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SUSTAINABLE BUILDINGS IN DIFFERENT COUNTRIES

Office skyscrapers in different climate zones

EDIFICIOS SOSTENIBLES EN DIFERENTES PAÍSES

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ABSTRACT

As cities cope with rapid population growth—adding 2.5 billion dwellers by 2050—and deal with expansive sprawl; politicians, planners and architects have become increasingly interested in the vertical city paradigm. Although skyscrapers provide countless benefits to society, they are one of the main consumers of energy as well as the main sources of environmental pollution. In order to offer a better future to next generations, we must start investing in sustainable construction, based on best practices that emphasize long-term affordability, quality and efficiency.

Energy efficient design requires different design strategies according to each different climate. This makes it essential for architects, builders, contractors and homeowners to understand the resources of their unique local climate and how it influences the performance of their buildings. Designing passively means working with external weather conditions instead of fighting against it.

The current work in sustainable skyscrapers design reflects a long-lasting need to reduce energy consumption and minimize the building's ecological footprint while still providing first-class living and working environments. The scope of the study is narrowed to office skyscrapers in three different locations and climates. A comparison of the sustainable features the skyscrapers need is carried out according to dry hot, rainy cold and humid subtropical climates. The case studies concern very well-known sustainable skyscrapers as the Bahrain World trade Center in Bahrein, The Lakhra Center in Russia and the Ping An Center in China.

ACKNOWLEDGEMENT

To Davide, for his unconditional love and support.

Gratitude to my **parents** for their help and encouragement and to the **professors** for their guidance.

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GLOSSARY

BREEAM	Building Research Establishment’s Environmental Assessment Methods
BWTC	Bahrein World Trade Center
CO2	Carbon dioxide
CTBUH	Council on Tall Buildings and Urban Habitat
EPW	Energy Plus Weather
HQE	Haute Qualité Environnementale
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
OECD	Organisation for Economic Co-operation and Development
PAFC	Ping An Financial Center
UNEP	United Nations Environment Program
USGBC	The U.S. Green Building Council

1. INTRODUCTION

1.1 Background & Antecedents

Man has always built monumental structures for the gods such as temples and pyramids which pointed to the sky; however, today's monuments which are tall buildings; symbolize power, richness, prestige and glory. From the ancient Tower of Babel to the world's tallest building Burj Khalifa, the major difficulties were overcame with human ingenuity.

The feasibility of tall buildings has always depended on the available materials, the level of construction technology and the site conditions. In consequence, the advances that we have reached in structural design and analytical techniques have made it possible to reach different heights in buildings. Nevertheless, every new construction comes with its difficulty and challenge that has to be overcome.

High-rise buildings emerged in the late nineteenth century in the United States of America. Today, these buildings are a worldwide architectural phenomenon. 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 mentioned before. They are likely the first and best choice to lower the impact on land use in cities. However, they also have negative impacts as building construction consumes 40% of raw stone, gravel and sand used globally each year and 25% of raw timber (OECD, 2019). Buildings also account for 40% of global energy, 25% of global water, produce 40% of waste that go to landfills and they emit approximately one-third of global greenhouse gas (GHG) emissions. Unfortunately the planet cannot support the current level of energy and resource consumption associated with buildings anymore.

The urban population of the world has grown rapidly from 751 million in 1950 to 4.2 billion in 2018 (United Nations, 2018). Whereas 30 per cent of the world population lived in urban areas in 1950, the proportion of urban dwellers climbed to 55 per cent in 2018 and is projected to rise to 68 per cent in 2050. This continuous increase in the world population results nowadays in a big energy conflict among other issues that threatens human's life (Zandi et al., 2010). Issues as; energy shortage, global warming, urban sprawl, air pollution, overflowing landfills, water shortage, disease and global conflict that will be the legacy of the twenty-first century unless we move quickly towards the notion and implementation of sustainability. Survival of the human race depends upon the survival of our cities (Ali et al., 2008).

Sustainability is comprehensive therefore a complex subject. It is of vital importance to all because it deals with the survival of human species and almost every living creature on the planet. In order to create a better life, sustainable and eco-friendly architecture is one of the main aims that humans have made as the ultimate model for all their activities. For this reason, moving towards a greener architecture is the main goal of the present architecture of our time (Mahdavinejad et al., 2014).

Studies have shown that the vertical development of cities seems to be the best inevitable solution that will change our urban design methods and that has no other way but to be sustainable and green.

1.2 The research questions

From the previous sections, multiple doubts arise as interesting topics for research. Most of them are related to the concept of high-rise building and sustainability in architecture, how and in what way they are? Which are the factors that define the level of sustainability of a skyscraper? Does the location and climate of the high rise building affect his sustainability level?

Therefore, this End of Master Work presents an in-depth review of the strategies that designers and engineers took in the last years to raise a sustainable skyscraper and the plans to follow in the future to identify possible areas of opportunity that could benefit from the application of these sustainability measures.

1.3 Aim and Objectives

The aim of this thesis is to determine the design factors that make a skyscraper sustainable and how climate and therefore the location of the skyscraper might influence these factors.

The objectives of this study are to highlight the issues that this building type instigates like overshadowing problems of adjacent open spaces and buildings and to understand what makes it exceptional. Also, to analyse design strategies in order to promote skyscraper energy efficiency by considering a climatically responsive design and factors like the orientation, the thermal properties of the building envelope as well as the altitude effect. For that, another objective will be to make a comparison between three different skyscrapers in three different climate zones and to contrast results.

1.4 Research Methodology

The research methodology used involves:

- An introduction to basic concepts of high-rise building; definition, types, building usage and evolution of this kind of construction.

- The impact of the building industry on environment. Starting with a clear definition and origins of the word “sustainability” according to the three pillar approach. Statistics of the Green House Gas emissions, energy use, water use and resources consumptions for instance proved that actions should be taken in the construction industry and laws that regulate construction should be more strict. We also analysed the relationship between sustainability and the building construction sector by listing the impacts of the construction in relation with the environmental, social and economic aspects. That will take us to understand the meaning of sustainable construction and how can we achieve and measure it.

- Methodology of work or the tools we are going to use to compare the skyscraper cases we chose from different climates. Climate consultant in this case will help us analyse the sustainable strategies needed and requested in each climate type and how to apply it to the building.

- Case study analysis: Bahrain WTC, Lakhta Centre and Shanghai Tower. A general presentation of the skyscraper and the concept by which it was inspired will be followed by a description of its location and therefore climate type and an analysis of the sustainable practices incorporated in the building, which lead to energy efficiency, water saving and reduce the building's carbon footprint.

- An analysis and evaluation of the results will be followed up by discussion and conclusion.

1.5 Limitation and Scope

Scope

This work's scope is narrowed to office skyscrapers. This type of high rise building will be analysed and compared in different climates.

Limitations

The fact that we are evaluating the most sustainable and tallest skyscrapers doesn't make this comparison an easy task. The complexity of the design of the chosen skyscrapers and the lack of data limits the accuracy of the comparison due to the fact that it is not possible to model the buildings in Revit in order to run an energy simulation later on. We tried to collect all the data available on the internet and scientific databases regarding the design and construction of the three mentioned skyscrapers.

Another limitation we faced was the fact that most energy calculation software are not free or accessible. Therefore, we used Climate consultant and some online sheet calculations that were available to carry on the study.

2. THEORITICAL FRAMEWORK

2.1 High-rise Building

2.1.1 Definition

The notion of size or appearance of tallness is a relative matter. It is very hard to define or distinguish a “tall building”, “high-rise building” or “skyscraper” just in terms of size. Unfortunately, there is no consensus on what compromises a tall building or at what height or number of stories it can be called tall. All of these three mentioned terms mean the same type of building which is built extremely high – in which skyscraper is a more assertive term. Although the high-rise building has been accepted as a building type since the late 19th century, tall buildings have been constructed since ancient times for several purposes and therefore the history of tall buildings is much older than a century.

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. A skyscraper can be understood as a very tall multi-storeyed building, or a very tall high-rise building. The Council on Tall Buildings and Urban Habitat (CTBUH) has classified these TALL BUILDINGS in two additional sub-groups: A “supertall” is a tall building 300 meters or taller, and a “megatall” is a tall building 600 meters or taller. This definition will be used in this dissertation.

As of today, there are 146 supertalls and only 3 megatalls completed globally (CTBUH, 2019).

