsibilities are divided between offices within two primary institutions, the Office of Green Building Evaluation Label Management within the Centre for Science and Technology of Construction and the Green Building Research Development Centre within the Chinese Society for Urban Studies. The Office of Green Building Evaluation Label Management is authorized by the national government and has the administrative authority to implement GBEL program. It works closely with the Green Building

Development Research Centre, which specializes and provides technical support in researching and developing green building standards and providing green building. The Green Building Development Research Centre may also provide technical consulting services to building developers and owners who are interested in applying for GBEL program. Only these two national offices are authorized to approve Three-Star Building Label rating applications. Moreover, by June 2012, about 30 local authorities are carrying on GBEL evaluation in their local regions (provinces or special cities), these agencies are only authorized to approve One-Star and Two-Star Rating applications (Ye, et al., 2013) (Khanna, et al., 2014). Figure 3.5 illustrates the Green Labelling Program management structure.

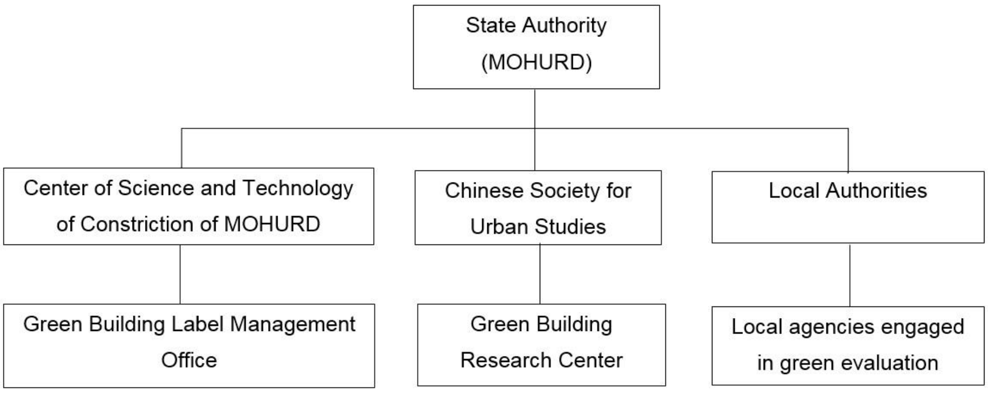

Figure 3.5 - GBEL evaluation agencies (Ye, et al., 2013)

China's national Evaluation Standard for Green Building includes two different evaluation standards for residential and public buildings, i.e., office, retail, hotel buildings and government buildings. GBEL can be applied either for the design stage or for the operation stage.

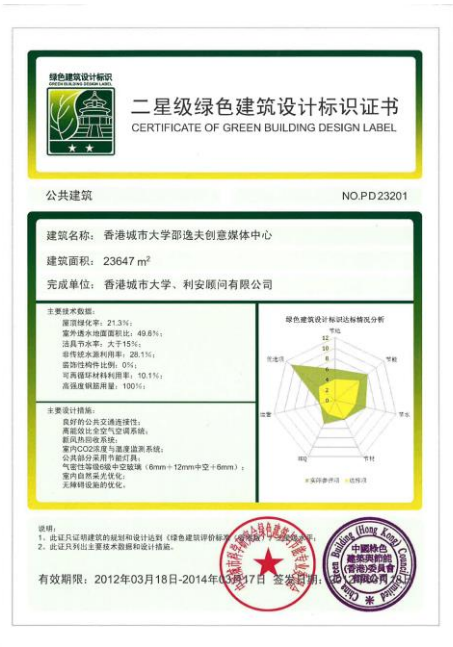

Figure 3.6 - Green Building Design Label certificate (City University of Hongkong, 2012)

GBEL for design stage is also known as Green Building Design Label (GBDL), which helps pre-certify a green building and rates the building design according to Green Building Evaluation Standard. And a GBDL certificate is valid for two years (see Figure 3.6). Evaluation at design stage mainly requires detailed drawings and modelling as proof. (Khanna, et al., 2014).

Operational Green Building Label (GBL) is more comprehensive evaluation of pre-certified Green Buildings than GBDL as it also considers quality control during the construction process. Operational GBL can only be awarded after a minimum of one year of building operation and is valid for three years (Song, 2008). Operational GBL assessment process also requires an on-site visit; documentation of construction materials and their sources; property management plans for water, energy, and material conservation; and itemized financial documents such as bills of quantities (Zhang, 2011). However, reporting of actual operational energy consumption is not required because operational GBL focuses primarily on building design and successful implementation of the design in the construction process (Khanna, et al., 2014). Whether in design stage or operation stage, both stages utilize a “Three-Star” rating system, with three star awarded to the highest achievable rating level and followed by Two-Star and One-Star.

According to ESGB, evaluating provisions rating system is divided into six components, namely Land Use & Outdoor Environment, Energy Efficiency, Water Efficiency, Resource Efficiency, Indoor environment and Operational management. The green building evaluation system is composed of three types of criteria for each of the six categories being evaluated: prerequisites that must be included in the building, general elements, and optimized (preferred) elements where one point is awarded for each item that is included in the building design. For example, energy-efficiency prerequisites for residential buildings include meeting energy-savings standard requirements for heating and HVAC design and installing built-in temperature controls and heat metering in buildings that have central heating or air conditioning. General energy-efficiency items include use of highly efficient equipment, lighting, energy recovery units, and renewable energy technologies such as solar water heaters, solar photovoltaics (PV), and ground-source heat pump systems. Preferred items include more efficient heating and air conditioning and greater renewable energy integration (MOHURD, 2007) (MOHURD, 2008).

Table 3.4 and Table 3.5 show the number of credits at each six categories of GBEL for residential and public buildings respectively. Some of these requirements are not applicable before building operates, provision compliance requirement is adjusted correspondingly in case of design stage (Ye, et al., 2013).

Table 3.4 - Item quantity in each section for residential buildings (Ye, et al., 2013)

Provision Category	Land Use & Outdoor Environment	Energy Efficiency	Water Efficiency	Resource Efficiency	Indoor environment	Operational management
Prerequisites	8	3	5	2	5	4
General items	8	6	6	7	6	7
Optimized items	2	2	1	2	1	1

Table 3.5 - Item quantity in each section for public buildings (Ye, et al., 2013)

Provision Category	Land Use & Outdoor Environment	Energy Efficiency	Water Efficiency	Resource Efficiency	Indoor environment	Operational management
Prerequisites	5	5	5	2	6	3
General items	6	10	6	8	6	7
Optimized items	3	4	1	2	3	1

Table 3.6 - Criteria for Green Building Evaluation Label rating evaluation for residential buildings (Ye, et al., 2013) (Khanna, et al., 2014)

Prerequisites included (27)	**Minimum score**			**Total General items**
	★	★★	★★★	
Land Use & Outdoor Environment	4	5	6	8
Energy Efficiency	2	3	4	6
Water Efficiency	3	4	5	6
Resource Efficiency	3	4	5	7
Indoor environment	2	3	4	6
Operational management	4	5	6	7
	Preferred items			
	N/A	3	5	9

Table 3.7 - Criteria for Green Building Evaluation Label rating evaluation for public buildings (Ye, et al., 2013) (Khanna, et al., 2014)

Prerequisites included (26)	**Minimum score**			**Total General items**
	★	★★	★★★	
Land Use & Outdoor Environment	3	4	5	6
Energy Efficiency	4	6	8	10
Water Efficiency	3	4	5	6
Resource Efficiency	5	6	7	8
Indoor environment	3	4	5	6
Operational management	4	5	6	7
	Preferred items			
	N/A	6	10	14

GBEL rating is determined by the minimum score for each of the six components, not the total score. Therefore, a building must meet a minimum number of requirements in all six categories to qualify for a specific rating. Each requirement corresponds to one point. For example, as shown in Table 3.7, in order to achieve Three-star level, a public building must meet all 26 of the prerequisites, then 5 of 6 of the general items in the Land Use & Outdoor Environment category, 8 out of 10 of the general items in the energy saving and energy utilization category, 5 out of 6 of the general items in the water saving and water resource utilization category, 7 out of 8 of the general items in the material saving and material resource utilization category, 5 out of 6 of the general items in the indoor environmental quality category, 6 out of 7 of the performance items in the operation and management category and 10 out of 14 of the optimized Items. This arrangement gives equal weight to all six categories and does not allow better performance in one category to offset poor performance in another. Hence, a building must meet a minimum number of requirements in all six categories to qualify for a specific rating, including the optimized items (strategic, harder to reach targets). Table 3.6 and Table 3.7 show the minimum requirements and rating evaluation systems for residential and public buildings, respectively (Khanna, et al., 2014).

In order to a better understanding of Chinese "Three-Star" assessment system, there are 6 tables which explain details of each requirement of all six categories of GBEL for public building, these tables can be found in appendices section (A to F). Some labelling requirements of GBEL often refer to the national standard. The Green Building Evaluation Standards (GB/T 50378-2006), which is the main guideline for the green building label and evaluation, cites other national building codes.

The increased capital costs is constantly main barrier to achieve more green buildings goal. However, the increased capital costs for one-star buildings in China is relatively low, therefore no incentives are offered for that building type in the twelfth Five Year Plan.

According to Shanghai building energy-saving projects of special support measures (implementation since September 15, 2012), for Two or Three-star certified green building projects in Shanghai, the support funds amount are:

- The maximum subsidy per square metre of building area is 60 RMB;
- Individual project maximum support fund is 6 million RMB
- The maximum subsidy for affordable housing projects is 10 million RMB

Even with support funds, the investment for a sustainable building is till significantly higher than a standard building, it is a long-term investment. So how much more and how long will take to compensate the capital cost without any subsidy? Table 3.8 shows the values based on Government reports.

Table 3.8 - Increased capital costs for green buildings in China (MOHURD, 2012)

Rating	Average incremental capital cost in residential buildings RMB/m2	Average incremental capital cost in public buildings RMB/m2	Payback period (years)
One star	60	30	1-3
Two-star	120	230	3-8
Three-star	300	370	7-11

In case of one-star buildings, the average incremental capital cost per square metre in public buildings is half of the average in residential buildings. As for the other two categories, two-star and three-star, public building's average incremental capital cost for same floor area is 92% and 23% higher than the residential buildings, respectively (Ye, et al., 2013).

Despite the high investment, green building market in China is growing at a fast rate. Since beginning of GBEL, while 113 projects had received a rating by the end of 2010, nearly 500 projects had a received a GBEL by the end of August 2012. Out of 494 projects, 60% were found in one of ten cities: Shanghai, Suzhou, Shenzhen, Tianjin, Beijing, Nanjing, Guangzhou, Hangzhou, Wuhan, and Chengdu (see Figure 3.7) (Khanna, et al., 2014). Figure 3.8 shows that more than three quarters of GBELs are in the east coast, which is the region with a rapid economic growth in China. Shanghai as the largest urban area, thus leads the ranking of GBEL.

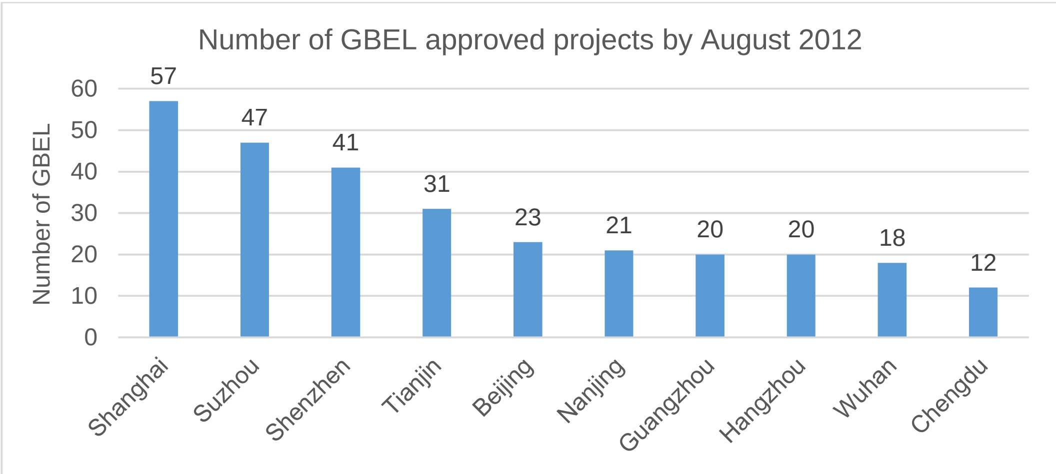

Figure 3.7 - Top ten cities by number of GBEL approved projects, as of August 2012 (Khanna, et al., 2014)

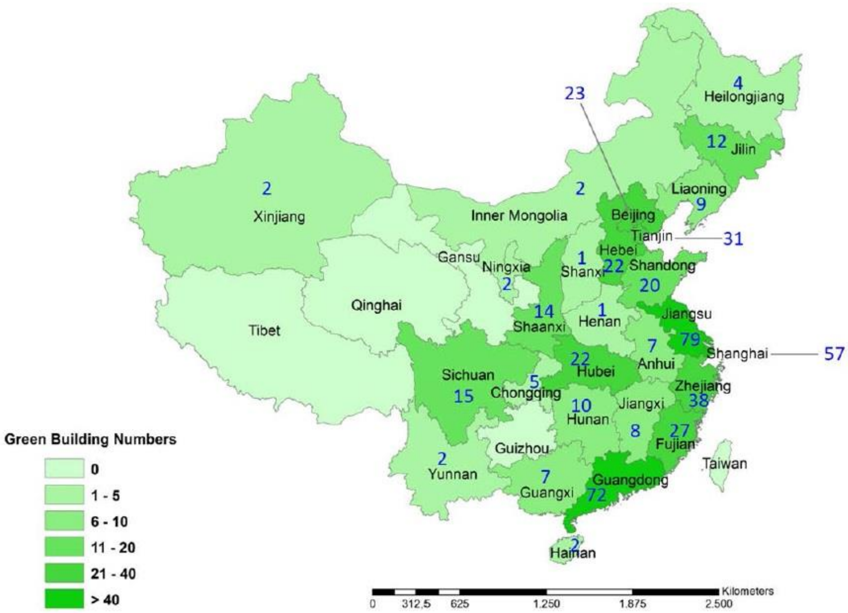

Figure 3.8 - Number of GBEL certified projects Map view (Khanna, et al., 2014)

3.3 Leadership in Energy & Environmental Design

U.S. Leadership in Energy & Environment Design (LEED) program is a voluntary green building rating system developed by the U.S. Green Building Council (USGBC) began as early as 1994, and was officially launched in 2000 with the first assessment system for new construction and since then has expanded its influence around the world (Khanna, et al., 2014). The most recent version LEED v4 started in the end of 2013.

LEED for Building Design and Construction (LEED BD+C) can be applied to different kind of buildings, from commercial high-rises to data centres, has eight green building rating systems (USGBC, 2014a):

- **New Construction and Major Renovation**: Addresses design and construction activities for both new buildings and major renovations of existing buildings. This includes major HVAC improvements, significant building envelope modifications and major interior rehabilitation.
- **Core and Shell Development:** For projects where the developer controls the design and construction of the entire mechanical, electrical, plumbing, and fire protection system – called the core and shell – but not the design and construction of the tenant fit-out.
- **Schools**. For buildings made up of core and ancillary learning spaces on K-12 school grounds. Can also be used for higher education and non-academic buildings on school campuses.
- **Retail**. Addresses the unique needs of retailers – from banks, restaurants, apparel, electronics, big box and everything in between.
- **Data Centres**. Specifically designed and equipped to meet the needs of high density computing equipment such as server racks, used for data storage and processing.
- **Warehouses and Distribution Centres**. For buildings used to store goods, manufactured products, merchandise, raw materials, or personal belongings, like self-storage.
- **Hospitality**. Dedicated to hotels, motels, inns, or other businesses within the service industry that provide transitional or short-term lodging with or without food.
- **Healthcare**. For hospitals that operate twenty-four hours a day, seven days a week and provide inpatient medical treatment, including acute and long-term care.

There are four levels of LEED certification: certified, silver, gold and platinum (see Figure 3.9). The total score earned in a project determines the level of certification that the project will receive.

Figure 3.9 - Four levels of LEED certification (USGBC)

In order to get a better understanding of LEED assessment system´s credits, Table 3.9 was added. It is a summary of prerequisites and credits of the LEED v4 for New Construction and Major Renovations, is composed by 8 topics:

Table 3.9 - LEED v4 for New Construction Rating System (USGBC)

Category	Possible Points	%	**Summary of Credits**
Location & transportation	32	26%	LEED for Neighbourhood Development location
			Sensitive land protection, High priority site
			Surrounding density and diverse uses
			Access to quality transit, Bicycle facilities, Reduced parking footprint and Green vehicles
Sustainable Sites	10	8%	Construction activity pollution prevention (required)
			Site assessment and Site development - protect or restore habitat
			Open space, Rainwater management, Heat Island reduction and Light pollution reduction
Water Efficiency	11	9%	Outdoor water use reduction (required)
			Indoor water use reduction (required)
			Building-level water metering (required)
			Outdoor water use reduction and Indoor-use reduction
			Cooling tower water use and Water metering
Energy and Atmosphere	33	26%	Fundamental commissioning of building energy systems (required)
			Minimum energy performance (required)
			Building-level energy metering (required)
			Fundamental refrigerant management (required)
			Enhanced commissioning, Optimized energy performance, Advanced energy metering and Demand response
			Renewable energy production, Enhanced refrigerant management and Green power and carbon offsets
Materials and Resources	13	10%	Storage and collection of recyclables (required)
			Construction and demolition waste management planning
			Building life-cycle impact reduction
			Building product disclosure and optimization - environmental product declarations
			Building product disclosure and optimization - sourcing of raw materials
			Building product disclosure and optimization - material ingredients
			Construction and demolition waste management
Indoor Environmental Quality	16	13%	Minimum indoor air quality performance (required)
			Environmental tobacco smoke control (required)
			Enhanced indoor air quality strategies
			Low-emitting materials, Construction indoor air quality management plan and indoor air quality assessment
			Thermal comfort, Interior lighting, Daylight, Quality views and Acoustic performance
Innovation	6	5%	Innovation
			LEED accredited professional
Regional Priority	4	3%	Regional priority
Total Possible Points	125	100%	

In addition, there are 8 tables in appendices section (G to N), which explain the intent of each credit of LEED v4 Building design and construction for new construction and major renovation, and respective points.

3.4 Comparison between "Three-Star" Assessment and Leadership in Energy & Environmental Design Rating

According to the report, LEED in Motion: Greater China (2014b). 1,961 LEED projects certified in PRC with 1,657 LEED projects in Mainland China. Total of 110 million gross square metres of construction space in PRC and 92.22 million square metres in Mainland China. PRC has become the second largest market of LEED certification.

3.4.1 Main Differences between "Three-Star" Assessment and LEED Rating

In terms of the specific rating systems, the Chinese GBEL has similarities and differences with the US LEED program. Firstly, will be analysed their differences.