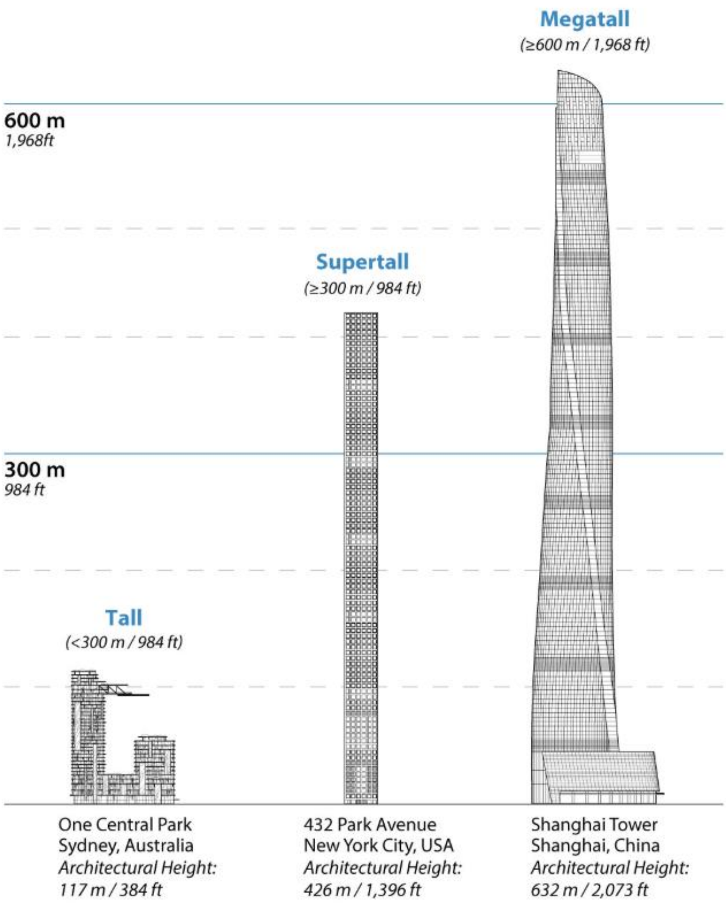


Fig. 1 Classification of tall buildings (CTBUH, 2019)

2.1.2 The 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. Nevertheless, during the late nintheeth century two major developments let to the skyscrapers that dominate major city skylines throughout the modern world. It was with the invention of the world's first safety lift or elevator by Elisha Graves Otis in 1853 that enabeld people to travel safely upwards at a greater speed and lees effort and the creation of steel frames in the 1870s 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 (Craighead, 2009).

The very first tall building with elevator was built in Chicago in 1885, the ten-story Home Insurance Building (see Figure 2), 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, it was definetly impressive at that time.

Fig. 2 Home insurance Building, 1885

This 10-story building, designed by engineer William Le Baron Jenney, is generally considered the world's first skyscraper. It was built in Chicago in 1885, using a steel frame. It was demolished in 1931.

At the turn of the century, tall buildings began to spring up in New York City — in 1903, the triangular-shaped 22-story Flatiron (Fuller) Building, 285 feet (87 meters) high; in 1909, the 50-story Metropolitan Life Insurance Building, 700 feet (213 meters) high; and in 1913, the 57-story Woolworth Building, 792 feet (241 meters) high.

High-rises and skyscrapers may have started in United States, but this trend quickly speared to other countries. For instance, 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 (Diamond, 2007).

In Fig. 3 we can see the evolution of the number of buildings with a height of more than 200m from 1960 until today. This chart shows how the construction industry experienced an evolution in high rise buildings during the 20th century.

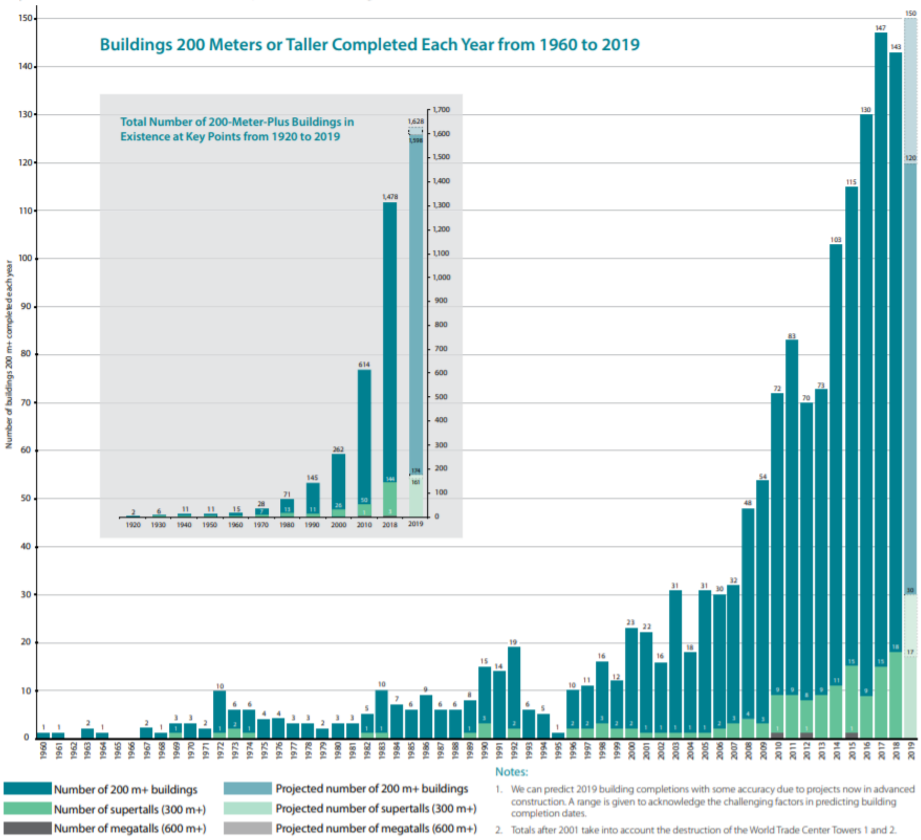


Fig. 3 Number of 200-meter-plus buildings completed each year from 1960 to 208, with projections through 2019. (CTBUH, 2019)

2.1.3 Types of Skyscrapers

There are different types of high-rise buildings classified according to their primary use:

Office buildings

An office building is a “structure designed for the conduct of business, generally divided into individual offices and offering space for rent or lease.

Hotel buildings

The term “hotel” is an all-inclusive designation for facilities that provide comfortable lodging and generally, but not always food, beverage, entertainment, a business environment, and other ‘way from home ’ services. There are also hotels that contain residences. Known as hotel-residences, this type of occupancy is later addressed in mixed-use buildings.

Residential and apartment buildings

A residential building contains separate residences where a person may live or regularly stay. Each residence contains independent cooking and bathroom facilities.

Mixed-use buildings

A mixed-use building may contain offices, apartments, residences, and hotel rooms in separate sections of the same building.

In this dissertation, we will be focusing in the comparison on office skyscrapers.

2.1.4 The era of the MEGA-TALL

Since the first appearance of high-rise buildings, we have witnessed different designs and construction shapes. Due to the creation of lighter materials and the advances in technology which makes the design and execution of big projects easier; construction is experimenting a continuous evolution and skyscrapers have become much more common today than in the past.

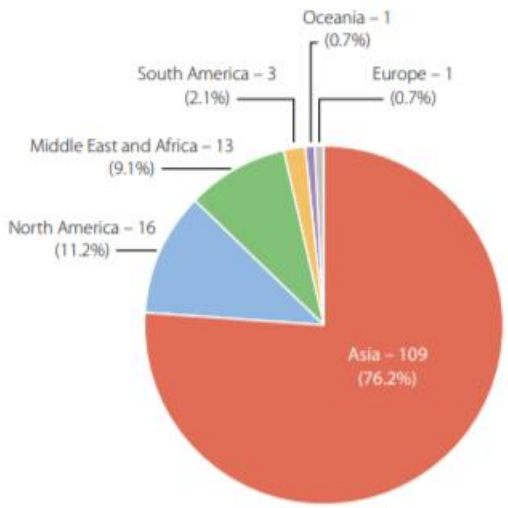


Fig. 4 Buildings of 200 meters or taller completed in 208 by region. (CTBUH, 2018)

The 19th century brought some ideas and inventions that made skyscrapers possible. During the 20th century we have seen how this new type of construction expanded. However as the 21st century started, Taipei 101 took the title of the "world's tallest building" in 2004, at 508 metres. Then, at the end of the decade, Burj Khalifa has set new standards at 828 metres (CTBUH, 2018).

According to a research report by the Council of Tall Buildings and Urban Habitat (Safarik et al., 2015), skyscrapers 200 m high and more around the world until 2015 were located as follows: China (348), South Korea (48), Rest of Asia (140), Australia (27), Europe (37), Middle East (120), USA (169).

The world is witnessing the completion of a significant number of buildings with over 600 metres height (that's twice the height of the Eiffel Tower; 301 metres). The term "Supertall" is no longer adequate to describe these buildings. It is the beginning of the era of the "Megatall".