Table 3.10 - Differences between GBEL and LEED

	GBEL (Three-Star system)	**LEED BD+C**
History	Initiated by MOHURD (Ministry of Housing and Urban-Rural Development) in 2006	Initiated by USGBC (United States Green Building Council) in 2000
Organization operation	Governmental	Non-governmental
Application	People´s Republic of China (nationwide)	Worldwide
Rating system	Public (including retail, office, hotel buildings and government buildings) and Residential	New Construction and Major Renovation, Core and Shell Development, Schools, Retail, Data Centres, Warehouses and Distribution Centres, Hospitality, Healthcare
Operational rating stage	Operational GBL - One year after occupancy	For new construction: immediately after completion
Level of certification	3 levels: One-star to Three-star. Three-star is the highest level	4 levels: Certified, Silver, Gold, Platinum. Platinum is the highest level
Rating method	Must achieve the minimum score in all six categories, not determined by the total score	Determined by the total score summed over all categories

Table 3.10 outlines basic differences between GBEL and LEED. Unlike LEED, GBEL was initiated by the national government and operated by both national and local governments. In the implementation process, the government plays a more critical role for GBEL than LEED. In addition, LEED, which has a longer history, measures more rating categories in a more systematic way than "Three-Star"

assessment system. Another difference is that GBEL issues two kinds of labels: Design Label and Operation Label. The GBDL which is valid for two years is issued right after the construction phase, while the operational GBL which is valid for three years can only be issued one year after occupancy. A performance verification of one year ensures a more accurate assessment of the real performance of buildings. Other main distinction is the rating method, which is analysed in next subchapter.

3.4.2 Rating Methods

The rating method is one of the key difference between two assessments. Under China's GBEL, all the requirements are attributed the same way, each of them corresponds to one point. In order to qualify for a specific level, the building must meet the minimum rating or credits within each category, i.e. the final rating result does not depend on total score. For One-Star level, a public building must achieve 3 out of 6 general items in Land Use & Outdoor Environment category. There is a minimum score to meet in each category, so to qualify for a specific rating result (see Table 3.11).

Table 3.11 - Number of items required for GBEL rating for public building

Prerequisites included (26)	**Minimum score in General items**			***Total General items***
	★	★★	★★★	
Land Use & Outdoor Environment	3	4	5	6
Energy Efficiency	4	6	8	10
Water Efficiency	3	4	5	6
Resource Efficiency	5	6	7	8
Indoor environment	3	4	5	6
Operational management	4	5	6	7
	Preferred items of all 6 categories			
	N/A	6	10	14
The minimum final result of each level after satisfying the minimum score of all six category	22	35	46	

Table 3.12 - LEED v4 New Construction and Major Renovation rating points (USGBC)

Category	Possible Points
Location & transportation	32
Sustainable Sites	10
Water Efficiency	11
Energy and Atmosphere	33
Materials and Resources	13
Indoor Environmental Quality	16
Innovation in Design	6
Regional Priority	4

On the other hand, LEED rating method is much simple compared to GBEL, determined by the total score summed over all categories can be in Table 3.12. A building 40-49 points gets Certified level; 50 -59 points earns Silver; 60-79 points qualifies to Gold; and 80 points and above earns Platinum. GBEL rating method seems less flexible than LEED, but more objective.

3.4.3 Prerequisites and Rating Criteria Weighting

Both “Three-Star” and US LEED have a lot of similarities, these are two green building rating systems use similar rating criteria based on credit systems with some flexibility for what general items or optimized items building developers want to pursue, along with prerequisites that must be met for certification. “Three-Star” for public building has 26 prerequisites, while LEED v4 NC has 12 prerequisites (Table 3.13 and Table 3.14). In GBEL, the indoor environment quality category has the highest distribution weight, follow by land, energy, and water efficiency with 5 prerequisites in each category, this could mean there is more concern and focus in these 4 areas. However GBEL is relatively junior compared to LEED, with time and practice Chinese government will realize which category is more important, and possibly some modifications will be made to improve the system. In case of LEED, energy and atmosphere takes the weighting of 33%, this number can related to the fact that US has more experiences in green building and after the first 3 versions of LEED, they came to the conclusion that should focus more on energy and atmosphere category in order to achieve better performance.

Table 3.13 - GBEL Public building prerequisites weight distribution

	Prerequisites	Weight
Land Efficiency	5	19%
Energy Efficiency	5	19%
Water Efficiency	5	19%
Resource/Material Efficiency	2	8%
Indoor Environment Quality	6	23%
Operational Management	3	12%
Total prerequisites	26	100%

Table 3.14 - LEED v4 NC prerequisites weight distribution

	Prerequisites	Weight
Sustainable Sites	1	8%
Water Efficiency	3	25%
Energy and Atmosphere	4	33%
Materials and Resources	2	17%
Indoor Environmental Quality	2	17%
Total prerequisites	12	100%

Although GBEL is composed by 6 categories and LEED v4 New Construction by 7 sections (without Regional priority), but the credits within those categories are very similar, both systems mainly focusing on land/location, energy, water, resource/material efficiency, and indoor environmental quality. Save for the GBEL's additional operational management category and LEED´s innovation section. A comparison of the relative weighting of each evaluation criteria category is shown in Figure 3.10 and Figure 3.11.

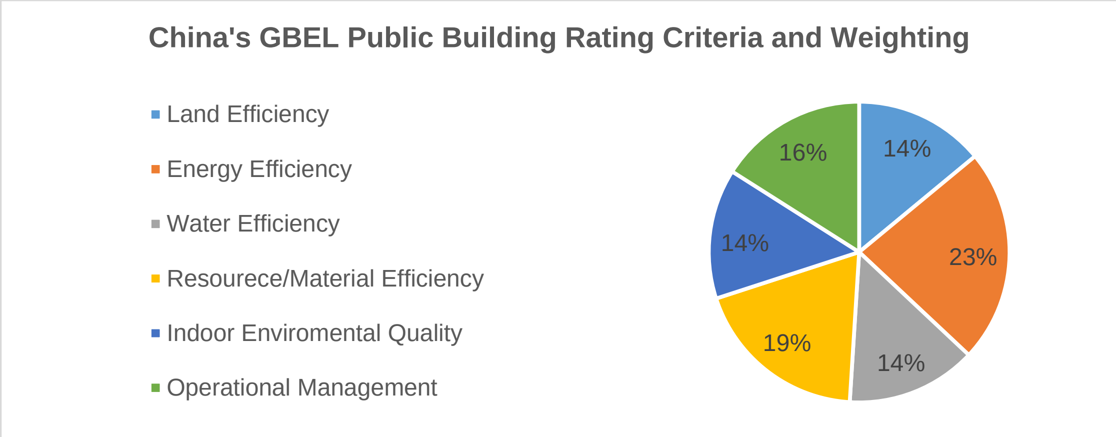

Figure 3.10 - GBEL Public Building Rating Criteria and Weighting not include optimized items

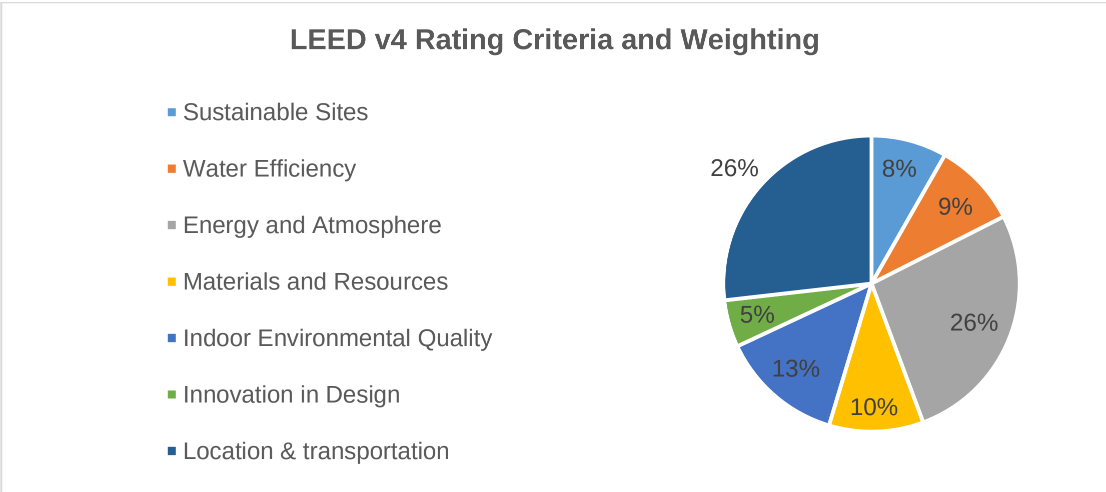

Figure 3.11 - LEED v4 New Construction Rating Criteria and Weighting not include Regional Priority

The figures above show that China's GBEL has more equal weight distribution in terms of the total points possible across the six categories of options, although energy efficiency and resource and material efficiency are given slightly higher share of total available options than the other four categories. LEED gives location and transportation, energy and atmosphere category the highest shares in terms of total point allocation, but the indoor environmental quality category has the second greatest weighting before material and resource efficiency. Within each category of credits or options, the emphasis of available credits or options also differ between the two rating systems due to different national conditions. For further details consul appendices A to N.

In the area of water efficiency, LEED credits promote water conservation planning, wastewater recycling and water resource conservation whereas the GBEL options focus on consumption of rainwater, reclaimed wastewater and reclaimed sea water (Geng, et al., 2012).

3.4.4 Conclusion

The difference between GBEL and LEED reflects the different goals and philosophies of the organization designing and running them. LEED was designed by the USGBC, a collaboration between developers, architects, engineers, and green building material suppliers, to generate a market for green buildings, green building products and services, and promote sustainable design.

GBEL on the other hand is a Government-led project. While GBEL shares market transformation goals, it also has an overriding policy goal that fits into China's long-term environmental and energy policy: namely reducing building energy consumption.

These assessment programs together with innovation technologies will continue to have a huge impact in green and sustainable industry of China. One of the most remarkable example of sustainable super high-rise in China nowadays is Shanghai Tower, which will be analysed in Chapter 4.

4 Case study – Shanghai Tower

The 632 metres tall Shanghai Tower designed by the American architectural firm Gensler sits on a 30,370 square metres plot (Gensler, 2008), which is located in Lujiazui Finance and Trade Zone, Pudong district, Shanghai. This 127-story high-rise is a mixed use megatall building with retail, office, hotel, observation deck and restaurant. Shanghai Tower´s construction started on November of 2008, topped out in 2013 and will open to public by the summer of 2015 (see Figure 4.1).

Figure 4.1 - Shanghai Tower timeline (Nichols, 2014)

Following are the companies involved in this mega project (CTBUH, 2015):

- Owner/developer: Shanghai Tower Construction & Development Co., Ltd.
- Design architect: Gensler
- Architect of record: Tongji Architectural Design (Group) Co., Ltd. and East China Architectural Design & Research Institute (ECADI)
- Structural engineer: Thornton Tomasetti
- MEP engineer: Cosentini Associates
- Project manager: Shanghai Jianke Project Management Co.
- Main constructor: Shanghai Construction Group
- Other consultants
    - Cost: Rider Levett Bucknall
    - Fire: Rolf Jensen & Associates
    - Landscape: SWA
    - Life safety: Arup
    - Vertical Transportation: Edgett Willams Consulting Group Inc.
    - Wind: RWDI

- Cladding: Beijing Jangho Curtain Wall Co., Ltd.; Wuhan Lingyun Building Decoration Engineering Co Ltd.; Yuanda
- Elevator: Mitsubishi Elevator and Escalator
- Paint/Coating: AkzoNobel
- Sealants: Dow Corning Corporation
- Steel: Bao Steel Group; Jiangsu Huning Steel Mechanism Co., Ltd.

Shanghai Tower is the second tallest building in the world after Burj Khalifa in Dubai and the tallest in China. It is also the first Chinese super high-rise exceeds 600 metres. The building incorporates 106 elevators and three of those are super high speed models capable of traveling at 18 metres per second and the tower has the farthest-traveling single elevator, which travels up to 578.55 metres tall (SRIBS, 2014).

Shanghai tower is not simply a high-rise building, this is a new way of envisioning and creating cities, it is a 127-story vertical city. By incorporating sustainable best practices and achieving the highest level of performance, Shanghai Tower is considered as the most green and sustainable skyscraper of nowadays, achieved LEED Gold pre-certification certificate in 2010 and Green building design label highest score Three-star in 2012. Incorporate sustainability into a megatall building is not simple task, but it is possible.

Further on in this Chapter will be analysed the most innovative sustainable technologies and strategies applied on this tremendous vertical city.

4.1 Location and Transportation

Lujiazui zone in Shanghai has gone from farmland to financial centre in two decades, resulting in a skyline and architectural landscape. Shanghai Tower is the third and final planned super high-rise building in Pudong area that completes the development of the Lujiazui Central Financial District. Can be seen in Figure 4.2 and Figure 4.3 that Shanghai Tower is surrounded by two equally super-awesome towers, one of which is the Shanghai Jin Mao Tower (middle) and the other is the Shanghai World Financial Tower (right). Shanghai Tower completes the precinct’s harmonious trio of buildings, this is the world's first adjacent grouping of three supertall/megatall buildings.

“This tower is symbolic of a nation whose future is filled with limitless opportunities,” said Mr. Qingwei Kong, President of the Shanghai Tower Construction & Development Co., Ltd. (Gensler, 2010), Shanghai Tower now stands as a signature icon for the city of Shanghai.

Shanghai has an excellent public transportation service and a very complex metro system with 13 lines (see Appendix O), which contributes significantly to decreasing private vehicle use.

Figure 4.2 – Lujiazui (Gensler, 2014)

Figure 4.3 - Skyscraper trio (Gensler, 2008)

The three mixed use towers (Jin Mao Tower, Shanghai World Financial Centre and Shanghai Tower) are interconnected, served by Shanghai Metro and accessible from across the city. That means Shanghai Tower is directly connected to Lujiazui underground station, which meets one of the requirement of GBEL - “The transport organization of a site shall be reasonable, with the walking distance for arriving at a public transport station not exceeding 500m.” Concludes that Lujiazui is an area with easy access to almost every corner of Shanghai, and it is an ideal location for a vertical city like Shanghai Tower (see Appendix O).

Besides the excellent public transportation, there is still a small amount of people in Shanghai, who prefer riding bicycle to their work, which is a very healthy daily physical activity and a great help to decrease the existent CO_2 level. Note the requirement LTc1 Neighbourhood Development location of LEED V4 for NC says “avoid development on inappropriate sites. To reduce vehicle distance travelled. To enhance liveability and improve human health by encouraging daily physical activity.” In order to accomplish this requirement and encouraging more bicycle use as daily transportation, every building should have a parking lot for bicycle, in case of Shanghai Tower, there is 750 square metres reserved for bicycle parking.

4.2 Design Concept

Gensler won the Shanghai Tower project in an invited multi-stage competition among leading international architects. What secured the win were the tower’s design and performance. Shanghai tower takes inspiration from Shanghai’s tradition of parks, neighbourhoods and nine-layer pagoda. Its curved façade and spiralling form symbolize the dynamic emergence of modern China. By incorporating sustainable best practices, this Tower is designed for high energy efficiency and sustainability, provides multiple separate zones for office, retail and leisure use offering unprecedented community access (Gensler, 2010).

The site area of Shanghai Tower is 30,370 square metres (see Figure 4.4), which incorporates five-floor podium area. The tower stands at 632 metres high with 127 floors above ground and 5 floors below ground, which includes 2000 car parking spaces. Building´s total construction area is 576,000 square metres, above ground floor area of 410,000 square metres (see Figure 4.5) and underground construction area is 166,000 square metres. As a green building, a full 33% of the site is green space, with landscaping that breathes fresh air into the city and shades paved areas that radiate heat (Gensler, 2008).

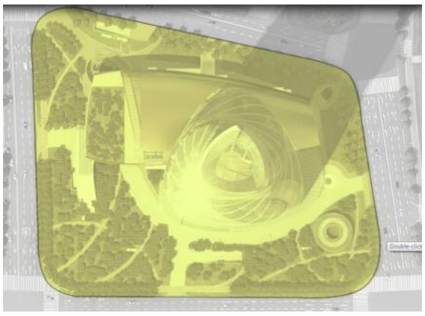

Figure 4.4 – Plot area (Gensler, 2008)

Figure 4.5 - Total construction area (Gensler, 2008)

Figure 4.6 - Green space (Gensler, 2008)

Shanghai Tower envisions a new way of inhabiting supertall/megatall buildings, it is a vertical city, also the only super high-rise building wrapped in sky gardens. The tower takes the form of nine cylindrical buildings stacked atop each other, enclosed by the inner layer of the glass façade, can be seen in Figure 4.7. Table 4.1 shows the floor area of each zone (not include the area of MEP and refuge floors). Every neighbourhood is encircled by public space within the double-skin façade and rises from a “sky lobby” at its base - a light-filled garden atrium that creates a sense of community and supports daily life, serves much as plazas and squares, bringing people together throughout the day. And “sky lobbies” harken back to the city’s historic open courtyards that combine indoors and outdoors in a landscape setting.

A majority zones of Shanghai Tower have 12 to 15 stories, separate elevators transport people among different zones. Every single neighbourhood is dedicated to a primary use, but is enriched by complementary amenities and services. The highest of the nine zones houses cultural venues, and an observation deck with sweeping views of the Shanghai skyline and the landscape of the city, which is served by the tallest single-lift elevator in the world. A luxury hotel and boutique office are housed in zone 7 and 8. The central floors (zones 2 to 6) are comprised of high performance offices, all are filled with natural light, connect to the garden atriums, by having shops and restaurants in each “sky lobby”, helps to lower the demand for trips to the ground level that saves energy. Near the base (zone 1) houses a six-story retail podium, which is comprised of two distinct zones – two levels below grade and four above. The retail complex concentrates shopping and dining. As for the ground floor serves as an “urban market,” connecting people to each other and below-grade parking links via walkways to the nearby super high-rise towers and to Shanghai’s Metro (Gensler, 2010) (Shanghai Tower Façade Design Process, 2010).