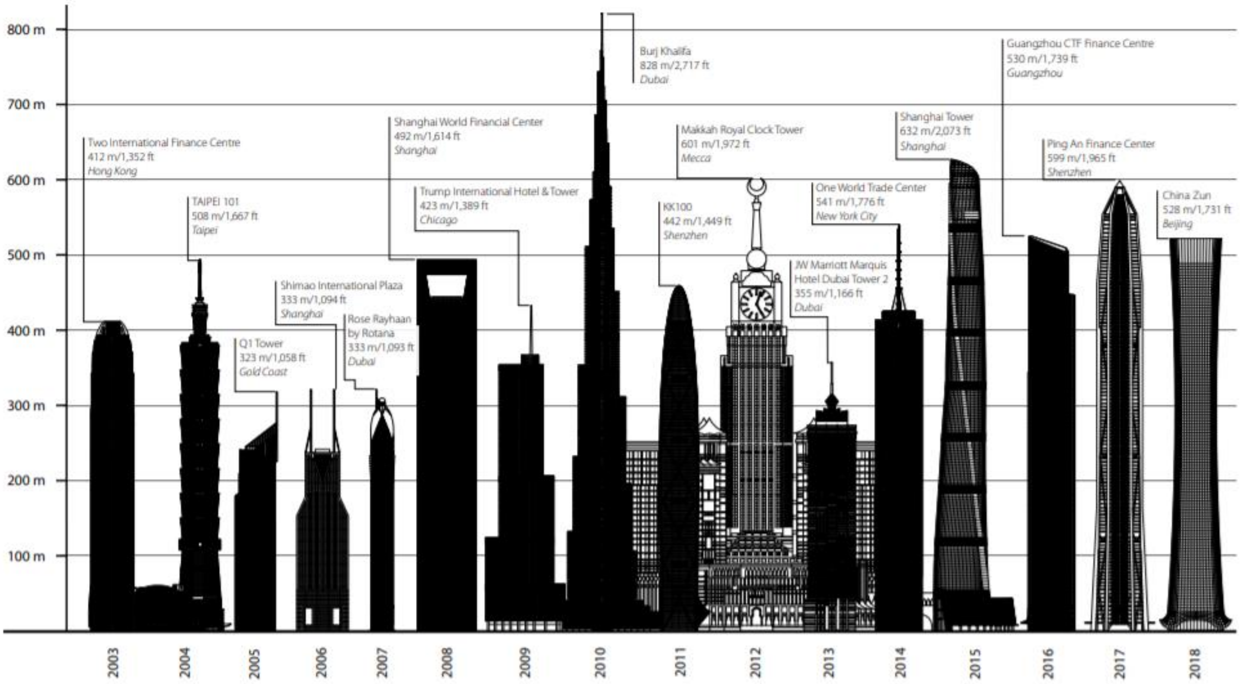


Fig. 5 World's tallest buildings completed each year (CTBUH, 2018)

High-rise building could be the right option to solve different problems that today's world is facing. They offer the ability to accommodate larger populations in cities; and we all know that the utilization of vertical space in urban areas is the only way to accommodate the needs of this growing population. Also, the prospect of traveling for a long time, to and from work, is detrimental to social well-being of the commuter and results in losses of fuel and productivity. Although high rise buildings require an enormous amount of energy to be built and maintained; if the building is designed with sustainable features that will makes it more energy efficient than any other kind of building. This will be discussed in further chapters.

2.2 Sustainable development

2.2.1 General concept

Sustainability is a very common concept of the last decades used in plentiful of disciplines and in a big variety of contexts. Even though it might seem odd but sustainability is not a new idea since it started to emerge during the late 17th century when the attention towards the negative influence of forest over utilization for goods and services came up and the first environmental movements appeared as a consequence of the impact of the industrial revolution **(MacDicken et al., 2015).** Later on and with the growth of the term, the definitions surrounding it increased. One of the firsts and most recognised definitions is the one developed by the World Commission on Environment and Development also known as the report of the Brundtland **(WCED, 1987)** stating that "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". A very powerful definition that strongly appeals to the present generation except that until today there is no clear way of how to work it out. This definition grew in consequence of the 1972 UN Conference on

Human Environment in Stockholm that stated that the post-war economic development model based on a non-stop growth in consumption may exceed certain basic environmental limits.

During the same year, the economist Edward Barbier **(1987)** published a crucial model of sustainable development that rests on three pillars: Social, economic and environmental. Subsequent papers **(Hill and Bowen, 1997)** added other pillars such as technical, political or institutional. Nevertheless, Barbier’s model is the basis of today’s definition of sustainability.

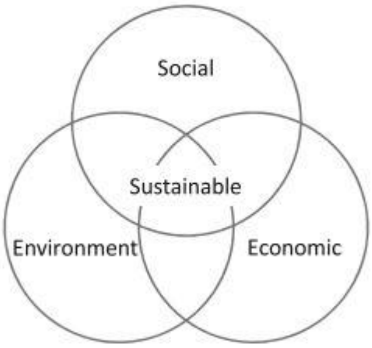


Fig. 6 A generic graphical representation of the three pillar approach (Purvis et al., 2018)

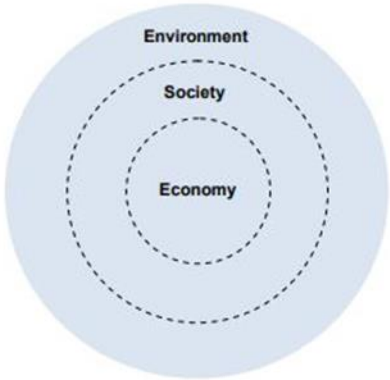


Fig. 7 Modified illustration of the three pillars of sustainability (Lethonen, 2004)

The three-pillar approach was criticized by Lehtonen **(2004)** mainly due to the fact that its elements are not qualitatively equal and that they might lead institutions and government to justify their means in terms of sustainability. In order to address the weaknesses found in this definition, he proposed a slightly different illustration that recognises that the activities of the human society should be retained within the environmental constraints and that the economic activities should be carried out to service the entire human society.

For different reasons, the term Sustainable Development is frequently considered vague and could be subjectively interpreted by different institutions which leads to a conflictive scenario **(Gomes, 2003).** However, to understand better the framework concept of sustainability, a chronological summary of the most important steps made towards it are cited on the table below.

1968	**Paris Biosphere**	Conference held in Paris that sounded the alarm of environmental degradation and the need for action.
1972	**Limits to Growth**	The so called "Club of Rome" report, making the world aware of that resources were not unlimited. "Limits" was published just prior to the Stockholm conference.
1972	**Stockholm**	First Conference of the United Nations on Environmental Call of the scientists for nature conservation.

1980	**World conservation strategy**	Document prepared by the international union for the conservation of nature (IUCN) the UN environment program (UNEP) and the World wildlife fund (WWF) an integrated approach to global problems.
1986		Catastrophe of Chernobyl in Ukraine
1987	**Brundtland Report for the United Nations**	For a development which does not penalise the future generations. Identification of two risks: The greenhouse effect and the ozone layer destruction.
1987 - 1993	**Protocol of Montreal/London and Copenhagen Amendments**	Commitment of the Stated to stop the CFC consumption and production by 1/1/1995 and the HCFC consumption by 2015
1992	**Rio de Janeiro**	Conference of the United Nations on environment and Development: AGENDA 21, convention on biodiversity and climate, statement on the forests. First perspective setting of the Northern and Southern approaches
1994	**Berlin**	First Parts Conference: Consensus to decrease back by 2000 the CO2 emissions by the Stated of the IPCC (International Panel on Climate Changes)
1996	**Geneva**	Second Parts Conference on the climatic changes: Approval without reserves by the States of the IPCC (International Panel on Climate Changes)
1996	**Istanbul**	Habitat II Summit of the United Nations which recognised the cities as partners of the United Nations and confirms the Rio commitments.
1997	**Kyoto**	Third Parts Conference for the problem of global warming. By 2012 emissions of six major greenhouse gases must be reduced.
2001	**New York**	Habitat 2+5 implementation of the outcome from Habitat II
2002	**Johannesburg**	RIO+10 Conference on poverty, access to safe drinking water and sanitation. Increase the use of renewable energies and restore depleted fish stocks.
2012	**Rio de Janeiro**	Resulted in a focused political outcome document which contains clear and practical measures for implementing sustainable development.
2015	**Paris Agreement COP21**	For the first time, all nation is brought to a landmark agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future.

Table 1. Highlights of the most important steps towards sustainability

2.2.2 Impact of the construction industry on the Environment

Buildings play an important role in consumption of energy all over the world. The building sector has a significant influence over the total natural resource consumption and on the emissions released.

- **Energy consumption**

The construction industry nurtures a big part of the economic and social development. However, the price comes very high, as the building sector consumes about 40% of primary energy utilization (Levermore, 2008). Buildings demand energy all over their life cycle, both directly and indirectly. Directly for their construction, operation, rehabilitation and eventually demolition; indirectly through the production of the materials they are made of and the technical installations implied. Therefore, the life cycle energy consumption of the construction industry can be divided into operational and embodied energy. The first one is used for the occupation/operation of buildings (including heating/cooling, ventilation, hot water, etc.); the second one refers to the energy used for the construction, maintenance, renovation, and demolition of built environment (Cabeza et al., 2014). The embodied energy includes at the time direct energy which is the energy required for the on-site construction operations (construction, maintenance/renovation, demolition) and indirect energy which is the energy required to providing products and services for the construction operations.

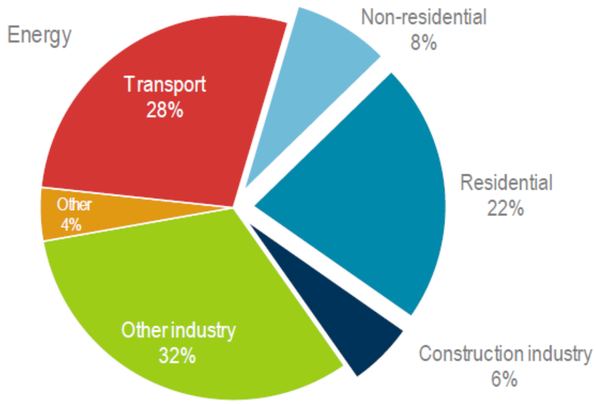


Fig. 8 Global share of buildings and construction final energy consumption, 2017 (IEA, 2018)

The buildings and construction sector is a key factor in the fight against climate change: it accounted for 36% of final energy use.