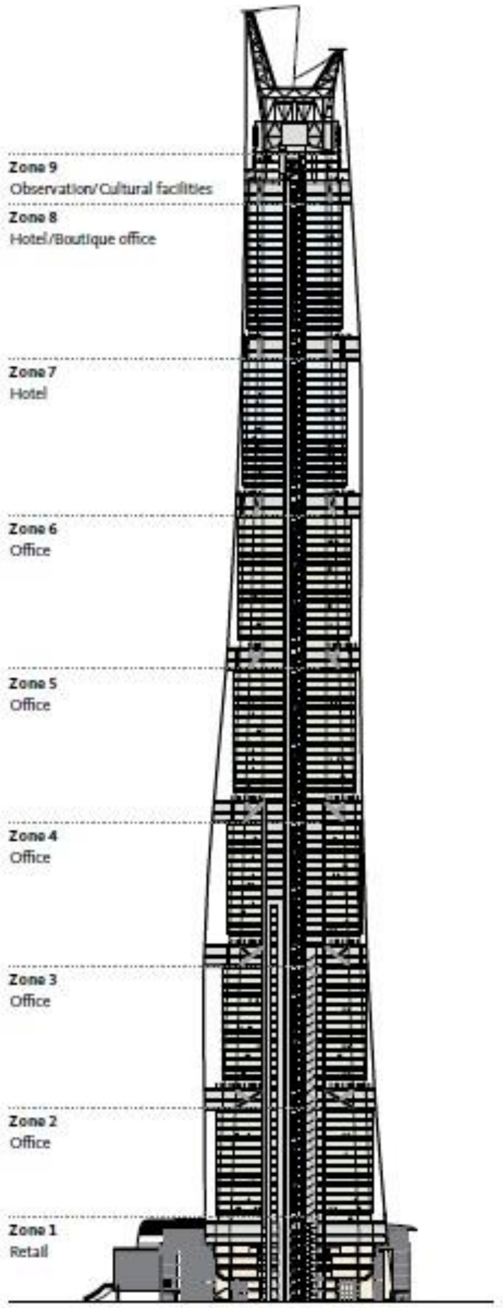

Figure 4.7 – Shanghai Tower nine neighbourhood (Gensler, 2010)

Table 4.1 – Floor Area per zone, not include the area of MEP and refuge floors (Gensler, 2010)

	Floor area m²
Zone 9 (Observation deck)	2080
Zone 8 (Boutique Office)	8775
Zone 8 (Hotel)	18292
Zone 7 (Hotel)	31613
Zone 6 (Office)	34991
Zone 5 (Office)	41343
Zone 4 (Office)	45340
Zone 3 (Office)	53023
Zone 2 (Office)	57480
Zone 1 (Retail)	57415

4.3 Foundation and Structure

Soil conditions in Shanghai is a clay-based mixture typical of a river delta, thus Shanghai Tower construction site sits on a soft soil, rich in clay. Duo to Tower´s dimension, weight and unfavourable soil condition, a very complex foundation system was required. According to Gensler (2010), engineering team decided placing 955 reinforced concrete bored piles (1 metre in diameter) to deep into ground, then continuously poured 61,000 cubic metres of concrete to create the six-metre thick mat-slab foundation. This foundation mat serves as the bottom platform of the main tower, it took a small army of workers (see Figure 4.8 and Figure 4.9), a fleet of trucks and 19 cement pumps worked in two shifts for more than 60 consecutive hours to complete the pour.

Figure 4.8 – Shanghai Tower construction site (Tang, et al., 2014)

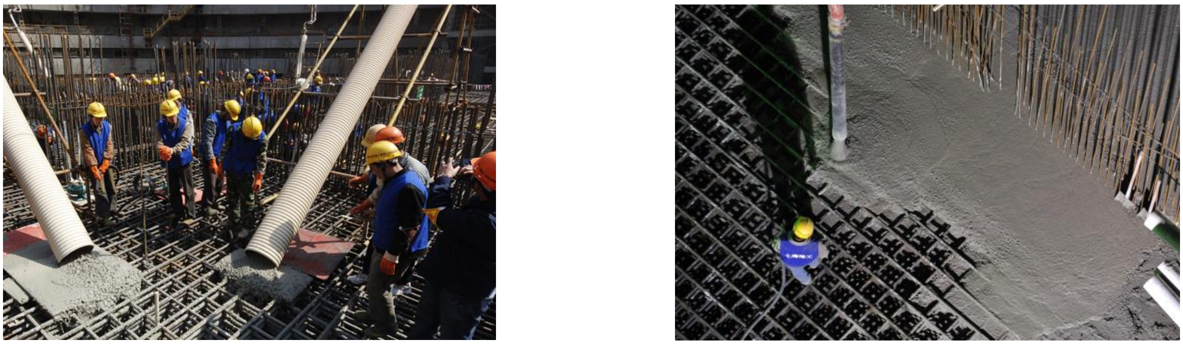

Figure 4.9 – Pour detail (Ray, 2010)

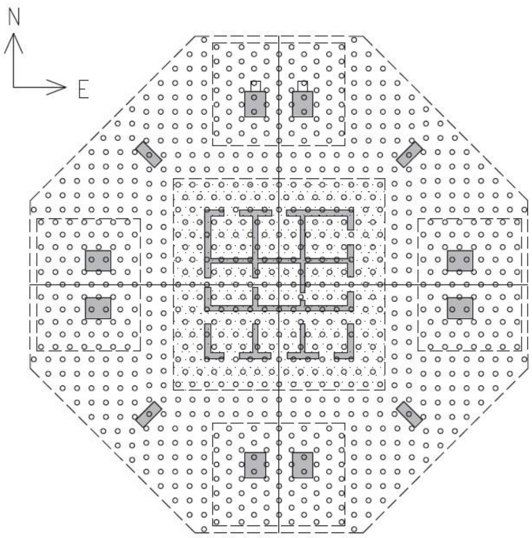

Figure 4.10 - Arrangement of piles of Shanghai Tower – plane (Tang, et al., 2014)

The piled raft foundation is in the shape of an octagon. Core tube and super column regions under concentrated loads are laid out in a quincunx matrix arrangement. Other columns are laid out in a square matrix arrangement (Xiao, et al., 2011), as shown in Figure 4.10. And according to Tang, et al (2014), the depth of embedment is 31.2 metres and the bored piles are buried in the depth of 82 metres (outside core zone) and 86 metres (inside core zone), as indicated in Figure 4.11. The groundwater level is generally 1 metre to 1.7 metre below the ground surface.

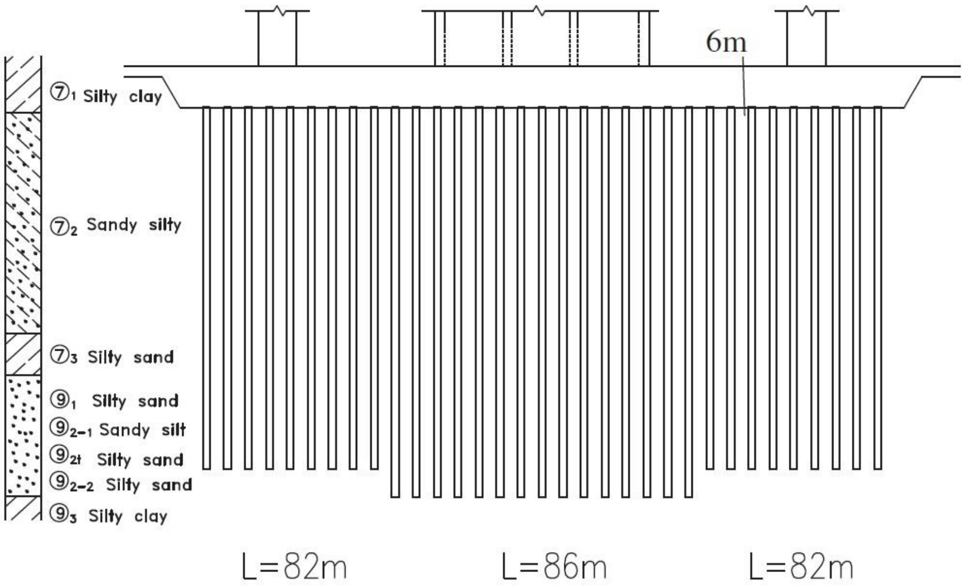

Figure 4.11- Arrangement of piles of Shanghai Tower – section (Tang, et al., 2014)

Figure 4.12 - A pair of super-columns on the 60th floor

Besides of clay-based soils typical of a river delta, Shanghai also has a windy climate and it is an active earthquake zone, structural team was facing amount of challenges. According to Jun, et al (2010) the structural engineers sought to simplify the building structure system, with a 90 by 90 foot concrete core (about 27.5 by 27.5 metres). The core acts in concert with an outrigger and super-column (measuring 5 x 4 metres at the base), Figure 4.12 shows a pair of super-columns on the 60th floor. Two super-columns at each end of each orthonormal. In addition, four diagonal super-columns along each 45 degree axis are required by the long distances at the base between the main orthonormal super-columns. These distances are approximately 50 metres and reduces to 25 metres to the diagonal columns. Plus double-belt trusses that support the base of each vertical neighbourhood, as shown in Figure 4.13. This makes for an easier and faster construction process – a significant cost savings for the client. Due to Shanghai Tower´s geometry, gradually narrows at each floor level consequently, the concrete core section reduces and gets simpler in zone 5 and zone 7, as shown in Figure 4.14.

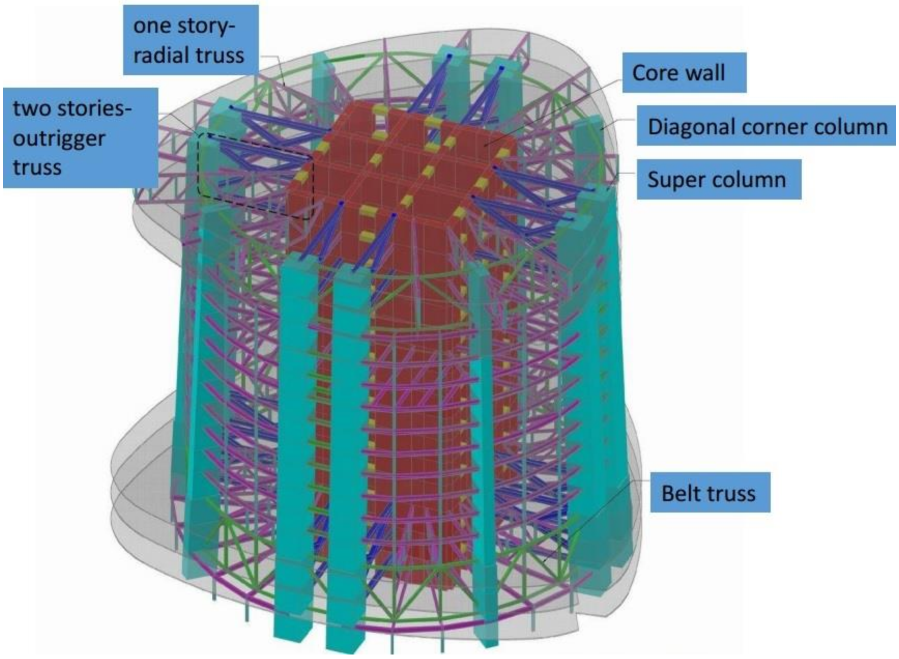

Figure 4.13 - Shanghai Tower structure in detail (Nichols, 2014)

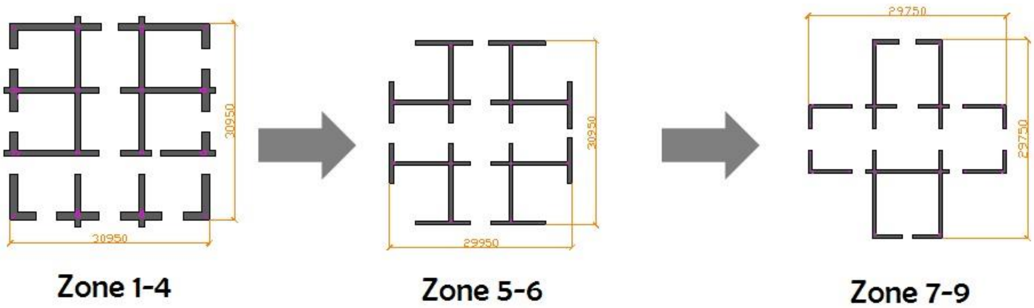

Figure 4.14 – Concrete core section in different zones (JKEC, 2012)

The core is concrete, the outrigger and belt trusses are structural steel, and the super-columns are composite structure with concrete-encased steel vertical sections. The encased steel sections in the super-columns are the key element to ensure the proper performance of the connections and thus the performance of the structure. The structure was designed to meet the performance based design which as required specified in the China Seismic Design Code, GB50011-2008 (Jun, et al., 2010)

The lateral and vertical resistance of the tower will be provided by the inner cylindrical tower. The primary lateral resistance is provided by the core, outrigger and super-column system. This system is supplemented by a mega-frame (see Figure 4.15) consisting of all the super-columns, including the diagonal columns together with a double belt truss at each zone that picks up the intermediate steel columns in each zone and the mechanical and refuge floors – at the interface of the adjacent zones (Jun, et al., 2010), as shown Figure 4.16.

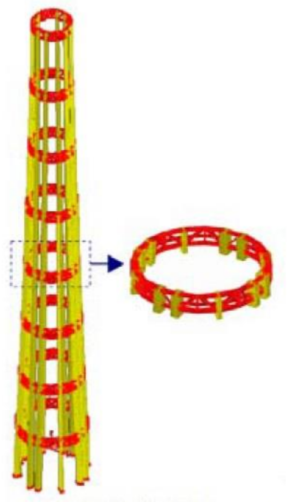

Figure 4.15 – Mega-frame (Jun, et al., 2010)

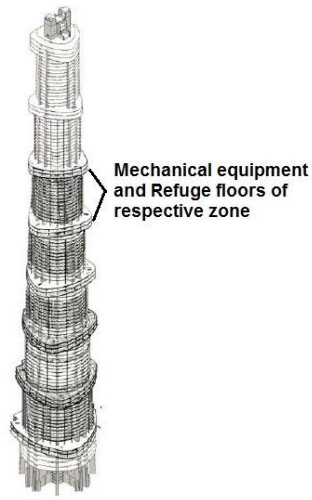

Figure 4.16 - Mechanical floors (Nichols, 2014)

Shanghai Tower is a high performance building, hence many kind of high-performance materials were selected for this megatall. For example (Han, et al., 2014), concrete C70 used for the super-columns in zones 1 to 3, C60 in zones 4 to 6 and C50 in zones 7 to 8, C60 was also used for the concrete shear walls and beams, and C50 used for the foundation. The Q345GJ steel used by the outrigger trusses, belt trusses and ring radial trusses. Shanghai tower's scale and complexity have created so many "firsts" for China's construction industry, but the structure design itself and BIM made for an easier and faster construction process. Workers positioned rebar and poured the mat foundation in March 2010. They affixed steel for the super-columns through the summer and, by December 2010 (see Figure 4.17), the structural core was taking shape. Figure 4.18 shows the concrete core construction progress in early 2011.

Figure 4.17 - Shanghai Tower – Concrete core construction in December 2011 (JKEC, 2012)

Figure 4.18 - Shanghai Tower – Concrete core construction in February 2011 (Harry, 2011)

4.4 Building Shape

Shanghai Tower has a very unique design, a soft vertical spiral rotating at about 120 degrees, scaling at 55% rate exponentially and double skin façade. Early in the design stage, Gensler team anticipated that three important design strategies – the asymmetry of the tower's form, its tapering profile, and rounded corners – would allow the building to withstand typhoon wind forces common to Shanghai. Using wind tunnel tests, Gensler and structural engineer Thornton Tomasetti refined the tower's form, ultimately reducing building wind loads by 24%. The result is a simpler and lighter structure with unprecedented transparency and a 32% reduction of costly materials (Gensler, 2010) (Nichols, 2014).

According to *Shanghai Tower Façade Design Process (2010)* "The horizontal profile (see Figure 4.19) shape is based on an equilateral triangle. Two tangential curves offset at 60 degrees were used to create a smooth shape."

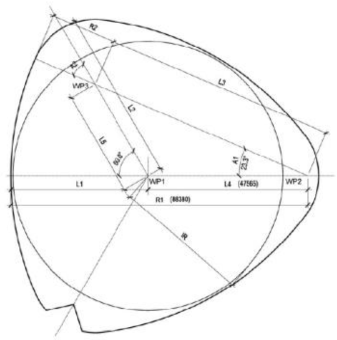

Figure 4.19 - Horizontal profile geometry (Shanghai Tower Façade Design Process, 2010)

4.4.1 Wind Tunnel Testing and Building Design

A large number of structures now being designed, especially very tall buildings, should always consider the relationship between importance of the wind and building height (see Figure 4.20). However, building shape optimization reduce wind loads on the building, allowing a simpler and lighter structure, this way contributing also to material saving, few examples can be seen in Figure 4.21.

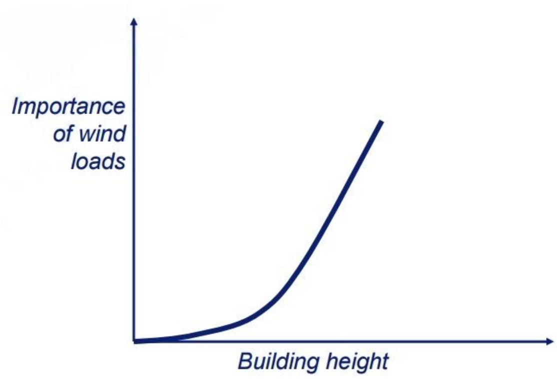

Figure 4.20 - Relationship between importance of wind and height (Irwin, 2010)

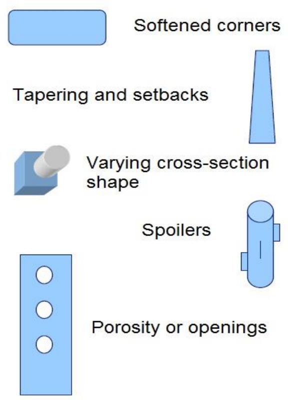

Figure 4.21 - Shape strategies (Irwin, 2010)

For designing Shanghai Tower, Gensler conducted a series of wind tunnel tests at RWDI for understanding the building performance and defining the optimal shape of the exterior skin of asymmetrical tapered tower that reducing wind load, consequently using a lighter, more efficient structure that conserves natural resources. All procedures were based on requirements set out in

Section 6.6 of the ASCE 7-05 Standard and the Load Code for the Design of Building Structures GB 50009-2001 for the P.R.C. In addition, to predict the full-scale structural response and more detail pressure loads, the wind tunnel data were combined with a statistical model of the local wind climate. The wind climate model was based on local surface wind measurements taken at Hong Qiao International Airport and a computer simulation of typhoons. All testing was conducted on a 1:500 model (see Figure 4.22). In order to obtain more precise data on loading and the impact of wind vortex split on round exterior wall surfaces, a 1:85 scale model (see Figure 4.23) was needed to test for results of the Reynolds number correction factor (Shanghai Tower Façade Design Process, 2010).

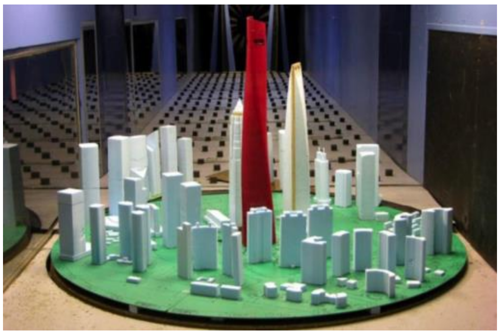

Figure 4.22 - Wind tunnel study, scale 1:500 (Shanghai Tower Façade Design Process, 2010)

Figure 4.23 - High Reynold number model study, scale 1:85 (Wind Engineering Reserch Needs, Building Codes and Project Specific Studies, 2009)

The Gensler design team had anticipated that significant reduction in both tower structural wind loading and wind cladding pressures could be established if the building further improved its geometry. To establish the best possible case for reducing these loads, several scenarios were proposed involving rotation at 90°, 120°, 150°, 180° and 210° (see Figure 4.24) and then scaling off 25%, 40% , 55%, 70% and 85% (see Figure 4.25). All these scenarios were analysed against each other and then compared to the base case scenario – in the form of a tapered box (Shanghai Tower Façade Design Process, 2010).