Electricity use in buildings has had the largest growth, with 15% growth globally since 2010. This shift to electricity is not immediately a clean energy transition, given the strong role of fossil fuels in global electricity production, particularly in emerging economies where electricity growth is strongest.

The growth of electricity in buildings is followed by that of renewable sources of energy, which increased by 14% between 2010 and 2017. Natural gas use increased by nearly 5% during that period, a portion of which substituted less-efficient coal use in buildings, which dropped by almost

8% globally since 2010. Other fuel types, including oil and traditional use of biomass, remained stable over the same period.

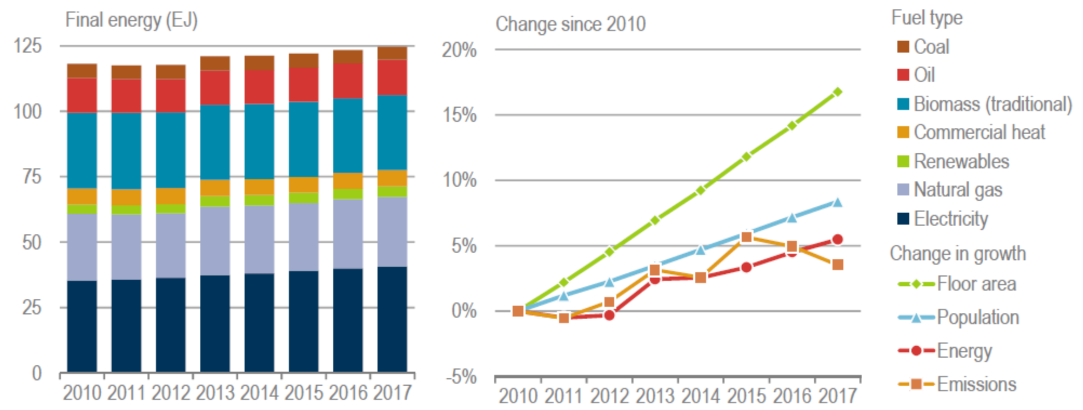


Fig. 9 Global buildings sector final energy use by fuel type and change in indicators, 2010-17 (IEA, 2018)

Space cooling energy use increased globally by more than 20% between 2010 and 2017, while appliance electricity demand grew by 18% and space heating decreased by around 4%. Space heating energy reductions, given the large use of fossil fuels for heat production relative to other end uses, are also contributing to the larger share of electricity use in buildings.

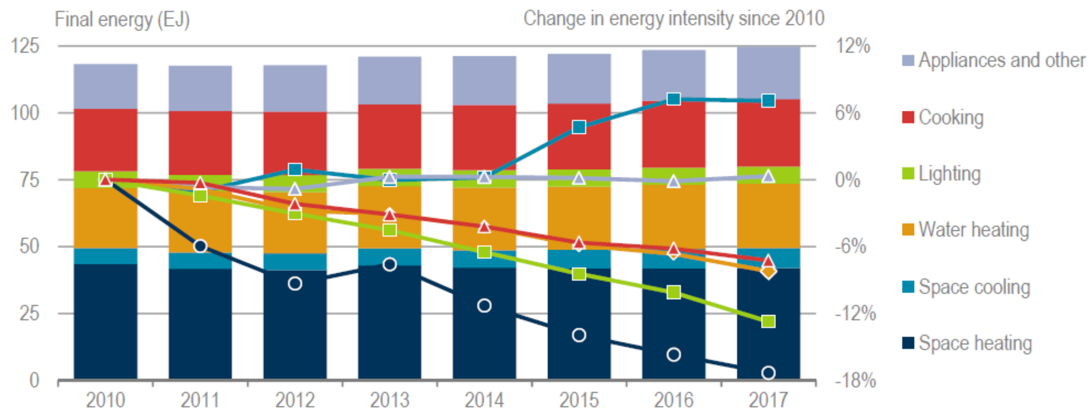


Fig. 10 Global buildings final energy use and change in intensity by end use, 2010-17 (IEA, 2018)

The shift to energy-efficient technologies, such as light-emitting diodes (LEDs) and heat pumps in some markets, has played a role in those energy intensity improvements. Building envelope measures have also helped to improve heating and cooling energy intensities per square metre (m2), through improved thermal performance (e.g. material choice) and better building design and orientation.

- **GHG emissions**

Largely involved in a variety of economic activities, buildings construction has become the most significant component in urban metabolism and regional development (Wolman, 1965). As the urbanization process is accelerating, the construction is too and therefore the migration to big part of the population to cities. Overall, the building sector is responsible for the 39% of energy-related carbon dioxide (CO_2) emissions in 2017 (UNEP, 2018).

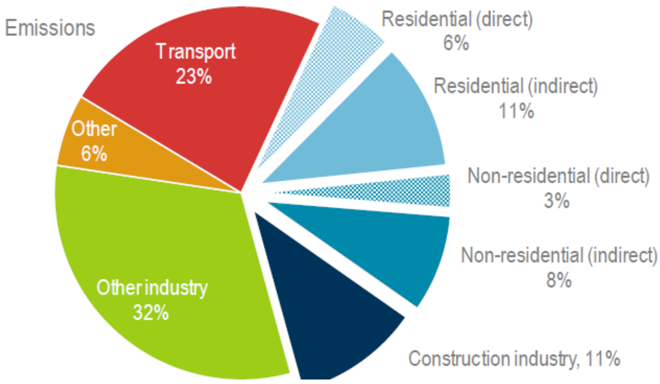


Fig. 11 Global share of buildings and construction final emissions, 2017 (IEA, 2018)

Buildings sector emissions according to Fig. 12 have levelled off in the last few years, stabilising at around 9.5 gigatonnes of carbon dioxide (GtCO2). Indirect emissions like those coming from power generation for the consumption of electricity and heat account for the dominant share of energy-related CO2 emissions in the buildings sector.

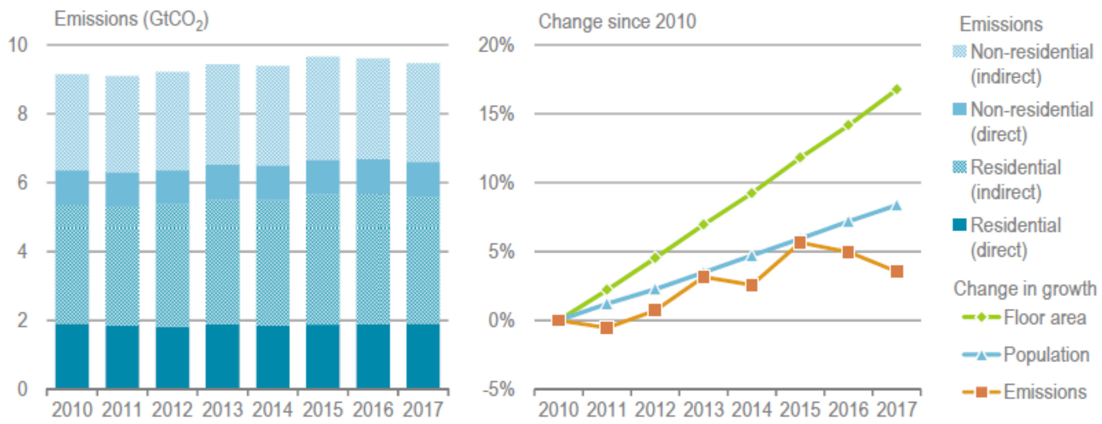


Fig. 12 Global buildings energy-related emissions by building type and change in indicators 2010-17 (IEA, 2018)

- **Water use**

During the entire life cycle of a building, water and energy are considered to be the two major pillars that support human activities in it and while there are many articles and researches done on the energy consumption; very few are done on water use (Bardhan, 2011).

Major building materials like bricks, cement, aluminium, glass etc. use considerable quantity of water in their manufacturing process through extraction and processing; though data on their water-foot print is not readily available. The United Nations Environment Program (UNEP, 2006) has indicated that over an entire life-cycle, the building industry consumes a global average of 30% of fresh water and generates 30% of world’s effluents.

Researchers in Australia (Crowford et al., 2005; McCormack et al., 2011) and their studies suggest that embodied water is many times greater than the volume of water used during a building’s life.

The UK concrete industry (The concrete center MPA, 2017) has agreed on a ‘Concrete Industry Sustainable Construction Strategy’ and has reported that “though no studies have been done on homes in the UK, a 2004 study in Australia estimated that a typical Australian house represents about 15 years' worth of operational water i.e. water used for cooking, cleaning, washing, drinking, toilet flushing and gardening. This study estimated that a kilo of concrete has about two litres of embedded water, a kilo of timber about 20 litres, a kilogram of steel about 40 litres, a kilo of aluminium about 88 litres, and that a kilogram of plastic has about 185 litres of embedded water." In a recent study, they realised that the applied strategy has given results. In the base year 2008, the value of concrete's water consumption was approximately 86 litres/tonne and in 2016 it has gotten to approximately 78 litres/tonne which means a 9.3% reduction.