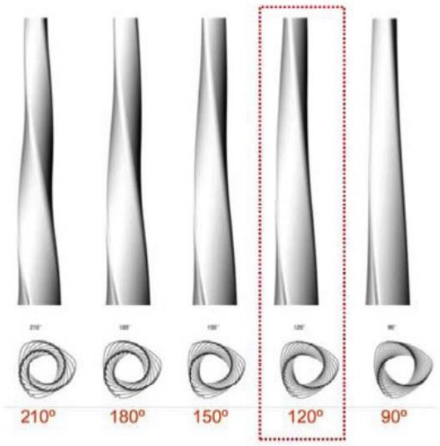

Figure 4.24 - Wind tunnel study rotation models (Shanghai Tower Façade Design Process, 2010)

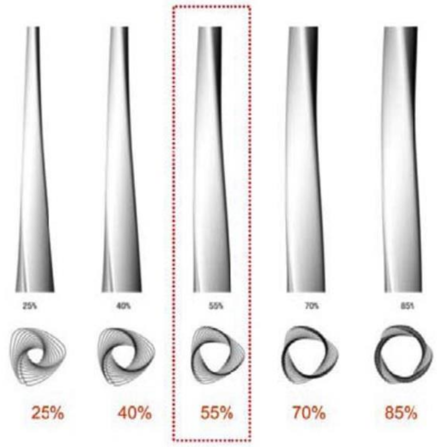

Figure 4.25 - Wind tunnel study scaling models (Shanghai Tower Façade Design Process, 2010)

As shown in Table 4.2, wind tunnel tests pinpointed that the most beneficial scaling factor of about 55% and rotation at 120°, which is account for the 24% savings of the wind load working on the structure as compared to base-case tapered box, this equates to about $50 million (USD) in savings in the building structure alone. However, the 180º rotation scenario would reduce loading by an additional 9%, but aesthetic concerns prevented the 180° rotation from being pursued.

Table 4.2 – Base reaction comparison of schemes with different twisting angle (Shanghai Tower Façade Design Process, 2010) (Nichols, 2014)

Configuration	My (MNm)	Ratio	Mx (MNm)	Ratio	Resultant base moment (MNm)	Ratio
Tapered box	5.45E+04	100%	4.98E+04	100%	6.22E+04	100%
100º	4.53E+04	83%	4.19E+04	84%	5.18E+04	83%
110º	3.97E+04	73%	4.31E+04	87%	4.92E+04	79%
120º	**3.43E+04**	**63%**	**4.29E+04**	**86%**	**4.75E+04**	**76%**
180º	3.39E+04	62%	3.65E+04	73%	4.18E+04	67%

Ongoing testing procedures included Reynolds number testing conducted with a final model at 1:85 scale (see Figure 4.23). During this testing, constraints particular to the site were exemplified with Jin Mao Tower and Shanghai World Financial Centre, which combined generate a localized increase in lateral turbulence intensity between 14% and 40% (Shanghai Tower Façade Design Process, 2010). The following conclusion was reached by RWDI "While the positive pressures are unaffected by the Reynolds number, the negative pressures could be increased at a high Reynolds number. Approaching wind turbulence tends to reduce the Reynolds-number effects. To account for potential Reynolds-number effects for cladding design, it is recommended that the exterior peak negative pressures around the building corners determined from the 1:500 scale model tests should be increased by 10%. This correction is applicable to the upper third of the building. For lower portions of the building, the Reynolds-number effects tend to be insignificant due to high turbulence levels. Similar corrections should also be considered in the structural wind loads for the curtain wall support system." (Kelly, 2009)

Figure 4.26 shows the final cladding loads testing results, which revealed peak positive loads (pressure) are at about 2.0 to 2.5 kPa for about 97% of the building, with 2.75 kPa maximum. Peak negative loads (suction), on the other hand, is at 4.5 kPa for about 85% of the building, with 6.5 kPa maximum. Peak negative loads are distributed considerably around corners and at the upper building half toward the top (Shanghai Tower Façade Design Process, 2010). These results are fundamental to curtain wall support system (CWSS) design, select the ideal glass panel and its respective thickness and dimension, which will be discussed forward.

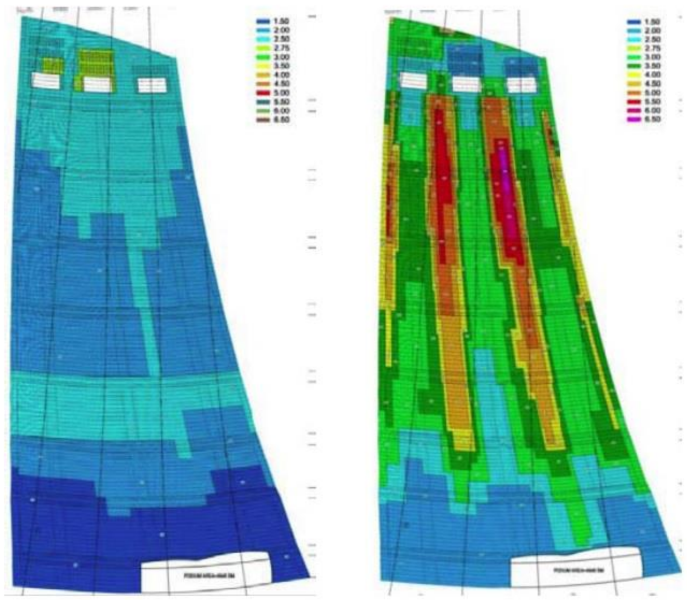

Figure 4.26 - Diagram of positive and negative wind cladding loads (Shanghai Tower Façade Design Process, 2010)

4.5 Sustainable Double Skin Curtain Wall

Shanghai Tower is one of the most sustainably advanced tall buildings in the world designed to achieve both LEED Gold certification and a China Green Building Three-Star rating. After defining the optimal shape of the exterior curtain wall by using wind tunnel testing, it is time to realize the benefits of double skin glass façade design.

4.5.1 Double Skin Curtain Wall Concept

Although Shanghai Tower is a mixed use building, but from zone 2 to 6 are office spaces and zone 7 to 8 are for hotel. Both office and hotel require a large amount of energy to operate. Compared to housing, office usually accommodates more people, and at the same time massive lighting and office equipment generate excessive heat. Artificial lighting is the biggest consumer in offices, followed by air-conditioning, which consumes more energy when used for cooling. In case of Hotel, main consumptions are space cooling/heating, domestic water and indoor pool heating, and artificial lighting. As a result, Gensler designed a double skin façade, utilizing natural light to reduce artificial light and, natural ventilation to reduce air conditioning energy consumption in whole building, this matter will be discussed further on.

Figure 4.27 - Curtain Wall A, CWSS and Curtain Wall B (left to right) (Nichols, 2014)

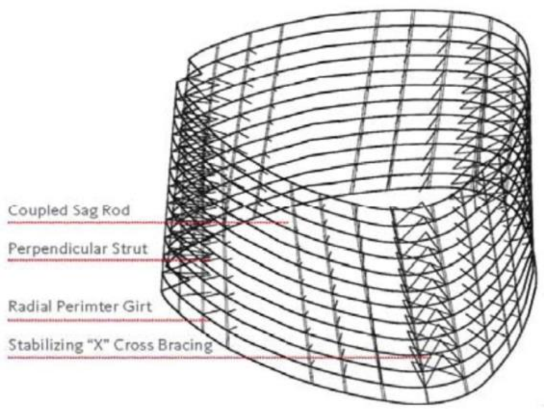

Figure 4.28 - CWSS (Shanghai Tower Façade Design Process, 2010)

The entire building is wrapped by two lays of transparent skins with a complex Curtain Wall Support System (CWSS), as shown in Figure 4.27 and Figure 4.28. The outer skin (curtain wall A) gradually narrows at each floor level, giving the glass tower an elegant tapered profile, while a V-notch in the curtain wall accentuates the spiralling geometry. And the shape of inner skin (curtain wall B) is cylindrical. Due to the interior curtain wall´s geometry – circular (in 2D), which requires 11.4% less glass than a building occupying the same total floor area but in a square design, demonstrated by the following equations.

Equation 1 $$Acir = \pi r^2 \Rightarrow r = \sqrt{\frac{A}{\pi}}$$

Equation 2 $$Asq = a^2 \Rightarrow r = \sqrt{A}$$

Equation 3 $$Pcir = 2\pi r$$

Equation 4 $$Psq = 4a$$

Equation 5 $$\frac{Pcir}{Psq} = \frac{2\pi\sqrt{\frac{A}{\pi}}}{4\sqrt{A}} = 88.6\%$$

A – Area P – Perimeter Cir – Circle Sq – Square

The main feature considered for the exterior wall performance is based on a bioclimatic concept of a passive atrium system, where two skins are located in such a way as to create a large, full height atrium space capitalizing on all the benefits that captured air and provide the natural convection of air (Shanghai Tower Façade Design Process, 2010), i.e., the ventilated atriums serve as an insulation which keep the temperature stable, act as a buffer between inside and outside, warming up the cool outside air in the winter and dissipating heat from the building interior in the summer (Gensler, 2010), therefore total thermal stresses and energy use in office spaces and the hotel are significantly reduced. Due to a completely passive greenhouse effect could be present in the atrium, there is minimal need for additional cooling and heating. In order to create a relatively comfortable atrium environment, the ventilation system is design with a great degree of efficiency (Shanghai Tower Façade Design Process, 2010), with only the first 15 feet (4.6 metres) of atrium mildly conditioned with the use of a perimeter Fan Coil Unit (FCU) that either heats or cools, primarily during weather extremes, leaving the majority of the atrium to be ventilated with a combination of natural updraft and regulated top exhausts, as well as with spill air on the first and last floor of each zone. And the condensation of moisture on the outer curtain wall in the atrium in winter is solved by equipping fin tube (Han, et al., 2014). Appendix P and Q indicates the atrium ventilation performance details in summer and winter respectively.

Moreover, the ventilated atriums house landscaped public gardens (see Figure 4.29). And these landscaped sky lobbies help to improve air quality, create visual connections between the city and the tower's interiors, and provide a place where building users can interact and mingle.

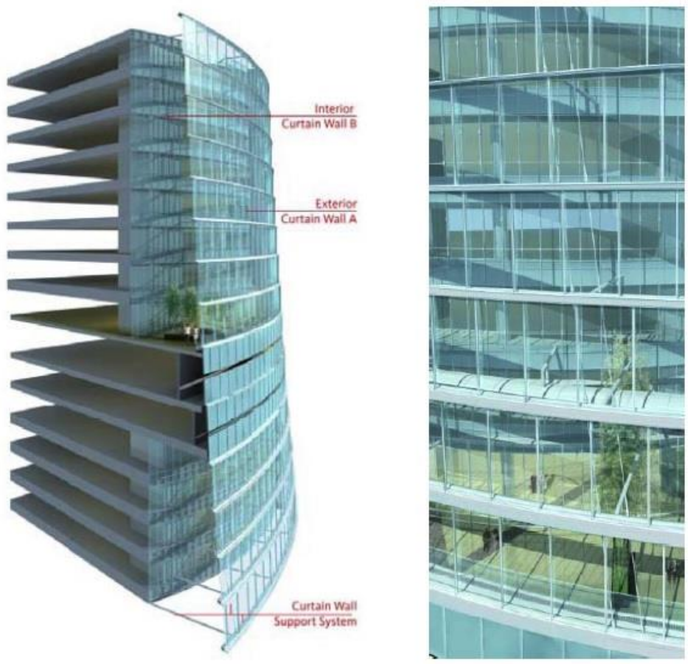

Figure 4.29 – Curtain wall system description (Shanghai Tower Façade Design Process, 2010)

At the interface of the adjacent zones, a two-story, full floor area is created strategically to house mechanical, electrical and plumbing equipment to provide optimal flexibility, reduce operating costs, and conserve energy. This area also serves as respective zone´s life safety refuge area. This full-floor platform creates a base for the atrium spaces directly above. As Gensler's founder, Arthur Gensler, told *The International Business Times*, "We hope Shanghai Tower inspires new ideas about what sustainable tall buildings can be. We've lined the perimeter of the tower, top to bottom, with public spaces, and we've integrated strategic environmental thinking into every move."

4.5.2 Light Pollution Studies

Building codes in China's urban districts are highly sensitive to the impact of sunlight reflecting off glass façades toward surrounding buildings. The ratio of glass on the building cannot be more than 70% and the glass has to have reflectance that does not exceed 15%. Therefore the light pollution category was the single most impactful variable in the overall exterior wall concept design and glass selection. The exterior curtain wall A glass ratio is very high, at about 87% (including spandrel area), and the interior curtain wall B has a glass ratio of about 60%. With these high glazing ratios, the design team needed to prepare a light pollution (Gensler, 2010) (Shanghai Tower Façade Design Process, 2010). Two final schemes – "staggered" and "smooth" were selected for testing in a three-kilometre radius of the surrounding neighbourhood (see Figure 4.30).

Considering all of the variables involved, the ultimate result was purely geometric, as the curtain panels confirmed the modelling and testing of both scenarios with the Ecotect software. Simply put, glass set vertically reflects less than glass angled to the sun. The largest angle on the tower was about 9°. The glass selected for the exterior have minimal visible light reflectance of about 12% (Shanghai Academy of Environmental Sciences, 2009) (Shanghai Tower Façade Design Process, 2010). However, Ecotect results revealed a difference favouring the staggered system, which would reflect less light onto neighbouring buildings, can be seen in Figure 4.31 and Figure 4.32. The outer curtain wall A design incorporates metal shelves at each floor level, producing the preferred staggered configuration (Gensler, 2010).

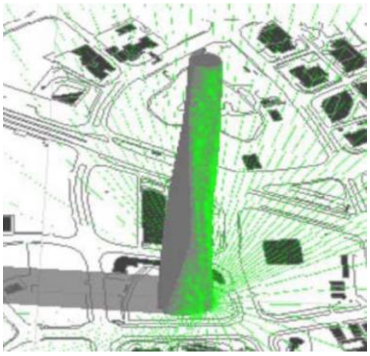

Figure 4.30 - Light pollution study model (Shanghai Tower Façade Design Process, 2010)

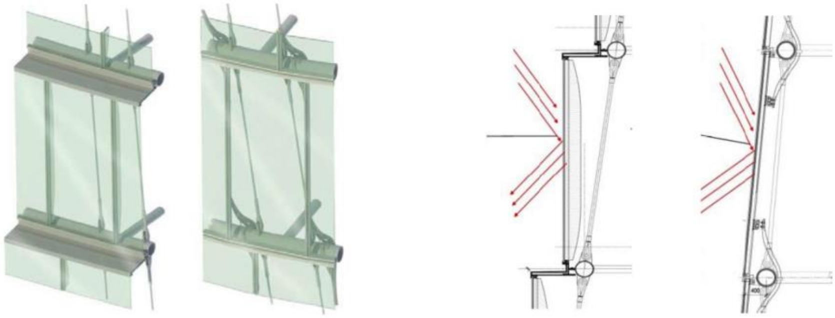

Figure 4.31 - "Staggered" and "smooth" schemes comparison (Shanghai Tower Façade Design Process, 2010)

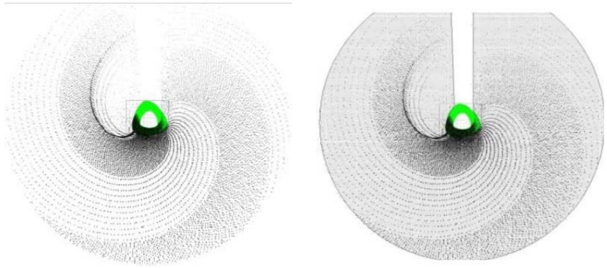

Figure 4.32 – Light pollution – “Staggered” (left) and “smooth” (right) schemes comparison (Shanghai Tower Façade Design Process, 2010)

4.5.3 Glass Selection

Shanghai experiences a subtropical maritime monsoon climate and so the weather is generally mild and fairly moist and experiences four distinct seasons: a warm spring, hot summer, cool autumn and cold winter. The city gets a moderate level of rainfall throughout the year, with constant and high relative humidity (up to 90%), combined with prescriptive city codes that are used to define required performance and make-up of exterior glazed walls components, and provided a new challenge to the design team. Building codes in China’s urban districts says: the exterior-wall-to-glass ratio could not be more than 70%; reflectance out cannot exceed an 15%; the shading coefficient (SC) must be to be between 0.4 to 0.5; and, if exterior glass creates a conditioned enclosure, then makeup has to be with a K value (thermal conductivity) of 1.5W/m² °C.

According to Zeljic (2010), the Façade Design Leader in Gensler, “if the exterior Curtain Wall A was to be considered as an enclosure for conditioned space of the building, then had to be an insulated glass unit. This created an additional challenge given the large size of the glass panels that varying from 2.2 by 4.5 metres to 1.2 by 4.3 metres. The glazing unit would have to be not only insulated unit makeup, impacting with that desired visual transmittance ratio (targeted very high – up to 0.8), but would also require individually thicker glass lights to respond to high wind-load peaks. In-plane glass deflection had to be less than 25 millimetres and with the insulated unit, there was a danger of two lights touching each other at high peak loads, thus creating the danger of possible peak incidental breakage. Although the idea of adding a spacer in the middle of the glass unit was possible, but not entertained. It has been calculated that if units were required to be insulated, then glass would have to be of a 15 mm glass + 10 mm air + 15 mm glass makeup. This was a significant increase from the 12 mm glass + SGP interlayer + 12mm glass laminated makeup that was targeted. At current weight, between 800 to 1,000 kilograms per glass unit (the largest units at Zones 2 and 3), this direction would result in an additional 25% increase in exterior glass weight. Ultimately, this would impact the CWSS in its effective size and visual appearance in atrium spaces, as well as on individual member weight, which would also impact the total building weight expected to be approximately 850,000 tonnes, spiralling all the way to potential redesign of an already approved complex foundation system on a limited site area.” It is common that the total exterior wall weight is within the ratio of up to 2% of total building weight; however, the intent of the design team was to truly follow principles of China’s Three-Star Rating, based on implementing high-efficiency standards with reduction and multiple usage of individual members where possible – *"Do more with less."*

After going through an extensive and complex review process, it was determined that Exterior Curtain Wall A was to be considered as a weather enclosure for ventilated and unconditioned atrium space, and that the true exterior wall is to be Interior Curtain Wall B. This allowed for Curtain Wall A to employ a laminated glass assembly and maintain efficient exterior wall-to-weight ratio, while maintaining desired transparency and glass area ratio. In addition, various strategies were employed to maintain atrium performance at a comfortable level (Shanghai Tower Façade Design Process, 2010).