Fig. 13 Water consumption as proportion of productionoutput litres/tonne (Sustainableconcrete.org)

Reducing water consumption and improving water efficiency in buildings is a major step towards sustainable water management. It is definitely linked with sustainable building concepts, sustainable development issues and Life Cycle Analysis (LCA) of buildings.

- **Resource consumption**

Construction materials have been always supplied from raw materials that were thought to be in plentiful supply and unlikely to be exhausted (DEH, 2006). Nevertheless, the mining and quarrying of raw materials have different environmental impacts such as land disturbance and pollution effects (Carpenter, 2011).

According to an OECD report (OECD, 2019), the world's consumption of raw materials is set to nearly double by 2060 as the global economy expands and living standards rise, placing twice the pressure on the environment that we are seeing today.

Without concrete actions to address these challenges, the projected increase in the extraction and processing of raw materials such as biomass, fossil fuels, metals and non-metallic minerals is likely to worsen pollution of air, water and soils, and contribute significantly to climate change.

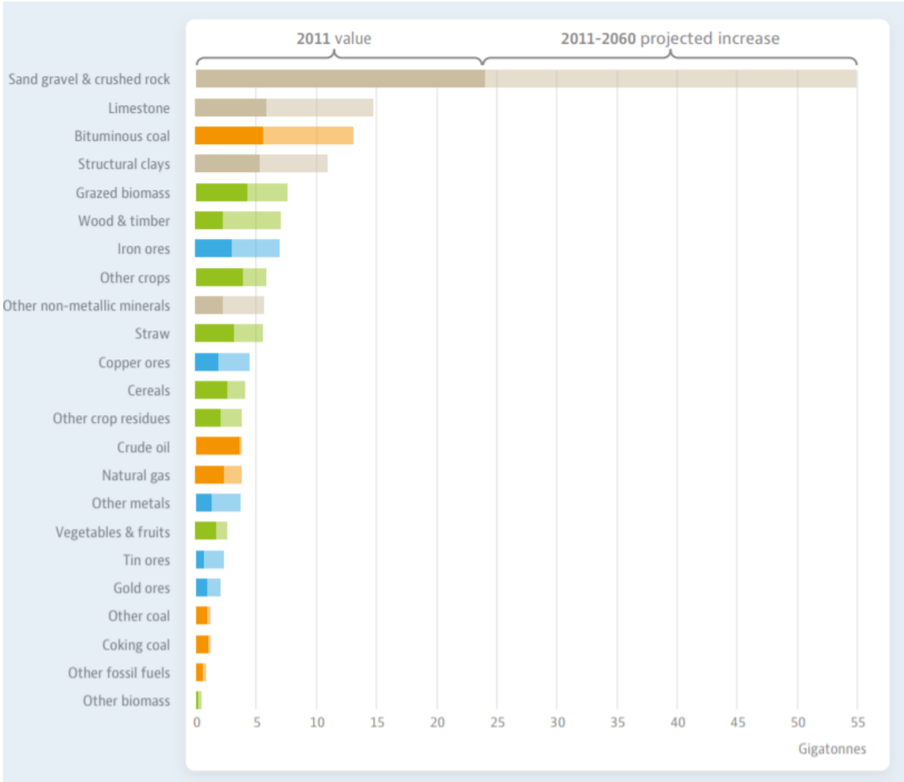


Fig. 14 Construction materials dominate total materials use in 2011 and 2060 (Source: OECD Global Material Resources Outlook to 2060)

➢ **Transportation**

In the EU-28 in 2011, transport is responsible for around 25% of greenhouse gas (GHG) emissions rendering it the second largest GHG emitting sector after the energy industry. In addition, despite the fact that emissions from other sectors (energy industry, manufacturing etc.) present a general decreasing trend, those from transport have increased by 19% from 1990 to 2011 (European commission, 2014).

Note that part of these emissions is generated by the transport of construction materials to the construction site.

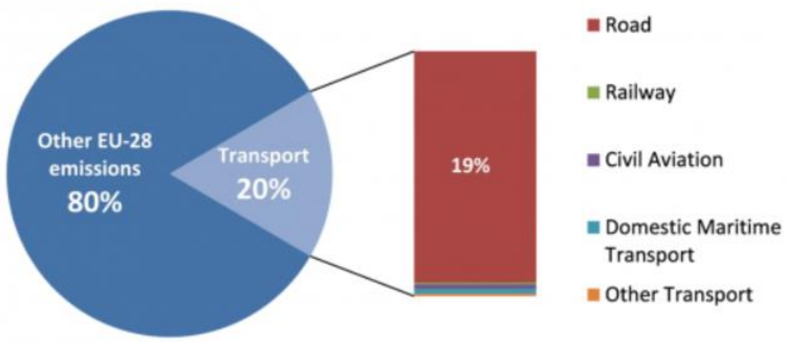


Fig. 15 EU-28 GHG emissions (tn of CO2 equivalent) by mode of transport in 2011

2.2.3 Sustainable Construction

Sustainability is as explained a complex concept, which has grown to be one of the major issues in the building industry. In the literature review, it is easy to find different terms that refer to sustainable construction such as “green building”, “sustainable building”, “high performance building” or “ecologically sustainable building”. Nevertheless, Charles Kibert introduced the first definition of sustainable construction during the First International Conference on Sustainable Construction in Tampa in 1994: **“Sustainable construction is the creation and responsible management of a healthy built environment based on resource efficient and ecological principles”** (Bourdeau, 1999).

The social, economic and environmental indicators of sustainable development are drawing attention to the construction industry, which is a globally emerging sector, and a highly active industry in both developed and developing countries (Ortiz et al., 2009).

Fig. 16 Sustainable building design factors

Sustainable construction depends on the entire life cycle of the built environment: The planning, design, construction, operation, renovation and retrofit and the end-of-life fate of its materials. It considers the resources of construction to be materials, land, energy, water, etc. (Kibert, 2003)

In 1994 a set of principles of Sustainable Construction were set (Kibert, 1994):

- Reduce resource consumption;
- 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.

Sustainability in construction concentrates on several areas like energy efficiency, water efficiency, indoor environment, site location, atmospheric considerations, and material usage. Material usage means the selection of materials that has sustainable indices like low embodied carbon footprint, recyclable content, reusable content, nontoxic content, and good thermal properties (Bunz, 2006).

2.2.4 Sustainability in High-rise building

Tall buildings are massive consumers of energy. They represent dominant elements in urban architecture due to their scale and purpose which is why they should be the main focus of sustainable design (Navaei, 2015). They are usually higher and isolated from the urban pattern of the surrounding built environment which results in increasing the energy use for mechanical heating and cooling water, transporting materials and users pumps for higher levels. It should be clear that the skyscraper is not an ecological building type.

Skyscrapers are built to keep balance of population growth and the space needed; however their consume of energy is quite considerable and it results in environmental pollution, overflow of wastes and deprivation of natural ventilation and light. It is believed by most engineers and designers that if the buildings of big and populated cities are designed and built under appropriate conditions, they can reach a level of sustainable and green architecture.

The design process of a skyscraper is a complex step where the designer has to understand the building performance under different conditions in order to deliver a high performance design that can result in different benefits such as energy efficiency, design flexibility, resource conservation, indoor environmental quality, etc.

There are different design factors to take into consideration in order to achieve a high performance skyscraper: Site design, water conservation and quality, energy efficiency, indoor environmental quality, conservation of materials and resources and the list is long. Such complex forms of the design that include conceptual, schematic, physical, economic, environmental and socio-cultural forms must be shared by different professional of different disciplines in order to deliver an optimum performance building (Ali et al., 2008).

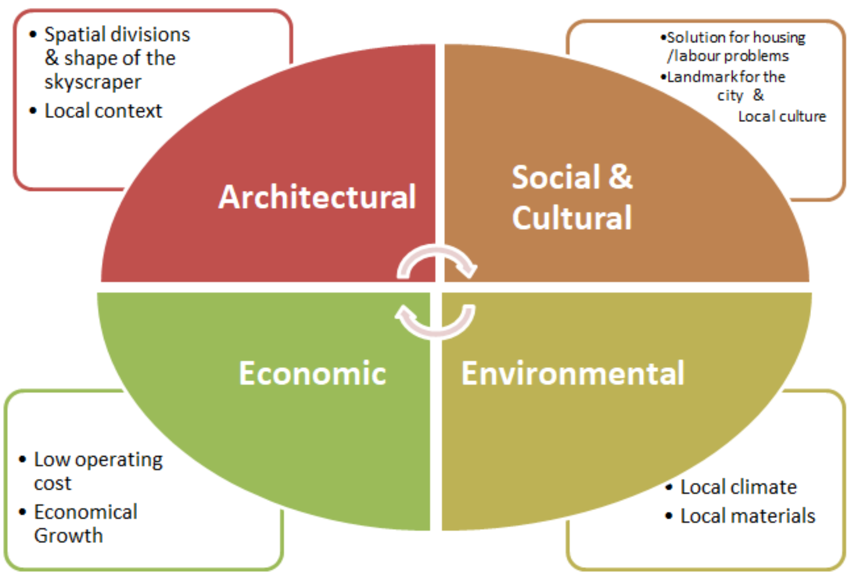


Fig. 17 Four dimension sustainability concept in Skyscrapers

Four different dimensions are affected by the sustainability of a skyscraper; Economics for instance are vital with any form of development. Governments see sustainable development as a key to sustained economic growth and therefore will view any new tall-building against the backdrop of economic success. Tall-buildings or the opportunity to develop can attract employers and develop economies. One of the main drivers for local authorities is to construct new tall-buildings is to generate a sustainable community.