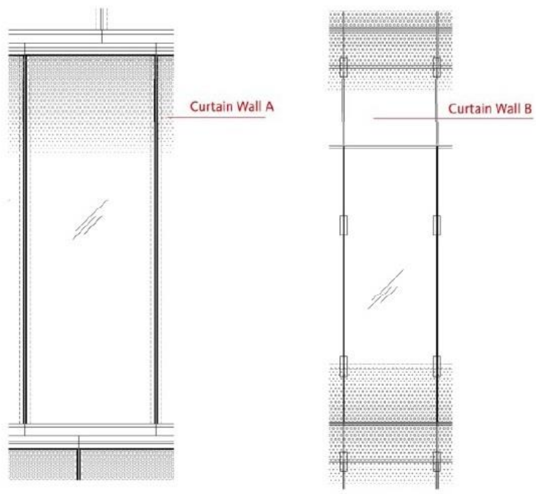

Figure 4.33 - Curtain wall A & B standard panels (Shanghai Tower Façade Design Process, 2010)

The final selection of glass composition for two major curtain wall Systems are (see Figure 4.33) (Shanghai Tower Façade Design Process, 2010) (SRIBS, 2014):

<u>Exterior Curtain Wall A</u>

26 mm laminated glass assembly – 12 mm low-iron glass +1.52 mm SGP interlayer + low-e coating + 12 mm low-iron glass, with following characteristics:

- SC = 0.88
- VT = 0.81
- K = 4.6 W/m² °C

<u>Interior Curtain Wall B</u>

30 mm insulated glass assembly – 10 mm low-iron glass with low-e coating + 12 mm air space + 8 mm low-iron glass, with following characteristics:

- SC = 0.43
- VT = 0.67
- K = 1.64 W/m² °C

To reduce heating and cooling loads, both the inner and outer curtain walls have a spectrally selective low-E coating (low thermal emissivity), its concept can be seen in Figure 4.34. This system only allows natural sunlight and shortwave heat energy to enter freely, thus reduces cooling costs in summer and heating costs in winter.

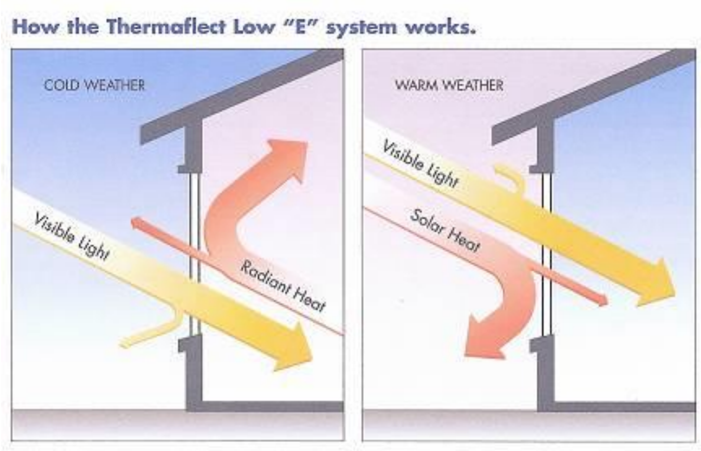

Figure 4.34 - Low-E in Cold weather and in Warm weather (Unknown, 2011)

According to Gensler (2010), fritted glass (see Figure 4.35 and Figure 4.36) on the outer wall provides additional sun-shading, aided by horizontal ledges at each floor level that will block high summer sun.

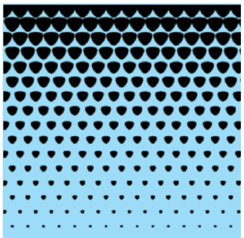

Figure 4.35 - Fritted glass (Gensler, 2010)

Figure 4.36 - Fritted glass of outer wall

The continuous glass skin admits the maximum amount of daylight into the atriums, reducing the need for artificial lighting. Floor to ceiling glass in the office and hotel floors yields similar benefits to those spaces. In addition, insulated glass of interior curtain wall blocks outside noise, to create a good indoor environment.

4.6 Other Sustainable Strategies used in Shanghai Tower

Sustainability is at the core of Shanghai Tower's development. In addition to Shanghai Tower´s peculiar height and unique architectural style, design team incorporated many other strategies that will generate a positive environmental impact. Due to these sustainable practices, Shanghai Tower earned both LEED Gold certificate and the highest score of Chinese Green Building Evaluation Label. The main objective of this subchapter is study some other sustainable technologies – renewable energy and mechanical, electrical, and plumbing (MEP) systems applied to this tremendous tower.

4.6.1 Ground Source Heat Pump

Ground source heat pump (GSHP) or Geothermal heat pump system exchanges heat between the constant temperature of soil and the building to maintain the comfort temperature of interior space. Because the underground soil temperature is relatively stable throughout the year, higher than the ambient air temperature in winter and, lower than the ambient air temperature in summer, therefore GSHP system is suitable for both heating and cooling.

Ground source heat pump system consists of three components: heat source system; the heat pump itself and a heat distribution system. A GSHP circulates a mixture of water and antifreeze (refrigerant) in a loop of pipe, called a ground loop, which is buried underground. Longer loops can draw more heat from the ground, but need more space to be buried in. If space is limited, then a vertical borehole can be drilled instead.

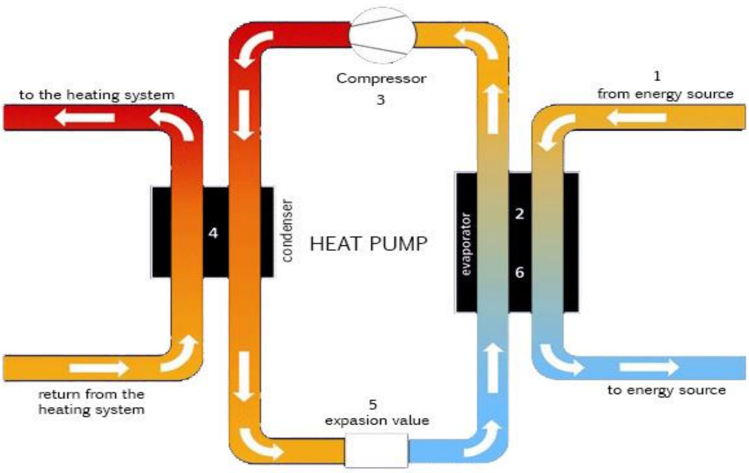

Figure 4.37 - Heat Pump circuit detail (Stratfordenergy, 2013)

Figure 4.37 shows the details of GSHP. The heat that is naturally present in the ground is absorbed by the refrigerant and then passes through evaporator into the heat pump. The refrigerant boils and evaporates, thus storing the generated energy. The refrigerant in gaseous form – warm gas at low pressure is then reduced in the compressor, which requires electrical power to function. When the warm gas is compressed, the pressure increases significantly and raises it to higher temperature, forming hot gas at high pressure. Then use this heat for operating an under floor heating system or producing hot water or can be used in a radiator. Afterwards the gaseous form refrigerant returns from the heat distribution system and goes through to a cooling process, the mixture returns to liquid form and, pass through expansion valve that causes a reduction in pressure and temperature, then it can again absorb heat from the soil. And so the ingenious cycle begins once again.

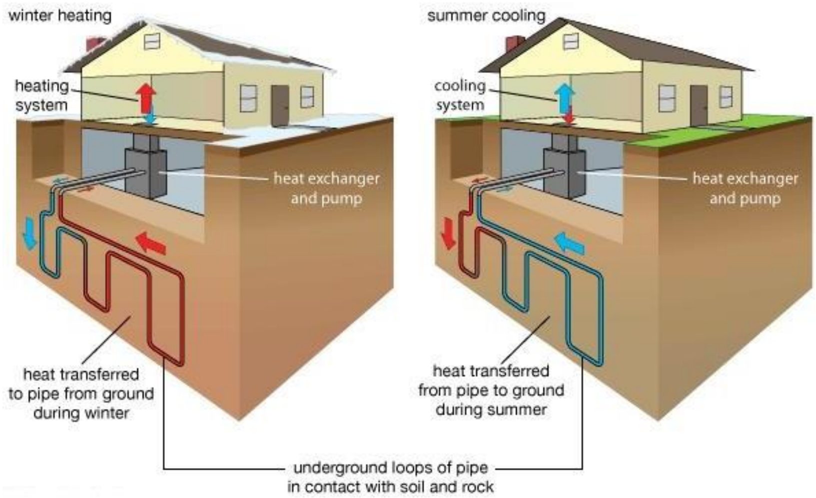

Figure 4.38 - Ground source heat pump system (Encylopaedia Britannica, 2012)

Simplifying, when the building needs heating, the system extracts heat energy from the ground, and pumps it into the building where it is boosted by the heat pump to a comfortably warm temperature. Conversely, when the building needs cooling, the heating process is reversed. Instead of extracting heat from the ground, heat is extracted from the air in the building and collected by the heat pumps and sent back into the ground, much as a refrigerator's compressor transfers heat from inside the refrigerator to the outside (see Figure 4.38).

According to the test, the annual temperature average of the underground of Shanghai Tower is 18.8ºC. Considering the safety of building structure and stability, 127 34-metre-long geothermal stakes were buried at 4-metre intervals. Each stake is designed as 191kW for cooling and 302kW for heating (Han, et al., 2014). GSHP system provides heating and air-conditioning to lower zones of Shanghai Tower. In summer, providing chiller water at 7ºC and return water temperature is 12ºC. In winter, supplying heated water at 51ºC and return water temperature is 46ºC (SRIBS, 2014).

GSHP system is much cheaper to operate than electric heating systems and, compare to traditional air source heat pump system, GSHP is 40% more efficient, can save 40% energy and operating costs. Moreover GSHP generate 40% to 70% less carbon monoxide gas than traditional heating systems (SRIBS, 2014). Hence, this system is eco-friendly.

4.6.2 Ice Storage Air-conditioning

Air-conditioning with ice thermal storage is green, cost-effective and reliable solution for cooling offices, schools, malls, convention centres and other buildings with daily comfort cooling requirements.

Ice Storage is like a battery for a building's air-conditioning system. It uses standard cooling equipment, plus an energy storage tank to shift all or apportion of a building's cooling needs to off-peak, night time hours. During off-peak hours, ice is made and stored inside ice storage tanks. The stored ice is then used to cool the building occupants the next day, as shown in Figure 4.39. Simply put, Ice Storage is a tank where ice can be accumulated during one period, stored and then thawed and used at another time. In the end of day, when the stored ice is fully melted, air-conditioning unit will automatically turn on the battery, then providing cold air to building as usual. Ice storage cooling system is compatible with majority of conventional air-conditioning units.

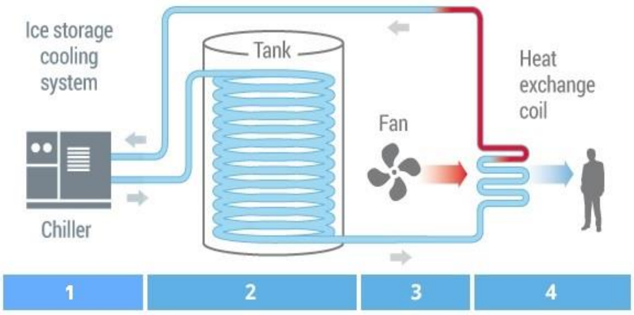

Figure 4.39 - Ice Storage Cooling System (Calmac, 2014)

The main reasons for using an ice storage air-conditioning system are:

- Where the cooling effect demand varies during the day, a smaller chiller can be used. As a result the initial cost of cooling equipment can be reduced considerably;
- Consuming energy at night or off-peak hours, when electric energy is more plentiful and less expensive;
- Reduce energy consumption during peak hours, hence reducing greenhouse gas emissions.
- Reduce electrical power infrastructure investment, due to electricity consumption peak load reduction. Two electrical profile of a building with and without ice storage system can be seen in Figure 4.40 and Figure 4.41.

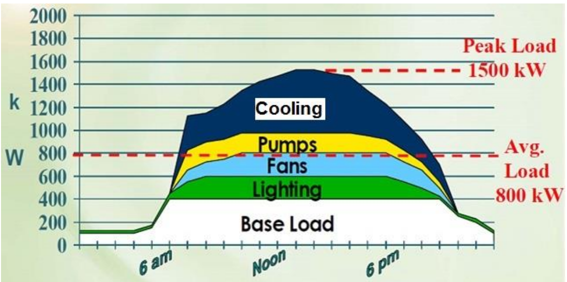

Figure 4.40 - Electrical profile with no ice storage (wahidmohamed, 2012)

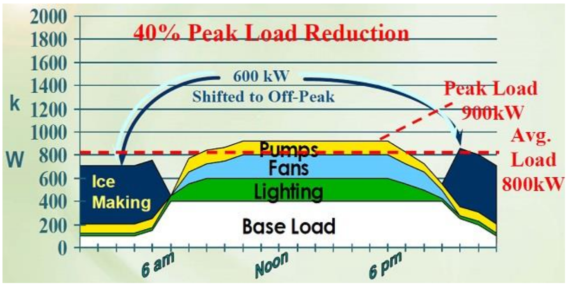

Figure 4.41 - Electrical profile with ice storage air-condition system (wahidmohamed, 2012)

An ice storage system is designed in Shanghai Tower to reduce the operation cost by reduce the peak loads need. The optimal capacity of the ice storage system is studied by the annual load profile of the low zone cooling system and the capacity of 26,400RTh is determined based on the energy price, the annual load profiles, investment and install cost (Cosentini, 2009).

The selected system is three dual-operating chiller units. The refrigerating capacity of the air conditioner is 1800 RT with a total ice storage capacity of 26,400 RTh (Liu, 2014). By adopting an indirect ice-melting steel disc tube component that melts ice internally there is increased energy saving and ease of control. The most efficient operating conditions are created by efficiently pumping ethylene-glycol through an elaborate air conditioning system. According to Han, et al., (2014) 6ºC chilled water is offered by the ice storage system through the heat exchanger, the ethylene-glycol solution enters the chillers at -1.57ºC and leaves at -5.56ºC to make the ice storage machine meet the maximum ice storage design capacity.

Parts of this system include single ice-maker chiller units alongside an ice-melting device. Also included is an ice-storage system teamed with a dual-operating conditioning unit. This system is entirety operated with low electricity without opening peak electricity. This system paired with dual-operating conditioner units, results in less frequent switching on and off ensuring that the previous day of ice could then be melted for the following day of cooling (Liu, 2014).

4.6.3 Combined Cooling, Heat and Power

A conventional electrical power is produced by inefficient process. A fossil fuel such as oil, coal, or natural gas is burned in a giant furnace to release heat energy. The heat is used to boil water and make steam, the steam drives a turbine, the turbine drives a generator, and the generator makes electricity (see Figure 4.42). There is amount of energy wasting during this process, for instance the water that's boiled into steam to drive the steam turbines has to be cooled down using giant cooling towers in the open air. Cold fluid from the cooling tower absorbs heat from a condenser and gets heated, this heat is rejected to the atmosphere via natural convection with the help of a cooling tower, i.e., the heat literally disappears into air, wasting huge amounts of energy.

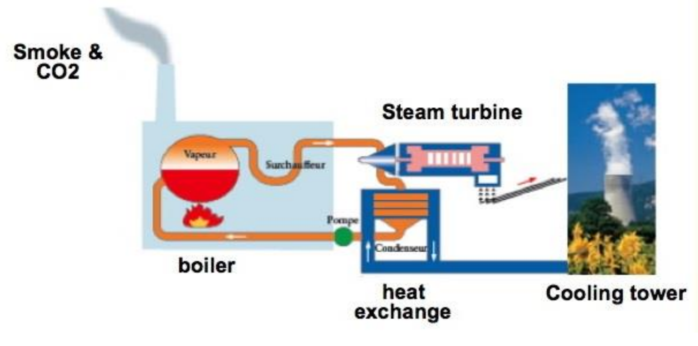

Figure 4.42 - Conventional electrical power plant (Barré, 2013)

Combined cooling, heat and power (CCHP) or Tri-generation is the simultaneous onsite generation of electricity, heat and cooling from a single fuel source. Waste heat from turbine provides energy to heat recovery unit, then produce heating and generate chilled water for air conditioning or refrigeration (see Figure 4.43). This simultaneous generation from a single fuel source makes CCHP system highly efficient compared to conventional power generation, and making it the ideal solution for organizations which have significant cooling requirements.

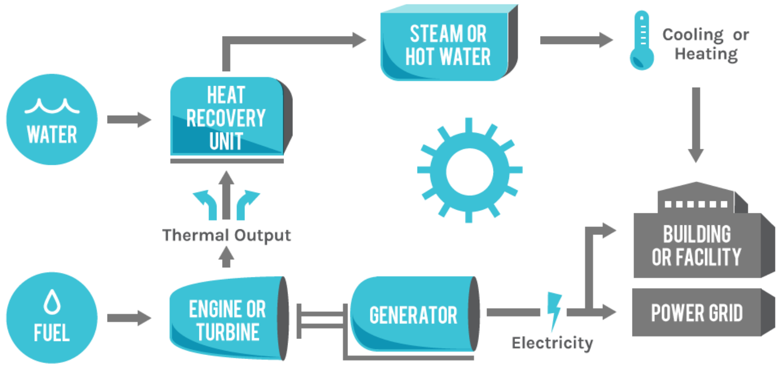

Figure 4.43 - Combined cooling, heat and power (Dynamicenergy, 2015)

Shanghai Tower design team incorporated a combined cooling, heat and power system to achieve higher energy efficiency. This system is installed in the lower energy centre (Han, et al., 2014), which is set up in floor B2.

According to Liu (2014), "CCHP system is made of two sets of 1.1MW gas internal combustion generating sets in addition to 2 sets of 1000kW lithium-bromide heating unit. Further are 2 sets of 1300kW grade plate type thermal water heat exchangers, automatic controls and a corresponding auxiliary system. The average annual load rate of the system powered on is 95% of the average annual energy efficiency of about 80% (the generating efficiency is about 40% and the waste heat utilization is about 45.8%). The system runs from 6am to 10pm, 16 hours per day, for 335 days of the year. Average annual output of the system is about 10.72million kWh, with an average annual cooling capacity of about 8.93 million kW. The average annual amount of heating is about 3.28 million kW saving 1,098 tonnes of standard coal per year and roughly 6,277 tonnes of carbon dioxide per year."

4.6.4 Wind Turbines

Supertall and megatall buildings are ideal for wind power, because of abundant wind resources on top of the building all year round. Hence Shanghai Tower design team has chosen this renewable energy.

The wind field analysis shows that wind power at the top of the Shanghai tower was 2 to 3 times more than at ground level. The average wind speed at ground level in Shanghai is 3m/s that means the wind speed at the top of Shanghai Tower reaches at least 6m/s, which is proper for generating wind power. In order to generate the maximum amount of wind power (Han, et al., 2014), 270 horizontally oriented wind turbines (single capacity of 500W), with the total capacity of 135kW wind turbines are installed on 122F, 123F and 124F, between the inner and outer curtain walls, as indicated in Figure 4.44. Generator room is located on 123F, equipped with three inverters of 50kW. The energy produced by wind turbines is rectified by the inverter and convert to 220kv AC then goes to the substation of 116F, later to the building electrical power supply network. In addition, there are 54 vertical axis wind turbines set on 565 to 569 metres high of tower (see Figure 4.45). With the daily average wind speed 6m/s, wind turbines at the top of the building will produce annually an estimated 157,500 kWh in renewable energy and will power the exterior lighting and public spaces (SRIBS, 2014).