Regarding the social and cultural aspect, the local community can gain a lot from the creation of a new building specially if it is a skyscraper. Any high-rise development provides an opportunity to provide facilities for the surrounding community and it can be an opportunity to employ and, if necessary, train the local workforce, to contribute both in the construction phase, and in delivering the building's primary work function. There are also opportunities for engagement with the local community. For those working in and visiting them, there can be the advantages of a prime location in terms of establishing a centre of excellence, transport links, and amenity. There is also the opportunity to sustain in-house catering, banking and sporting facilities as a result of the number of people in one building.

The main problem regarding environmental aspects in skyscrapers is Energy. However it is not just energy itself but how this energy have been generated. Certain locations can benefit from renewable energies in a higher rate than others. The key to having a net zero CO2 building is the ability to create energy on site. This is influenced by the geographical location, as well as specific site constraints.

2.3 Sustainable Assessment

Under these last two decades a significant number of environmental and sustainability assessment tools for buildings have been developed. Usually these methods are characterized by evaluating a series of partial and aggregate features of construction, resulting in environmental ratings or sustainability scores (Bragança et al., 2010).

The Building Research Establishment's Environmental Assessment Methods (BREEAM) was the first of its class to appear in the market in 1990 and also to determine the bases of the certification methods that followed. Ten years later, the United States Green Building Council (USGBC) released another worldwide assessment method; the Leadership in Energy and Environmental Design (LEED). Between these two systems, the French certificate Haute Qualité Environmentale (HQE) appeared in 1996 and the fact that all the documentation was available only in French definitely slowed down its international progression (Ebert et al., 2011). From then on, plenty of new tools and systems have been developed according to national standards and local environmental conditions as the figure below illustrates.

Some relevant certification systems are: CASBEE (Japan), MINERGIE (Switzerland), Escale (France), EU GreenBuilding Programme (Europe), GBAS and Three Star (China), Green Start and NABERS (Australia), HKBEAM (Hong Kong), GBTool (International), AQUA (Braziel), Green Leaf (Canada), DGNB and BNB (Germany), VERDE (Spain), Protocollo Itaca (Italy), etc.

Fig. 18 Creative spaces of certification systems for some buildings sustainability (Tebbouche et al., 2017)

However, these assessment criteria were never adapted to high rise buildings. In 2012, Nguyen (2011) developed a "TPSI – Tall-building Projects Sustainability Indicator". The System can be used as a managing tool to compare and improve the sustainability features of tall building design.

B-Building Performance	E-Environmental Performance
B1. Project Management (PM) B1.1. Overall Management B1.2. Design Process B1.3. Construction Issues B1.4. Contractual and Commission Process B1.5. Operation B1.6. Demolition	**E1. Resources Consumption (RC)** E1.1. Land Use E1.2. Water Use E1.3. Energy Use
B2. Indoor Environmental Quality (IEQ) B2.1. Prerequisite B2.2. Water Quality B2.3. Hygiene B2.4. Indoor Air Quality (IAQ) B2.5.Ventilation B2.6. Thermal Comfort B2.7. Lighting and View B2.8. Acoustics and Noise B2.9. Other Issues	**E2. Material Aspects (MA)** E2.1. Selection of Materials E2.2. Efficient Use of Materials
B3. Building Services (BS) B3.1. Building Amenities B3.2. Basic Building Equipment B3.3. Security and Safety B3.4. Vertical Transportation B3.5. Earthquake Resistance	**E3. Environmental Loading (EL)** E3.1. Waste E3.2. Pollution E3.3. Ecology and Microclimate
B4. Design Features (DF) B4.1. Design for Energy Efficient B4.2. Design for Functionality and Usability B4.3. Design for Flexibility and Adaptability	**E4. Social and Economic Aspects (SE)** E4.1. Social Aspects E4.2. Economic Aspects
Innovations IN1. Innovative Strategies and Technologies IN2. Exemplary Performance	

Table 2. Summary of TPSI categories and sub-categories (Nguyen, 2012)

This criteria would have been the perfect process to assess the three chosen skyscrapers. However, due to lack of information and data on the tall buildings, another methodology will be followed in order to assess the different sustainable features of each one of them according to the climate of the location.

3. METHODOLOGY

3.1 Introduction

There are several factors that affect the sustainability of a skyscraper. In this dissertation we will be focusing on energy consumption. The two main goals in order to design eco-friendly a skyscraper is to reduce as much as possible the energy consumption depending on the climate zone, the building shape and the operational energy features that the building will hold. Also, we have to generate as much energy as possible from renewable energy sources such as solar and wind energy.

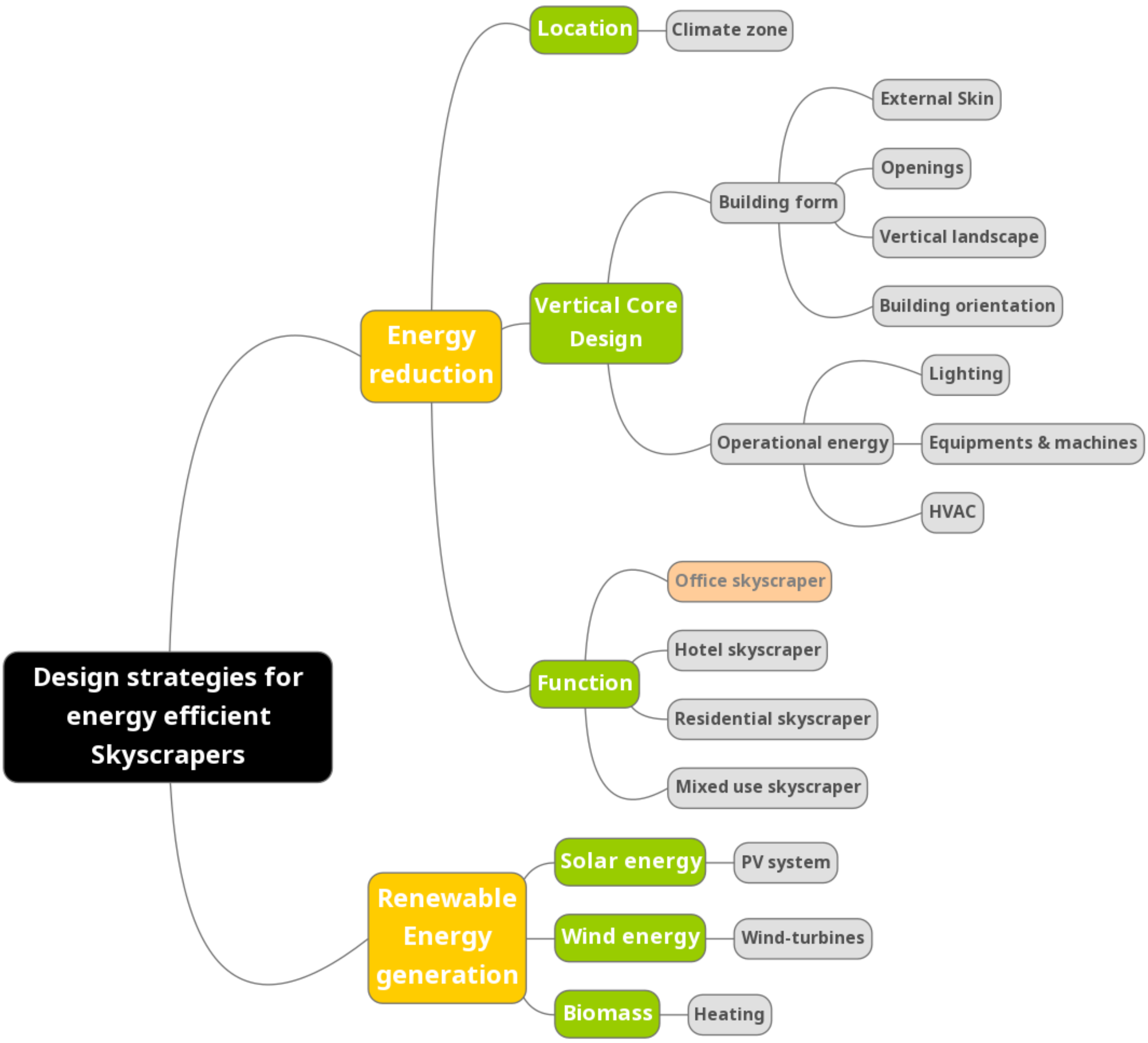


Fig. 19 Mindmap on energy reduction and generation in a skyscraper

So as of the first factor on which depends the reduction of energy consumptions, we have location. Designing buildings that are truly climate responsive depends first on gaining a detailed accurate understanding of the local climate.