Figure 4.44 - Horizontally oriented wind turbines (Skyscraper, 2014)

Figure 4.45 - Vertical axis wind turbines (JKEC, 2012)

4.6.5 Grey Water and Rainwater Recycling

In order to meet the requirements of the National Green Building Three-Star Standard, the non-traditional water resource utilization ratio of functional areas should not be less than 25% for Shanghai Tower Hotel. Non-traditional water resource utilization ratios of business offices should not be less than 40%.

For the effective conservation of water resources the water treatment system is optimized to recycle the bath wastewater from the hotel area, the toilet wastewater from the office area and the rainwater collected by the building. Then use the treated water for basement garage washing, plant irrigation and toilet flushing etc.

There are three sets of greywater collection and treatment systems located on 66F and B5 of the Shanghai Tower, the process of greywater treatment is designed as (Han, et al., 2014):

- Wastewater
- Grille wells
- Collect pool
- MBR membrane bioreactor
- Disinfection
- Water tank

According to Liu (2014), the greywater treatment system of the 66F is responsible for collecting and processing the recycled water of the 66F – 121F, treated water from this system will mainly use for toilet flushing water. On B5, there are two sets of greywater treatment system, which are responsible for collecting and processing of recycled water from B5 – 65F. Treated water from B5 will mainly use for toiled flushing, ground washing, car washing and plant irrigation. Furthermore, there are four sets of rainwater treatment systems, one is on 66F and other three are on B5. Treated rainwater will also be used for ground washing, car washing and plant irrigation etc.

Never the less, the quality of recycled water should meet the requirements of water quality standard of China. According to the design team, there are 237,000 m^3 of greywater, including 8700 m^3 of rainwater, which will be collected, treated and recycled in the buildings every year. The utilization rate of water recycling resources is up to 24% (Tongji University, 2012)

4.6.6 Energy Efficient Elevator

Elevator is one of the largest energy consuming equipment of high-rise buildings. Elevator Association of China estimates that the average daily power consumption of each elevator is around 40kWh, about 5% of the total building energy consumption (SRIBS, 2014). Thus energy efficient elevator will become the future of high-rise industry. However, this kind of elevator is not very popular in China, especially in the residential buildings. When the developers choose elevators for building, due to the relatively higher initial costs, they often choose not to invest in energy efficient elevator. Hence it is important to realize the advantages of this sustainable technology.

Elevator with regenerative drive system

According to Sniderman (2012), energy efficient elevator technology consists in “when power flows into the motor, it creates a lifting torque on the shaft and elevator sheave, lifting the carriage. When the carriage travels down, the motor acts as a generator, transforming mechanical power into electrical power and pumping current back into the facility’s electrical grid to use elsewhere.”

“When a cab goes up with a light load and down with a heavy load, the system generates more power than it uses. Over time these small amounts of power generated during each elevator’s sporadic decelerations add up to noticeable savings. They use less energy than non-regenerative drives, and reducing the excess heat in the building.” Figure 4.46 shows the basic concept.

For example (SRIBS, 2014), a 200 metres tall mixed use high-rise building in Shanghai with 38 elevators and 6 escalators, all with regenerative drive system. Comparing it to a non-regenerative drives system, surprisingly the building electrical power consumption for elevator and escalators reduced significantly to 25% to 31%, regenerative drive system of this building generated 2,065kWh renewable power per day.

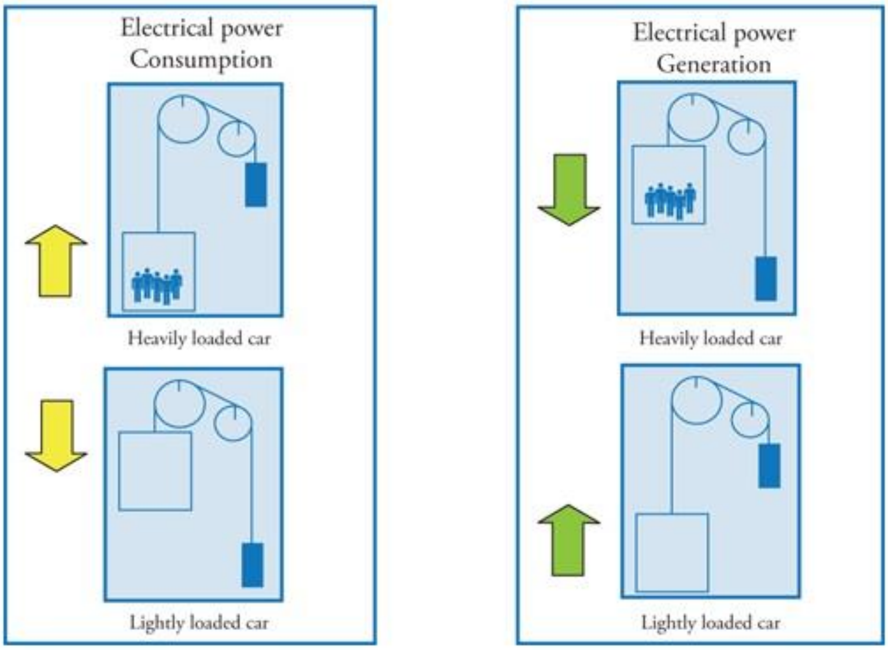

Figure 4.46 - Diagram depicting how the Regenerative Drive system works (Sniderman, 2012) (Otis Worldwide)

Double deck elevators

There are 106 elevators in Shanghai Tower, few of those are double deck elevators (see Figure 4.47). The real benefit of the double deck elevator is that while people can be transported in the same time as single deck elevators, the required shaft area is reduced (Russett, 2010).

Figure 4.47 - Double deck elevator (Russett, 2010)

Shanghai Tower has three super high speed double deck elevators are capable of traveling at 18m/s, four double deck elevators travel at 10m/s, and five single deck elevator travel at 8m/s. In addition, Shanghai Tower owns the world farthest-traveling single elevator, which travels up to 578.55 metres tall (SRIBS, 2014).

4.6.7 BIM - Building Information Modelling

The unique design and extraordinarily complex structure of Shanghai Tower have brought unprecedented challenges and created so many “firsts” for China’s construction industry, but BIM made for an easier, securer and faster construction process.

Until recently, traditional building design was largely reliant upon two-dimensional technical drawings (plans, elevations, sections, etc.). Building information modeling (BIM) extends this beyond to 3D – width, height and depth, with time as the fourth dimension (4D) and cost as the fifth (5D).

According to the characteristics and scale of the project of Shanghai Tower, the 3D and 4D BIM model were fundamental to construction processes. BIM was able to simulate the key difficulties of the construction schemes and provides construction guidance. BIM technology also improved the quality of the specialised construction schemes, making it more efficient. The construction scheme animation of the BIM software focuses on specific and difficult details, successively revelling relationships between construction processes and time sequences. Also, it illustratively describes, in detail, the relationship of each working procedure allowing construction personnel to clearly understand the construction sequences, and to accurately and efficiently accomplish important nodes of the construction work. This improves the efficiency and quality of the whole construction process (Liu, 2014).

The BIM technology is capable of detecting conflicts by collecting all the various professional models together in one workspace. The software then highlights and locates conflicts and adjusts quickly, thus significantly improving the work efficiency. At the same time, BIM reduces communication obstacles and provides the most convenient, intuitive or relaying information.

Through efficient site data management, instant modifications can be quickly reflected in the model thereby reflecting the best plan layout which is highly consistent with actual conditions. This immediacy improves the success rate of one-time installations and reduces the amount of repeated work.

This way, BIM technology has ensured construction safety, quality and fast progress of complex curtain wall system of Shanghai Tower. According to Jianke Project Management, by using BIM curtain wall was climbing up at the speed of one floor in every four days.

4.6.8 Sustainable Construction Management

In order to preserve nature resources and lower the negative influences of construction on the surrounding environment, the sustainable construction management was implemented to Shanghai Tower. Mainly addressed to soil balance, construction road use, noise, dust, water, light pollution, local material use and recycling construction solid, etc. (see Figure 4.48 to Figure 4.53) The construction monitoring and management data shows that the measures to control dust, noise and light pollution are effective and meet the requirements of Chinese Green Building Label standard.

Figure 4.48 - Recycle waste rebar (SRIBS, 2012)

Figure 4.49 – Dust control (JKPM, 2011)

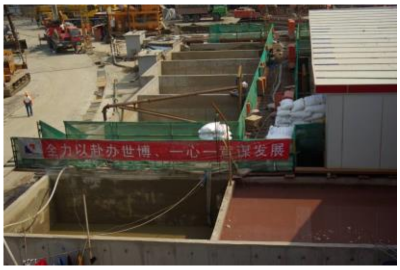

Figure 4.50 - Mud filter tank (JKPM, 2011)

Figure 4.51 – Isolation setting (JKPM, 2011)

Figure 4.52 - Noise testing (SRIBS, 2012)

Figure 4.53 - Reuse of mud pit fence (SRIBS, 2012)

As for building materials, construction engineers have always seek out building materials that are harvested and manufactured within an 800-kilometre radius of the site. Locally sourced materials are sustainable because these products reduce transportation related environmental impacts and boosts local economies. In addition, locally sourced materials with high-recycled content were being used when available. Of course, environment friendly materials, high performance materials, embedded waste materials and recycling the construction solid waste were also requested in the construction process of Shanghai Tower. Table 4.3 indicates the construction waste statistics – steel and gravel of 2009 and 2010. Waste steel recycling rate of those two years was 81% and, gravel recycling rate was 88.5%.

Table 4.3 - 2009 & 2010 Construction waste statistics (JKPM, 2011)

	Material	**Total amount of waste (tonne)**	**Total amount of waste recycling (tonne)**	**Recycling rate**
2009	Waste steel	11382.7	11047.7	98%
2009	Gravel	57077.8	48136.8	84%
2010	Waste steel	627.02	385.02	64%
2010	Gravel	29335.33	27220	93%
Total	Total amount of waste (tonne)	98422.85	86789.52	88%

According to the statistical results of the material use during the construction period, the ratio local material is 83.1%, the ratio of the high performance concrete is 39.8%. And the BIM technology was also introduced in Shanghai Tower to remove the potential risk of the collision during the construction effectively and reduce the implied probability for reworking or repairing of the project (Han, et al., 2014).

Last but not least, safety always comes at first place, the following figures show construction workers and engineers with their safety equipment on the construction site of Shanghai Tower.

Figure 4.54 - Construction workers examining CWSS

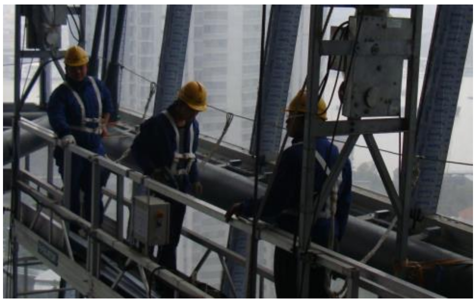

Figure 4.55 - Construction workers working on outer curtain wall

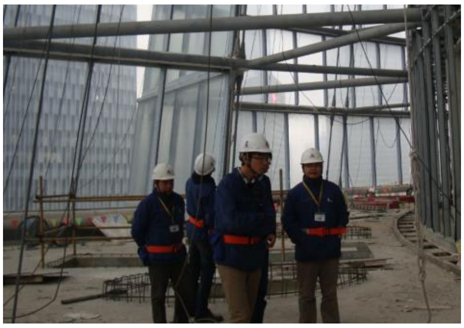

Figure 4.56 - JKPM engineers on Shanghai Tower construction site

Figure 4.57 - Me and my trainee colleague visiting Shanghai Tower construction site

4.7 The Tallest Green Skyscraper – Shanghai Tower

Shanghai Tower is not the tallest building, but it is the tallest green skyscraper in the world. According to Gensler (2010), its architecture design allowed reducing building wind loads by 24%. The result is a simpler and lighter structure with unprecedented transparency and a 32% reduction of costly materials. Tower´s curtain wall system and other sustainable strategies incorporated in building create about 21% energy efficiency, compared to ASHRAE 90.1–2004 in LEED Rating and about 12.5% over China's nationally recognized GBEL assessment. 7% of total efficiency is achieved as a result of various features used for exterior skin design. Moreover, Shanghai Tower's sustainable strategies will reduce water consumption by 40% and reduce building's carbon footprint by 34,000 tonnes per year.

5 Discussion

5.1 Policy in China

China became one of the largest developing and world's most populous country, the rapidly growing economy (industrialization and urbanization) has driven the country's high overall energy demand and the quest for securing energy resources. And the environmental pollution in China has reached a very high level, especially air pollution, that sometimes people are not advisable to leave their home because of the outdoor air quality. Unfortunately building industry is one of the main contributor to China´s current environment situation.

Table 5.1 - Differences between GBEL and LEED

	GBEL (Three-Star system)	LEED BD+C
History	Initiated by MOHURD (Ministry of Housing and Urban-Rural Development) in 2006	Initiated by USGBC (United States Green Building Council) in 2000
Organization operation	Governmental	Non-governmental
Application	People´s Republic of China (nationwide)	Worldwide
Rating system	Public (including retail, office, hotel buildings and government buildings) and Residential	New Construction and Major Renovation, Core and Shell Development, Schools, Retail, Data Centres, Warehouses and Distribution Centres, Hospitality, Healthcare
Operational rating stage	Operational GBL - One year after occupancy	For new construction: immediately after completion
Level of certification	3 levels: One-star to Three-star. Three-star is the highest level	4 levels: Certified, Silver, Gold, Platinum. Platinum is the highest level
Rating method	Must achieve the minimum score in all six categories, not determined by the total score	Determined by the total score summed over all categories

In 2006, the Chinese government launched the Evolution Standard for Green Building. Since then, the green and sustainable market has grown greatly, and this increase has much to do with policy measures implanted by the government. Green Building Evolution Label (GBEL) and U.S. Leadership in Energy & Environmental Design (LEED) rating systems are recognized and commonly used in China. They have a lot of similarities, both systems are volunteer assessment systems based on credit systems, and mainly focusing on land/location, energy, water, resource/material efficiency, and indoor environmental quality. But there is a slightly difference between GBEL and LEED, can be seen in Table 5.1. One of main difference is their rating method. In GBEL the rating result does not depend on the total score, in order to qualify for a specific rating result, there is a minimum score to meet in each category. On the other hand, LEED rating method is simpler compared to GBEL, is determined by the total score summed over all categories. GBEL seems less flexible compared to LEED, but GBEL is more objective.

However in the beginning, GBEL still was a new and junior certification system compared to LEED, there were doubts about GBEL, thus LEED was the first choice for some building developers. But over time, GBEL became more popular in China, after all GBEL was especially designed to solve the existing environmental issues in China, and it is not surprising that, for Chinese developers GBEL is more practical to apply than LEED, more suitable for China. With financial incentives from the government, many high-rise building developers in South and East of China have considered incorporating sustainable strategies into building design, by following guidelines of GBEL or LEED or both ratings.

In a relatively short period, green building has become a trend nowadays in China. Thereby the Chinese government has reached its initial goal, expand and promote green building and sustainable construction concept to every corner of China, more important was able to put theory into practice, achieving better performing green buildings in order to reduce high level environment pollution. In the past few years, China extensively promoted green building and sustainable construction. It is important to notice that sustainable construction is not just a trend or a "brand" to developers, but a continuing investment to a better future.

5.2 Sustainable High-rise in Shanghai

The main problems associated to climate of Shanghai are humanity and typhoon. Whether is in Shanghai or not, when comes to high-rise buildings should always considering the relationship between importance of the wind and building height. After analysing the case study – Shanghai Tower was able to realize that building shape optimization reduce wind loads on the building, consequently using a lighter, simpler and more efficient structure that conserves natural. In the case study wind tunnel testing was required to determinate building shape that results in better performance of the building. Generally depends on the building complexity and scale, not all the high-rises require wind tunnel testing. Figure 5.1 shows some shape strategies that lead to reduce wind loads on the structure.

Double skin façade presented in the case study is a passive strategy, and is based on a bioclimatic concept of a passive atrium system, where two skins are located in such a way as to create a large, full height atrium space capitalizing on all the benefits that captured air and provide the natural convection of air and natural lighting. Thus total thermal stresses and energy use in office and the hotel are significantly reduced. Although a passive greenhouse effect could be present in the atrium, there is minimal need for additional cooling and heating. Therefore double skin façade works at climates similar as Shanghai or little bit cooler, but won´t be a good solution to extremely hot or cold climates, due to intensive greenhouse effect and condensation of moisture on the outer curtain wall.

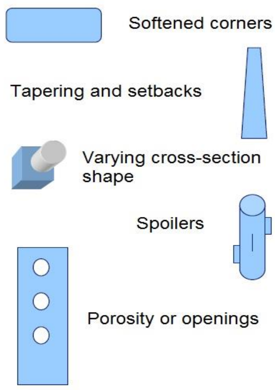

Figure 5.1 - Shape strategies (Irwin, 2010)

Other passive strategy – building orientation is fundamental to building´s energy performance. Orientation is related to solar gain, which affects the building's heating, cooling, daylight, ventilation and lighting, therefore a "right" building orientation reduces annual energy consumption. Orientation, in combination with window area and the type of glass, also affects the amount of light that can enter a space. However, in colder climates, possible heat loss through the window unit should be considered. Moreover in most climates, a southern orientation is preferred due to the ability to shade the summer sun to reduce unwanted solar gain while still capturing daylight to reduce the lighting energy load. The angle of the summer sun is much higher while the angle of the sun in the winter is lower which allows the light and heat to possibly enter the space. North oriented façades receive good ambient and indirect daylight, solar heat gain, too much direct light, and glare issues are minimized. Regarding the east and west orientation are not desirable, due to low sun angles, glare and increased solar heat gain is harder to control on the east and west façades. Note when using a glazing system with a high visible transmittance, glare issues need to be considered, if possible conduct light pollution studies as the case study. Nowadays many buildings use insulated glass for better energy performance, there is many kind of insulated glasses in the market, if possible should analyse the selected glass and façade with the assistance of software such as Ectotec and EnergyPlus. As for Shanghai the best façade orientation is south.

Further, depending on the climate, certain low-E coatings (low thermal emissivity) will allow or reject the solar heat gain through the glazing system. But this passive solar gain is not desirable in a very hot climate. Both Shanghai Tower´s inner and outer curtain wall glasses use low-E coatings, which allows natural sunlight and shortwave heat energy to enter freely, reflects longwave heat energy radiating from outside in warn weather thus reducing cooling costs; and preserve heat energy from inside in cold weather, like this lowering heating costs. In addition to incorporating passive strategies should also integrate the active systems into project, such as renewable energy, mechanical, electrical, and plumbing (MEP) systems.

The most common renewable energies for buildings are solar and wind. Solar is a perfect solution for places with sunshine all year around. In case of high-rise buildings install solar panels on the rooftop won't be in enough to supply the whole building, so would be interesting to add photovoltaic façade if possible. As for wind power, supertall and megatall buildings are ideal for this kind of renewable energy, because of abundant wind resources on top of the building all year round. Horizontal and vertical axis wind turbines are incorporated on top of Shanghai Tower, which will produce annually an estimated 157,500kWh in renewable energy. This way maximize the use of these natural resources (sun and wind), lowering the energy costs associated with buildings and achieving a low carbon footprint.

Besides of the passive strategies and renewable energies, MEP systems are also fundamental to reduce energy consumption and carbon footprint. For instance, CCHP is eco-friendly solution, the simultaneous onsite generation of electricity, heat and cooling from a single fuel source; GSHP, this system exchanges heat between the constant temperature of soil and the building to maintain the comfort temperature of interior space; Energy efficient elevator, the motor acts as a generator, transforming mechanical power into electrical power and pumping current back into the facility's electrical grid to use elsewhere. Many other active systems are essential to energy saving and reduce carbon footprint. Table 5.2 indicates the annual energy produced by wind, GSHP and CCHP systems. Table 5.3 shows these values per square metre. GSHP supplies partial cooling and heating for the lowest zone, while CCHP and wind power supply the office zone. CCHP is the main energy supply system of these three.

Table 5.2 - Annual energy supply values

	Cooling (kW)	Heating (kW)	Electricity (kWh)
GSHP	24257	38354	-
CCHP	8.93E+06	3.28E+06	1.07E+07
Wind Power	-	-	157500

Table 5.3 - Annual energy supply per square metre

Energy supply	Floor area (m^2)	Cooling (kW/m^2)	Heating (kW/m^2)	Electricity (kWh/ m^2)
GSHP for Zone 1 (retail)	57415	0.42	0.67	-
CCHP for Zone 2 to 6 (office)	232177	38.46	14.13	46.17
Wind Power for Zone 2 to 6	232177	-	-	0.68

Grey water and rainwater recycling is an excellent solution to all kind of high-rises for effective conservation of water resources. Water treatment system recycle the bath wastewater and the rainwater collected by the building, then use the treated water for basement garage washing, road washing and toilet flushing. The office zone (2 to 6) floor area is 232,177m^2, suppose each occupant occupies 5m^2, that means there will be about 46,435 occupants in zone 2 to 6. Consider 252 work days per year, each office occupant uses in average 2.5 times toilet during their working hours, so the total amount of recycled water will supply daily toilet flushing for 39,000 occupants, which represents 84% of total office zone occupants (see Table 5.4). Moreover, the total amount of recycled water would be enough for 5417 car washing per day.

Table 5.4 - Recycle water consumption

	dm^3	Activities	dm^3	Annually (times)	Daily (times)	Occupants
Total recycled water	245.7E+06	Car washing	180	1365000	5417	-
		Toilet flushing	10	24570000	97500	39000
Gray Water	237E+06					
Rain Water	8.7E+06					

Shanghai tower’s scale and complexity have created so many “firsts” for China’s construction industry, but Building Information Modelling (BIM) made for an easier and faster construction process. By detecting conflicts by collecting all the various professional models together in one workspace, removing the potential risk of the collision during the construction effectively and reducing the implied probability for reworking or repairing of the project. Further, BIM was capable of simulating the key difficulties of the construction schemes and provides construction guidance during tower´s construction process. The construction scheme animation of the BIM software focused on specific and difficult details, successively revelling relationships between construction processes and time sequences. Therefore BIM is the future of construction industry.

When it comes to material selection, locally sourced materials are more sustainable because these products reduce the environmental impacts associated with transportation and increases local economies. In order to preserve natural resources, locally sourced materials with high recycled content should be used when available. Of course, eco-friendly materials, high-performance materials, and recycling of solid waste are also part of sustainable construction. These points were achieved by Shanghai Tower, the ratio local material was 83.1%, and the ratio of the high performance concrete was 39.8%.

The solutions and strategies referred in this thesis are fundamental to reach sustainability for high-rises, allowing better performance over building´s life cycle. However, the investment for a sustainable building is till significantly higher than a standard building, it is a long-term investment. For instance, a building with the highest classification (tree-star) of GBEL will take between 7-11 years recovering the initial investment, in case of a two-star building will take 3-8 years.

Although some types of building development may be regarded as more sustainable than others. For example, the benefits of converting existing buildings rather than demolishing and rebuilding them in terms of reduced materials use and waste, but these will need to be balanced against the opportunities for designing a new building with low energy requirements, and which can utilize renewable energy.

Note that in some cases, even a sustainable skyscraper can have high environmental impact compared to traditional buildings. Therefore should consider whether is more important reducing the impact on land and decreasing the use of private vehicles or energy efficiency.

6 Conclusion and Future Work

6.1 General Considerations

The conclusions resulting from this study fall primarily on policy measures implemented in green buildings in China and strategies that turn high-rise buildings more sustainable in this category. Although the case study is in Shanghai, sustainable practices mentioned in this thesis can be applied in other cities with a similar climate – subtropical monsoon, with specific adjustment.

Shanghai Tower has the following measures: material saving architecture form, double skin curtain wall, sky lobbies, wind power, ground source heat pump, ice storage air conditioning, combined cooling, heat and power, grey water and rainwater recycling, energy efficient elevator and BIM. These measures result in better performance over building´s life cycle compared to other skyscrapers, allowing to reduce carbon footprint, greenhouse gas emission and natural resource consumption.

After this study was able to conclude that in the case of high-rise building is fundamental considering the relationship between importance of the wind and building height.

Building shape optimization reduce wind loads on the building, allowing a simpler and lighter structure, this way contributing also to material saving.

In order to reduce environment pollution and provide comfort indoor environment, it is important to invest in passive strategies, like natural ventilation, convection, daylighting and façade orientation, etc. With the assistance of software such as Ecotect, EnergyPlus and etc.

In addition to incorporating passive strategies should also integrate the active systems into project, such as renewable energy, including solar and wind, to maximize the use of these natural resources and lower the energy costs associated with buildings and reduce carbon footprint. Besides of renewable energy, other active systems - mechanical, electrical, and plumbing (MEP) technologies are also suitable. For instance, ice storage air-conditioning, tri-generation, energy efficient elevator, grey water and rainwater recycling, etc.

The Building Information Modelling (BIM) is a very useful technology, should include BIM to building design and construction process. Because this technology can simulate the key difficulties of the construction schemes and provides construction guidance, prevents reworking, this way saves time. And the construction scheme animation of the BIM software revels relationships between construction processes and time sequences.

When it comes to material selection, should always use locally sourced materials, eco-friendly materials, and high-performance materials. If there is locally sourced materials with high recycled content should be used when available.

The reason that sustainability has become so popular in China, is because the government took the initiative, set goals and implemented a series of regulations and guidelines for sustainable practicing. The government also created a voluntary rating system that encourages green development – Green Building Evaluation Labels (GBEL), also known as “Three-Star” rating system. Besides, green building developers are in title of receiving support funds for incorporating sustainable technologies into their project. Even with support funds from the government, the investment for a sustainable building is till significantly higher than a standard building, it is a long-term investment.

Besides GBEL, the American Leadership in Energy & Environmental Design (LEED) rating system is also commonly used in China, and some Chinese developers prefer to use both.

Difference between GBEL and LEED reflects the different goals and philosophies of the organization designing and running them. LEED was designed by the U.S. Green Building Council (USGBC), a collaboration between developers, architects, engineers, and green building material suppliers, to generate a market for green buildings, green building products and services, and promote sustainable design. GBEL on the other hand is a Government-led project. While GBEL shares market transformation goals, it also has an overriding policy goal that fits into China’s long-term environmental and energy policy: namely reducing building energy consumption.

Assessment programs together with innovation technologies will continue to have a huge impact in green and sustainable industry of China.

6.2 Future Work

For future work, it would be important to conduct a questionnaire (indoor comfort) to employees and guests of Shanghai Tower and conduct the same questionnaire to other two standard mixed use buildings´ users. Then compare the results and terminate whether Shanghai Tower has the best performance.

Shanghai Tower is a new building, therefore it would be interesting to analyse an existing mixed use supertall building, for instance Jin Mao Tower which gained LEED Gold certificate for existing buildings. Analysing the type of active and passive strategies are best suited for an existing building, which will improve building performance, taking into account its performance/cost relation.

Would also be interesting to analyse a same green residential high-rise building (about 30-story) in Shanghai and in Macau with the assistance of EnergyPlus. Comparing the results based on GBEL and LEED assessment, analyse if this building is suitable for local climate, and then propose solutions to each case study in order to achieve better building performance.

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Appendices

A. GBEL criteria for public building – I. Land-Saving and Outdoor Environment

GBEL buildings have to reach all the prerequisites first. The blue colour items regard to operation and construction stages of the project.

I. Land-Saving and Outdoor Environment (14 requirements) (MOHURD, 2006)	
Prerequisites (5)	5.1.1 The construction of a site shall not damage a local cultural relic, natural water system, moor, fundamental farmland, forest or any other protected area.
	5.1.2 The selected site of a building shall be free from such a threat as a flood, landslide or ammonia containing soil, and within the safe range of the building site, there shall be no such a dangerous source as an electromagnetic radiation danger, fire, explosion or poisonous substance.
	5.1.3 No light pollution shall be brought to a surrounding building, and the sunshine requirements from a surrounding residential building shall not be affected.
	5.1.4 There shall be no pollution source exceeding a discharging standard within a site.
	5.1.5 During the process of construction, concrete measures for environmental protection shall be drawn up and implemented to control construction–caused pollution and the influences on the surrounding areas of the construction site.
General Items (6)	5.1.6 The ambient noise of a site shall accord with the existing national standard “Ambient Noise Standards for Urban Region” GB 3096.
	5.1.7 The wind speed on a pedestrian zone around a building shall be less than 5 m/s, not affecting the snugness for outdoor activities, or building ventilation.
	5.1.8 Such a method as roof greening or perpendicular greening shall be reasonably used.
	5.1.9 Indigenous plants adapted to local climatic and soil conditions shall be selected as greening species, and multiple greening comprising trees and bushes shall be used.
	5.1.10 The transport organization of a site shall be reasonable, with the walking distance for arriving at a public transport station not exceeding 500m.
	5.1.11 Underground spaces shall be reasonably developed and utilized.
Preferred Items (3)	5.1.12 An abandoned site shall be used reasonably for construction. A polluted abandoned site shall be treated to relevant standards.
	5.1.13 An old building that is still usable shall be made full use of and be included into a planned project.
	5.1.14 The area ratio of outdoor permeable ground shall be greater than or equal to 40%.

B. GBEL criteria for public building – II. Energy-Saving and Energy Utilization

GBEL buildings have to reach all the prerequisites first.

II. Energy-Saving and Energy Utilization (19 requirements) (MOHURD, 2006)	
Prerequisites (5)	5.2.1 The thermo-technical performance indexes for an enclosure structure shall conform to the stipulations in the energy saving standards approved and put on record by the State.
	5.2.2 The energy efficiency ratio of a chilling and heating source set for an air-conditioning or heating system shall accord with the stipulations of Articles 5.4.5, 5.4.8 and 5.4.9 in the existing national standard “Energy Saving Design Standards for Public Building” GB 50189-2005.
	5.2.3 An electric boiler or electric water heater shall not be used as the heat source of a heating or air-conditioning system.
	5.2.4 The illumination power density value for each room or site shall not be higher than the specified current value described in the existing national standard “Design Standards for Building Illumination” GB 50034.
	5.2.5 The energy consumption for each part of a newly-constructed public building, chill-heat source, transmission-distribution system or lighting system shall be independently measured.
General Items (10)	5.2.6 An architectural site planning design shall be beneficial to the sunshine in winter and the aversion of the dominant wind direction in winter, and to the natural ventilation in summer.
	5.2.7 The opening area of the external windows of a building shall not be less than 30% of the total area of the external windows. A curtain wall of a building shall have parts that can be opened or shall be equipped with ventilating devices and air exchangers.
	5.2.8 The air-tightness of an external window of a building shall not be lower than the Grade-4 requirement stipulated in the existing national standard “External Window Air-tightness Classification and Inspection Methods” GB 7107.
	5.2.9 Chill-heat-storage techniques shall be used reasonably.
	5.2.10 Exhaust wind shall be used to pre-heat or pre-chill fresh wind so as to reduce fresh wind load.
	5.2.11 For an all-air air-conditioning system, the measures for realizing all-fresh-wind operation or adjustable fresh wind ratio shall be taken.
	5.2.12 When a building is subject to partial cooling or heat load and only a part of its spaces is used, effective measures shall be taken to save the energy consumption of the ventilating and air-conditioning system.

II. Energy-Saving and Energy Utilization (Table 2)	
	5.2.13 When an energy-saving unit system is used, the unit wind-volume power consumption of a wind machine for a ventilating and air-conditioning system and the conveyance energy efficiency ratio for a cool hot water system shall conform to the stipulations in Articles 5.3.26 and 5.3.27 in the existing national standard “Energy Saving Design Standards for Public Building” GB 50189-2005.
	5.2.14 Residual heat or waste heat shall be utilized to provide steam or domestic hot water for a building.
	5.2.15 The energy consumption for each part of a newly-constructed public building, chill-heat source, transmission-distribution system or lighting system shall be independently measured.
Preferred Items (3)	5.2.17 Distributive thermoelectric cooling supply technology shall be used to raise energy comprehensive utilization rate.
	5.2.18 According to local climatic and natural resource conditions, reusable energy resources such as solar energy and geothermal energy shall be made full use of. The hot water amount produced from renewable energy shall not be less than 10% of the hot water consumption for domestic use in a building, or the power generation amount produced from renewable energy shall not be less than 2% the power consumption in a building.
	5.2.19 The illumination power density value for each room or site shall not be higher than the specified current value described in the existing national standard —Design Standards for Building Illumination‖ GB 50034.

C. GBEL criteria for public building – III. Water-Saving and Water Resources Utilization

GBEL buildings have to reach all the prerequisites first.

III. Water-Saving and Water Resources Utilization (12 requirements) (MOHURD, 2006)	
Prerequisites (5)	5.3.1 During the phase of schemes and planning, a scheme for water system planning shall be formulated so as to overall plan and comprehensively utilize various water resources.
	5.3.2 Reasonable and perfect water supply and drainage system shall be established.
	5.3.3 Effective measures shall be taken to avoid pipe network leakage.
	5.3.4 A sanitary ware in a building shall be water saving one.
	5.3.5 When a non-traditional water source is used, safeguard measures for water-use safety shall be taken so as not to produce bad effects on human health and the ambient environment.
General Items (6)	5.3.6 The schemes for storing, treating and utilizing rain water shall be determined by making technical and technical comparisons.
	5.3.7 A non-traditional water source such as resurgent or rain water shall be used as non-drinking water for irrigating plants or washing a car.
	5.3.8 An efficient and water saving irrigation method such as spray irrigation or micro-irrigation shall be used for irrigating plants.
	5.3.9 When resurgent water is used as non-drinking water, a priority shall be given to utilizing resurgent water from a nearby concentrated resurgent water works, but if there is no such a works, other sources and treatment techniques of resurgent water shall be selected reasonably by making technical and economic comparisons.
	5.3.10 Water measuring metres shall be provided according to uses.
	5.3.11 For an office building or supermarket building, the utilization rate for non-traditional water sources shall not be less than 20%, while for a hotel building, not less than 15%.
Preferred Items (1)	5.3.12 For an office building or supermarket building, the utilization rate for non-traditional water sources shall not be less than 40%, while for a hotel building, not less than 25%.

D. GBEL criteria for public building – IV. Material-saving and Material Resources Utilization

GBEL buildings have to reach all the prerequisites first. The blue colour items regard to operation and construction stages of the project.

IV. Material-Saving and Material Resources Utilization (12 requirements) (MOHURD, 2006)	
Prerequisites (2)	5.4.1 The harmful matter content in a building material shall accord with the requirements in the existing national standard GB 18580-GB 18588 and "Limited Amount of Radioactive Nuclide in Building Material"
	5.4.2 Architectural form factors shall be succinct and shall not have many ornamental components.
General items (8)	5.4.3 The weight of the building materials produced within 500km of a construction site shall make up more than 60% of the total weight of the materials.
	5.4.4 Ready-mixed concrete shall be used as cast-in-place concrete.
	5.4.5 High-performance concrete and high-strength steel shall be used reasonably as building structural materials.
	5.4.6 Solid waste produced during the construction of a building, the dismantlement of an old building or the clearance of a site shall be classified, and the renewable and recyclable materials among the waste shall be recovered and reutilized.
	5.4.7 The recyclable serviceability of a material shall be considered for use when a material is selected during architectural design. Under the circumstances of ensuring safety and not polluting the environment, the weight of the used recyclable materials shall make up more than 10 % of the total weight of the used building materials.
	5.4.8 The integration of design and construction shall be involved for civil and decorating engineering, an existing building unit or facility shall not be damaged or dismantled, and repeated decoration shall be avoided.
	5.4.9 Inside an office or supermarket building, flexible partitions shall be used to reduce the material waste and trash from re-decoration.
	5.4.10 Under the condition of ensuring performance, the consumption of the building materials made of waste shall make up not less than 30 % of the consumption of the same kinds of building materials.
Preferred Items (2)	5.4.11 An architectural structural system that consumes a small amount of resources and has little effect on the environment shall be adopted.
	5.4.12 The utilization rate for reusable building materials shall be greater than 5%.

E. GBEL criteria for public building – V. Indoor Environment Quality

GBEL buildings have to reach all the prerequisites first. The blue colour items regard to operation and construction stages of the project.

V. Indoor Environment Quality (15 requirements) (MOHURD, 2006)	
Prerequisites (6)	5.5.1 For a central air-conditioning building, such parameters as room temperature, humidity and wind speed shall accord with the designing and calculating requirements of the existing national standard "Energy Saving Design Standards for Public Building" GB 50189.
	5.5.2 The inside and surface of a building enclosure structure shall be free from frost and mildew.
	5.5.3 For a building with central air conditioning, the fresh wind amount shall accord with the design requirements of existing national standard "Energy Saving Design Standards for Public Building" GB 50189.
	5.5.4 The concentration of indoor air pollutants such as free formaldehyde, benzene, ammonia, radon and TVOC shall accord with the stipulations in the existing national standard "Indoor Environmental Pollution Control Code for Civil Building" GB 50325.
	5.5.5 The indoor background noise in a hotel or office building shall conform to Grade 2 requirements for the indoor allowable noise standards in national "Sound Insulation Design Code for Civil Building" GBJ 118, while the indoor background noise level shall meet the relevant requirements of national "Health Standards for Supermarket (Store) and Bookstore" GB 9670.
	5.5.5 The indoor background noise in a hotel or office building shall conform to Grade 2 requirements for the indoor allowable noise standards in national "Sound Insulation Design Code for Civil Building" GBJ 118, while the indoor background noise level shall meet the relevant requirements of national "Health Standards for Supermarket (Store) and Bookstore" GB 9670.
	5.5.6 The indoor illumination intensity, uniform glare value, general coloration index, etc. of a building shall meet the relevant requirements of the existing national standard "Illumination Design Standards for Building" GB 50034
General items (6)	5.5.7 The measures promoting natural ventilation shall be included in architectural and structural designs.
	5.5.8 Air-conditioning terminals with easy regulation and the function of raising human snugness shall be used indoors.
	5.5.9 The sound insulation performance of an enclosure structure component of a hotel building shall meet Grade 1 requirements of the existing national standard "Sound Insulation Design for Civil Building" GBJ 118.