This dissertation's focus is on comparing three different skyscrapers in three different climate zones:

- Desert climate: Bahrain World trade Center (Manama, Bahrein)
- Continental Climate: Lakhta Center (St. Petersburg, Russia)
- Subtropical Climate: Ping An Finance Center (Shenzhen, China)

In order to carry that on, we have to evaluate the climate characteristics of each zone so we define the building features that are important for it to be energy efficient and sustainable. The best design strategies will be always to take advantage of the passive possible actions and pick some active ones when we have no other choice.

For that, we chose the software CLIMATE CONSULTAT to evaluate the relationship between the climate of the location of the skyscraper and the efficient design of it. Also, we estimated the solar electricity that can be generated in each location via an online sheet calculator that can be found in Annex III.

3.2 Procedure

The procedure we will follow consists on evaluating the skyscrapers locations mentioned above.

CLIMATE CONSULTANT is a graphic based computer program that will help us understand the local climate and how to optimize our building. It uses annual 8760 hour EPW format climate data and translates it into different graphic displays. The goal is to help users create more energy efficient and more sustainable buildings, each of which is uniquely suited to its particular spot on this planet.

EPW data is provided by the US Department of Energy. Each EPW climate data file contains hourly data for all 8760 hours per year. These files were assembled by climatologists from actual months of recorded data for that site. The approach the data follows tries to preserve the unique patterns of actual data, sequences of extremes data, and recurring weather patterns.

This software has no idea about our particular building; its height, its shape or its surrounding. It just evaluates the location indicated and says that many buildings will act this way in these conditions. And that's a good start to optimize our design.

As we mentioned, this software comes out with different results and graphs. However for this study we considered that the most important is the psychrometric chart.

3.2.1 Psychrometric Chart Concept

A psychometric chart for a specific location gives us the information about temperature (wet bulb and dry bulb) and humidity (relative and absolute). For this study, it is an important methodology to define the comfort of the building occupants and effective passive design strategies according to the location.

The Psychrometric Chart is an example of how three different attributes of the climate can be displayed concurrently to show if humans will be comfortable in spaces with these characteristics. More importantly it can also be used to show how to design buildings envelopes that can modify or filter these external climate conditions to create comfortable indoor environments.

This graphical representation of air processes is carried out by plotting multiple data points that represent the air conditions at a specific time and overlaying an area that defines the comfort zone. Each dot represents the temperature and humidity of each of the 8760 hours.

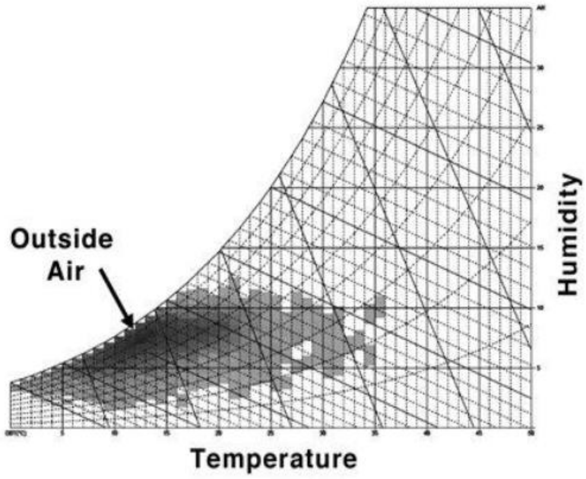


Fig. 20 A psychometric chart that shows temperature vs. humidity and that can be used to express human thermal comfort, design strategies and energy requirements (Source: Autodesk)

The comfort zone is defined as the range within occupants are satisfied with the surrounding thermal conditions. After plotting the air conditions and overlaying the comfort zone, it becomes possible to see how passive design strategies can extend the comfort zone.

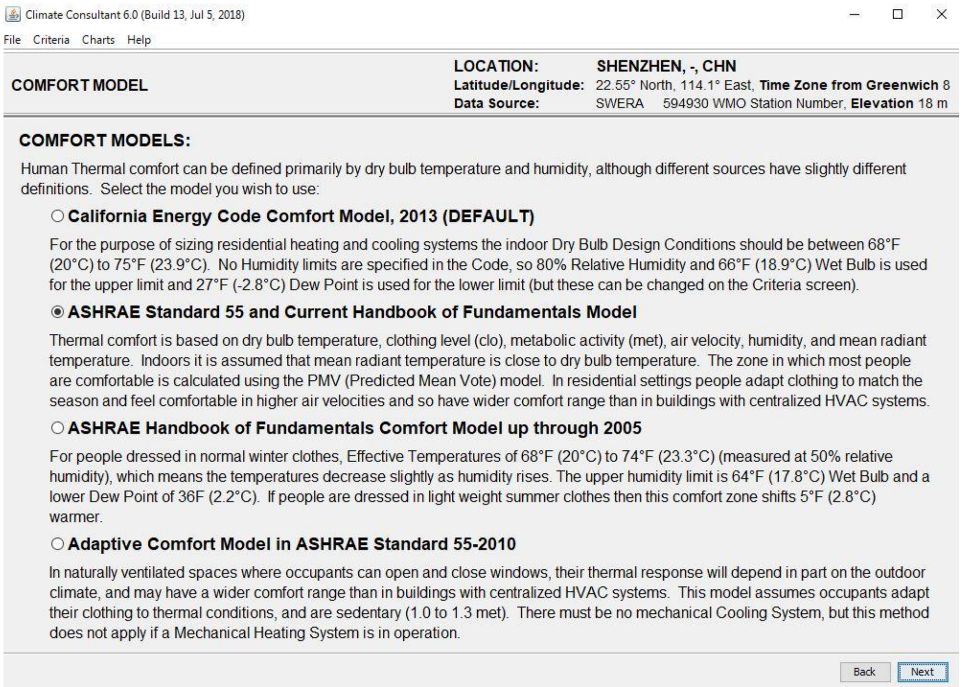


Fig. 21 Comfort models (Source: ClimateConsultant)

The choice of comfort models. Allows us to choose which standard we would like to use to control how the human comfort zone is defined. A detailes description of each option is described. The recommended model is the *ASHRAE Standard 55 and Current Handbook of Fundamentals Model.*

Next you can see the conditions of his american comfort standard that establishes the ranges of indoor environmental conditions to achieve acceptable thermal comfort for occupants of buildings.

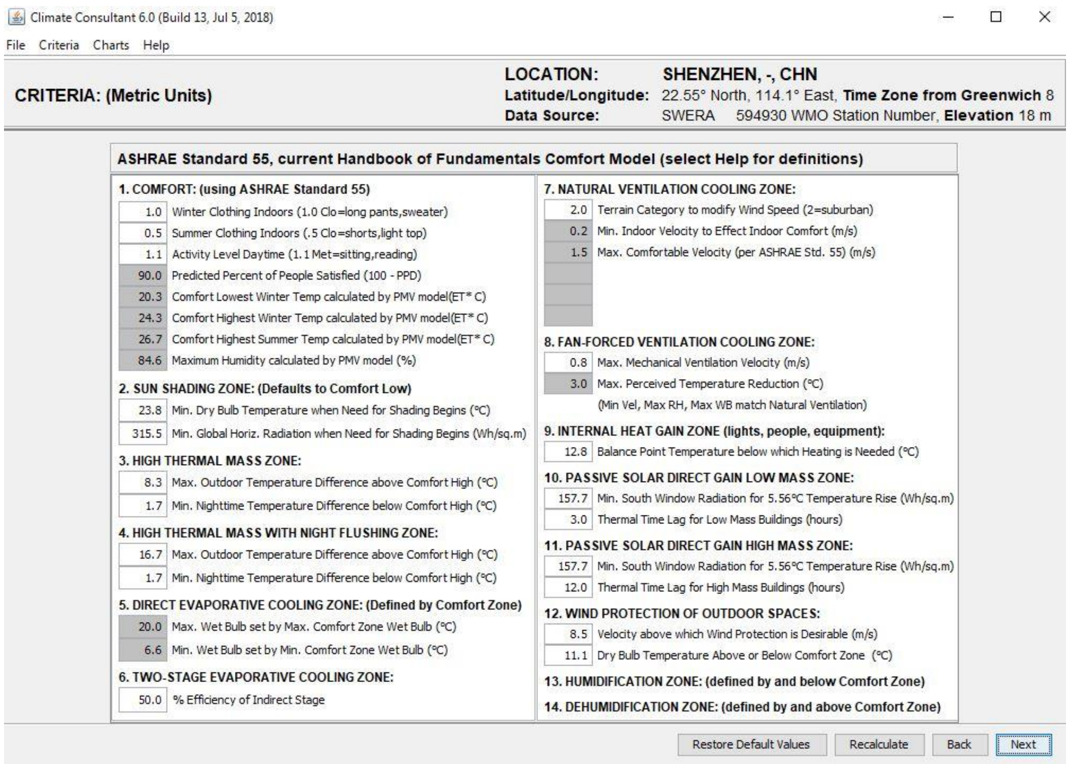


Fig. 22 Summary of the comfort model ASHRAE 55 (Source: ClimateConsultant)

3.2.2 Parameters

Once the location is defined, The weather data is imported and the comfort model is set, we get a chart as in the image below.