V. Indoor Environment Quality (continuation)	
	5.5.10 The layout of architectural plane and the arrangement of space functions for building shall be reasonable so as to reduce the noise interference from a neighbouring space and the indoor influence from outside noise.
	5.5.11 The indoor coefficient of lighting for more than 75% of the main-functional spaces in an office or hotel building shall meet the requirements in the existing national standard “Lighting Design Standards for Building” GB/T 50033.
	5.5.12 An entrance or main activity spaces of building shall be provided with obstacle-free facilities.
Preferred Items (3)	5.5.13 Adjustable external sunshades shall be used for improving indoor hot environment.
	5.5.14 An indoor air quality monitoring system shall be established to ensure a healthy and snug indoor environment.
	5.5.15 Reasonable measures shall be taken to improve the natural lighting effects in an indoor or underground space.

F. GBEL criteria for public building – VI. Operational Management

GBEL buildings have to reach all the prerequisites first. The blue colour items regard to operation and construction stages of the project.

VI. Operational Management (11 requirements) (MOHURD, 2006)	
Prerequisites (3)	5.6.1 A system for saving resources such as energy, water, etc. and for managing greening shall be worked out and implemented.
	5.6.2 No non-standard waste gas or water shall be discharged during the process of a building operation.
	5.6.3 Waste shall be collected and treated in a classifying way, with no secondary pollution.
General items (7)	5.6.4 The construction of a building shall coordinate the balance of earthwork and the construction of roads.
	5.6.5 A property management department shall pass the authentication of the environment management system of ISO 14001.
	5.6.6 The arrangement of equipment or pipes shall facilitate maintenance, renovation and replacement.
	5.6.7 An air-conditioning and ventilating system shall be checked and cleaned periodically according to the national Standard "Cleaning Code for Air-conditioning and Ventilating System." GB 19210
	5.6.8 An architectural intelligent system shall be positioned reasonably, with perfect functions of information network.
	5.6.9 The automatic monitoring system for ventilation, air-conditioning, lighting, etc. in a building shall have reasonable techniques and efficient operation.
	5.6.10 The power consumption, cooling and heat quantity in an office or supermarket building shall be measured and charged for.
Preferred Items (1)	5.6.11 A resource management and excitation mechanism shall be established and implemented, with the integration of management result, resource saving and enhancement of economic effects.

G. LEED v4 BD+C NC criteria – Location & transportation

Possible Points		Location & transportation (up to 32 points) (USBGC, 2014c)
LTc1	16	LEED for Neighbourhood Development location intents to avoid development on inappropriate sites. To reduce vehicle distance travelled. To enhance liveability and improve human health by encouraging daily physical activity.
LTc2	1	Sensitive land protection intents to avoid the development of environmentally sensitive lands and reduce the environmental impact from the location of a building on a site.
LTc3	2	High priority site intents to encourage project location in areas with development constraints and promote the health of the surrounding area.
LTc4	5	Surrounding density and diverse uses intents to conserve land and protect farmland and wildlife habitat by encouraging development in areas with existing infrastructure. To promote walkability, and transportation efficiency and reduce vehicle distance travelled. To improve public health by encouraging daily physical activity.
LTc5	5	Access to quality transit intents to encourage development in locations shown to have multimodal transportation choices or otherwise reduced motor vehicle use, thereby reducing greenhouse gas emissions, air pollution, and other environmental and public health harms associated with motor vehicle use.
LTc6	1	Bicycle facilities intents to promote bicycling and transportation efficiency and reduce vehicle distance travelled. To improve public health by encouraging utilitarian and recreational physical activity.
LTc7	1	Reduced parking footprint intents to minimize the environmental harms associated with parking facilities, including automobile dependence, land consumption, and rainwater runoff.
LTc8	1	Green vehicles intents to reduce pollution by promoting alternatives to conventionally fuelled automobiles.

H. LEED v4 BD+C NC criteria – Sustainable Sites

Must reach all the prerequisites first.

Possible Points		**Sustainable Sites (up to 10 points) (USBGC, 2014c)**
SSp1	Prerequisite	Construction activity pollution prevention intents to reduce pollution from construction activities by controlling soil erosion, waterway sedimentation, and airborne dust.
SSc1	1	Site assessment intents to assess site conditions before design to evaluate sustainable options and inform related decisions about site design.
SSc2	2	Site development - protect or restore habitat intents to conserve existing natural areas and restore damaged areas to provide habitat and promote biodiversity.
SSc3	1	Open space intents to create exterior open space that encourages interaction with the environment, social interaction, passive recreation, and physical activities.
SSc4	3	Rainwater management intends to reduce runoff volume and improve water quality by replicating the natural hydrology and water balance of the site, based on historical conditions and undeveloped ecosystems in the region.
SSc5	2	Heat Island reduction intents to minimize effects on microclimates and human and wildlife habitats by reducing heat islands.
SSc6	1	Light pollution reduction intents to increase night sky access, improve night-time visibility, and reduce the consequences of development for wildlife and people.

I. *LEED v4 BD+C NC criteria – Water Efficiency*

Must reach all the prerequisites first.

Possible Points		**Water Efficiency (up to 11 points) (USBGC, 2014c)**
WEp1	Prerequisite	Outdoor water use reduction intents to reduce outdoor water consumption.
WEp2	Prerequisite	Indoor water use reduction intents to reduce indoor water consumption.
WEp3	Prerequisite	Building-level water metering intents to support water management and identify opportunities for additional water savings by tracking water consumption.
WEc1	2	Outdoor water use reduction intents to reduce outdoor water consumption.
WEc2	6	Indoor-use reduction intents to reduce indoor water consumption.
WEc3	2	Cooling tower water use intents to conserve water used for cooling tower makeup while controlling microbes, corrosion, and scale in the condenser water system.
WEc4	1	Water metering intents to support water management and identify opportunities for additional water savings by tracking water consumption.

J. LEED v4 BD+C NC criteria – Energy and Atmosphere

Must reach all the prerequisites first.

Possible Points		**Energy and Atmosphere (up to 33 points) (USBGC, 2014c)**
EAp1	Prerequisite	Fundamental commissioning of building energy systems intents to support the design, construction, and eventual operation of a project that meets the owner's project requirements for energy, water, indoor environmental quality, and durability.
EAp2	Prerequisite	Minimum energy performance intents to reduce the environmental and economic harms of excessive energy use by achieving a minimum level of energy efficiency for the building and its systems.
EAp3	Prerequisite	Building-level energy metering intents to support energy management and identify opportunities for additional energy savings by tracking building-level energy use.
EAp4	Prerequisite	Fundamental refrigerant management intends to reduce stratospheric ozone depletion.
EAc1	6	Enhanced commissioning intents to further support the design, construction, and eventual operation of a project that meets the owner's project requirements for energy, water, indoor environmental quality, and durability.
EAc2	18	Optimized energy performance intents to achieve increasing levels of energy performance beyond the prerequisite standard to reduce environmental and economic harms associated with excessive energy use.
EAc3	1	Advanced energy metering intents to support energy management and identify opportunities for additional energy savings by tracking building-level and system-level energy use.
EAc4	2	Demand response intents to increase participation in demand response technologies and programs that make energy generation and distribution systems more efficient, increase grid reliability, and reduce greenhouse gas emissions.
EAc5	3	Renewable energy production intents to reduce the environmental and economic harms associated with fossil fuel energy by increasing self-supply of renewable energy.
EAc6	1	Enhanced refrigerant management intends to reduce ozone depletion and support early compliance with the Montreal Protocol while minimizing direct contributions to climate change.
EAc7	2	Green power and carbon offsets intents to encourage the reduction of greenhouse gas emissions through the use of grid-source, renewable energy technologies and carbon mitigation projects.

K. LEED v4 BD+C NC criteria – Materials and Resources

Must reach all the prerequisites first.

Possible Points		**Materials and Resources (up to 13 points) (USBGC, 2014c)**
MRp1	Prerequisite	Storage and collection of recyclables intents to reduce the waste that is generated by building occupants and hauled to and disposed of in landfills.
MRp2	Prerequisite	Construction and demolition waste management planning intents to reduce construction and demolition waste disposed of in landfills and incineration facilities by recovering, reusing, and recycling materials.
MRc1	5	Building life-cycle impact reduction intents to encourage adaptive reuse and optimize the environmental performance of products and materials.
MRc2	2	Building product disclosure and optimization - environmental product declarations intents to encourage the use of products and materials for which life-cycle information is available and that have environmentally, economically, and socially preferable life-cycle impacts. To reward project teams for selecting products from manufacturers who have verified improved environmental life-cycle impacts.
MRc3	2	Building product disclosure and optimization - sourcing of raw materials intents to encourage the use of products and materials for which life cycle information is available and that have environmentally, economically, and socially preferable life cycle impacts. To reward project teams for selecting products verified to have been extracted or sourced in a responsible manner.
MRc4	2	Building product disclosure and optimization - material ingredients intends to encourage the use of products and materials for which life-cycle information is available and that have environmentally, economically, and socially preferable life-cycle impacts. To reward project teams for selecting products for which the chemical ingredients in the product are inventoried using an accepted methodology and for selecting products verified to minimize the use and generation of harmful substances. To reward raw material manufacturers who produce products verified to have improved life-cycle impacts.
MRc5	2	Construction and demolition waste management intends to reduce construction and demolition waste disposed of in landfills and incineration facilities by recovering, reusing, and recycling materials.

L. LEED v4 BD+C NC criteria – Indoor Environmental Quality

Must reach all the prerequisites first.

Possible Points		Indoor Environmental Quality (up to 16 points) (USBGC, 2014c)
EQp1	Prerequisite	Minimum indoor air quality performance intents to contribute to the comfort and well-being of building occupants by establishing minimum standards for indoor air quality (IAQ).
EQp2	Prerequisite	Environmental tobacco smoke control intents to prevent or minimize exposure of building occupants, indoor surfaces, and ventilation air distribution systems to environmental tobacco smoke.
EQc1	2	Enhanced indoor air quality strategies intents to promote occupants' comfort, well-being, and productivity by improving indoor air quality.
EQc2	3	Low-emitting materials intents to reduce concentrations of chemical contaminants that can damage air quality, human health, productivity, and the environment.
EQc3	1	Construction indoor air quality management plan intents to promote the well-being of construction workers and building occupants by minimizing indoor air quality problems associated with construction and renovation.
EQc4	2	Indoor air quality assessment intents to establish better quality indoor air in the building after construction and during occupancy.
EQc5	1	Thermal comfort intents to promote occupants' productivity, comfort, and well-being by providing quality thermal comfort.
EQc6	2	Interior lighting intents to promote occupants' productivity, comfort, and well-being by providing high-quality lighting.
EQc7	3	Daylight intents to connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space.
EQc8	1	Quality views intents to give building occupants a connection to the natural outdoor environment by providing quality views.
EQc9	1	Acoustic performance intents to provide workspaces and classrooms that promote occupants' well-being, productivity, and communications through effective acoustic design.

M. LEED v4 BD+C NC criteria – Innovation

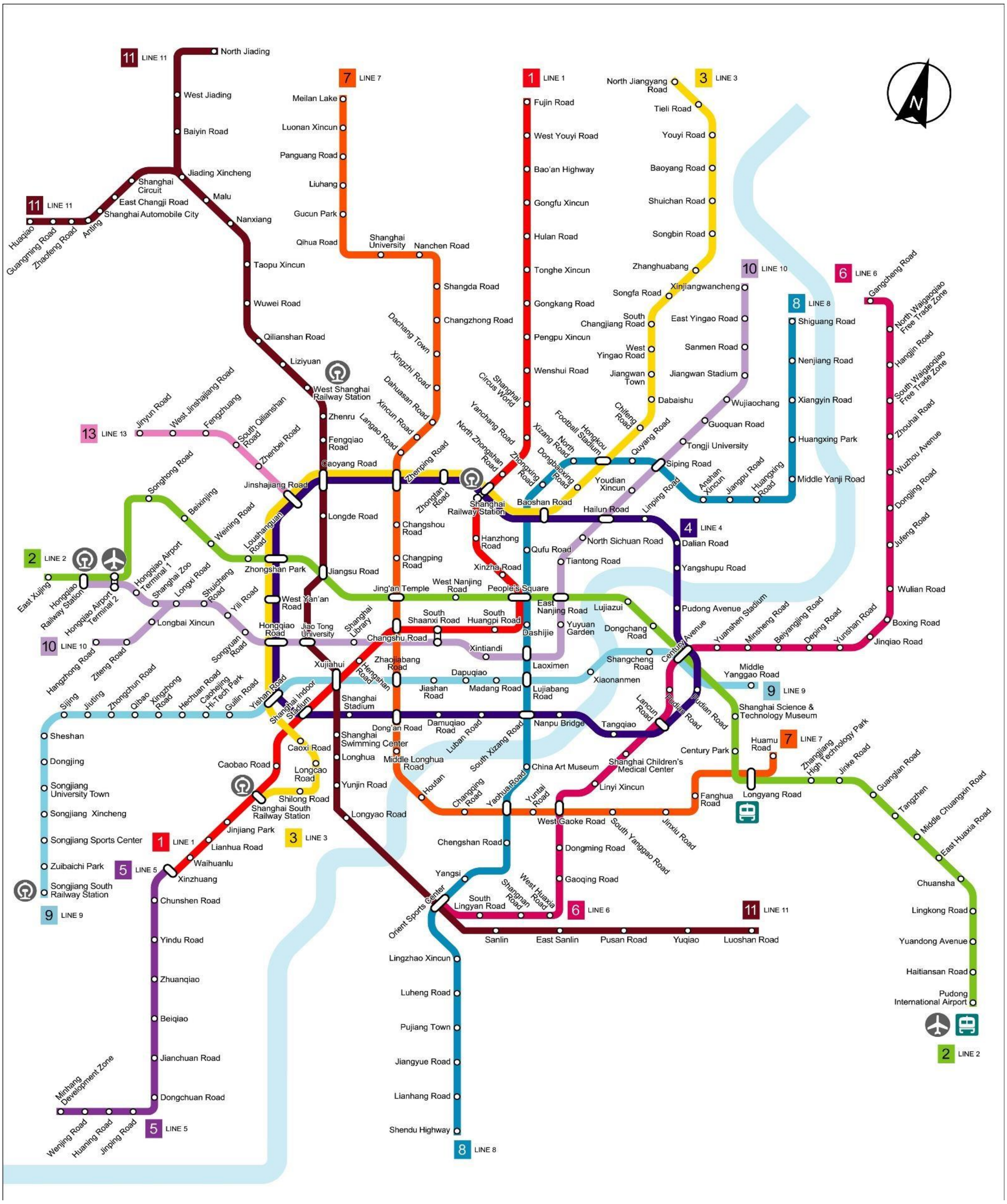
Possible Points		**Innovation (up to 6 points) (USBGC, 2014c)**
INc1	5	Innovation intents to encourage projects to achieve exceptional or innovative performance.
INc2	1	LEED accredited professional intents to encourage the team integration required by a LEED project and to streamline the application and certification process.

N. LEED v4 BD+C NC criteria – Regional Priority

Possible Points		**Regional Priority (up to 4 points) (USBGC, 2014c)**
RPc1	4	Regional priority intents to provide an incentive for the achievement of credits that address geographically specific environmental, social equity, and public health priorities.

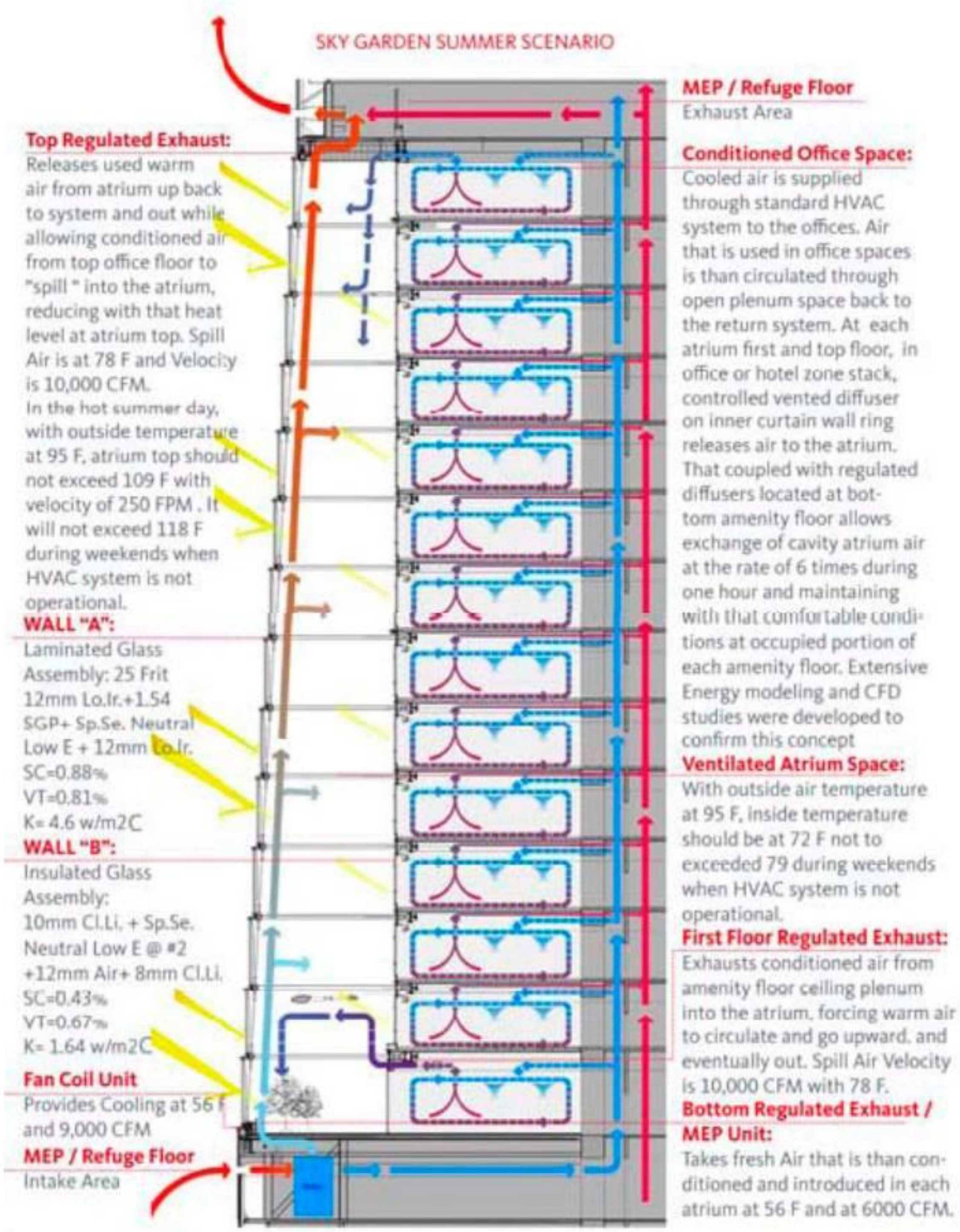
O. Shanghai Underground Map

(Shanghai Metro, 2014)



P. Atrium Energy Performance: Summer Concept

(Shanghai Tower Façade Design Process, 2010)



Q. Atrium Energy Performance: Winter Concept

(Shanghai Tower Façade Design Process, 2010)