We will get RED and GREEN dots. On the horizontal axis we have the dry bulb temperature which represents how hot it is and on the vertical axis we will have the humidity ratio which represents how much moisture is in the air. The curving lines are the % of relative humidity which is the % of moisture until the air reaches saturation (condensation, precipitation).

Different Design Strategies are represented by specific zones on this chart. The percentage of hours that fall into each of the 14 different Design Strategy Zones gives a relative idea of the most effective passive heating or passive cooling strategies. Climate Consultant analyses the distribution of this psychrometric data in each Design Strategy zone in order to create the unique list of Design Guidelines.

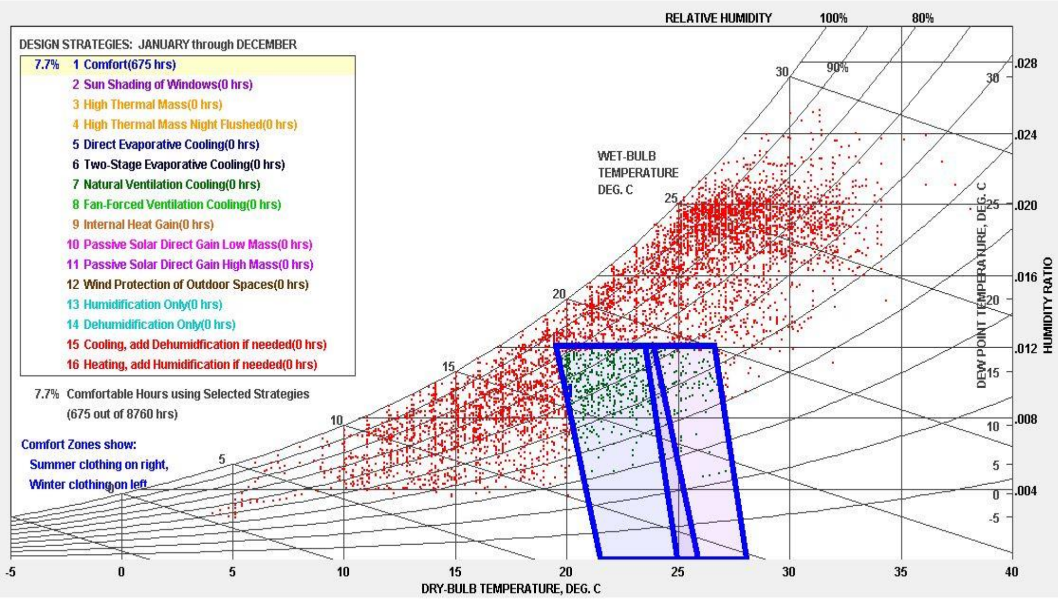


Fig. 23 A Psychrometric Chart before applying any strategies. On the right, the design strategies table. (Source: Self elaboration)

<u>Passive strategies</u>

- Comfort

The first blue boxes describe comfort region (summer clothing on the right and winter clothing on the left; their version of winter clothing is a suit, and for the summer clothing a shirt and t-shirt). So in this region, the occupants of the building can change clothing to adapt to temperatures and get comfort.

- Sun shading of windows

In order to control the amount of sunlight that is admitted into our building we need sun shading systems. In warm, sunny climates excess solar gain may result in high cooling energy consumption; in cold and temperate climates winter sun entering south-facing windows can positively contribute to passive solar heating; and in nearly all climates controlling and diffusing natural illumination will improve daylighting. This is why; sun shading is one of the important passive strategies to adopt. In Climate Consultant, these hours overlap with the comfort zone.

Fig. 24 How to take advantage of the sun in winter time and avoit it in summer by solar shading. (Source: Autodesk)

- High thermal mass

In building design, thermal mass is a property of the mass of a building which enables it to store heat, providing "inertia" against temperature fluctuations. A common analogy is thermal mass as a kind of thermal battery. When heat is applied (to a limit) by radiation or warmer adjoining air, the battery charges up until which time it becomes fully charged. It discharges when heat starts to flow out as the adjoining air space becomes relatively cooler.

Thermal mass depends on the building material used in the construction.

- High thermal mass Night flushed

Night Flushing is an interesting use of natural ventilation. By using the natural cooling effect of the night and the cooler air at night simply allowing the cool night air to circulate a structure during the night allows the loss of the heat build-up, or heat mass gathered by the structure during the day. In order to achieve this cooling one simply needs to allow the night air to circulate the building, in simple structures by simply opening the windows during night time. The cool night air carries away the heat absorbed by the structure during the day.

- Direct evaporative cooling

Evaporative cooling is a concept that is defined as making air cool via increasing its water vapour content. In other words, air becomes cooler while its humidity level increases (Cuce et al., 2016).

The process of evaporative cooling can be used to cool buildings. This can be as simple as including a water feature, such as a fountain in a courtyard, or a pond near a building or on a building roof, or might involve spraying water over a building roof.

Direct evaporative cooling is generally best suited to hot dry climates, where conditions encourage evaporation and the resulting humidification of the cool air supplied to the building can be beneficial. On the contrary, humid climates are not appropriate for the said system since the air is almost saturated; hence the cooling capacity of the system is limited.

- Two stage evaporative cooling

Includes direct and indirect cooling.

- Natural ventilation

Natural ventilation, unlike fan-forced ventilation, uses the natural forces of wind and buoyancy to deliver fresh air into buildings. Fresh air is required in buildings to alleviate odours, to provide oxygen for respiration, and to increase thermal comfort.

Natural ventilation has become an increasingly attractive method for reducing energy use and cost and for providing acceptable indoor environmental quality and maintaining a healthy, comfortable, and productive indoor climate rather than the more prevailing approach of using mechanical ventilation. In favourable climates and buildings types, natural ventilation can be used as an alternative to air-conditioning plants, saving 10%–30% of total energy consumption. The amount of ventilation will depend critically on the size and placement of openings in the building.

- Fan forced ventilation

Forced ventilation is a type of building ventilation system that uses fans or blowers to provide fresh air to rooms when the forces of air pressure and gravity are not enough to circulate air through a building.

- Internal heat gains

Internal heat gain is the sensible and latent heat emitted within an internal space from any source that is to be removed by air conditioning or ventilation, and/or results in an increase in the temperature and humidity within the space. It can be prevented by the right insulation of the envelope of the building.

- Passive solar direct gain

Direct-gain passive solar systems rely on south-facing windows to bring solar energy directly into a house. That sunlight is absorbed by materials in the house, which warm up, store some of that heat, and re-radiate it back into the room, warming the space.

- Wind protection of outdoor spaces

<u>Active strategies</u>

- Humidification
- Dehumidification
- Cooling and dehumidification if needed
- Heating and humidification if needed

3.2%	1 Comfort (281 hrs)
9.1%	2 Sun Shading (797 hrs)
4.9%	3 High Thermal Mass (429 hrs)
0.0%	4 High Thermal Mass/Night Flushing (0 hrs)
3.2%	5 Direct Evaporative Cooling (278 hrs)
7.8%	6 Natural Ventilation Cooling (686 hrs)
7.5%	7 Fan-Forced Ventilation Cooling (655 hrs)
17.5%	8 Internal Heat Gain (1534 hrs)
11.3%	9 Passive Solar Direct Gain Low Mass (994 hrs
7.6%	10 Passive Solar Direct Gain High Mass (667 hr
6.5%	11 Humidification (568 hrs)
30.8%	12 Wind Protection (2700 hrs)
1.2%	13 Conventional Air Conditioning (106 hrs)
62.0%	14 Conventional Heating (5433 hrs)

Fig. 25 Climate consultant strategies (Source: ClimateConsultant)

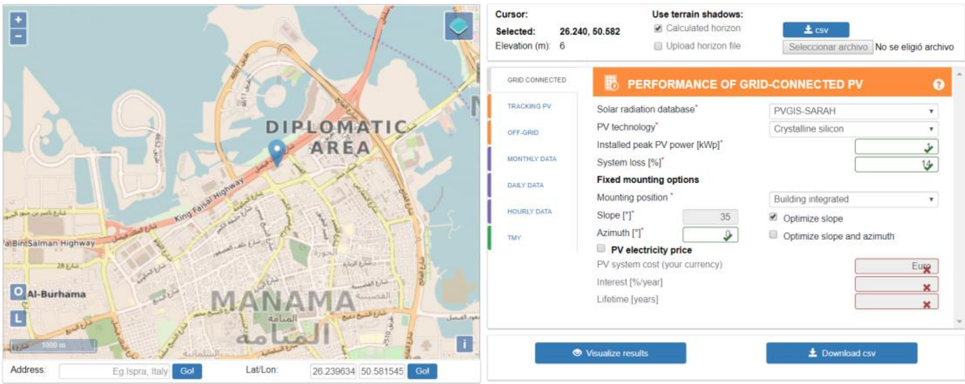
Many of these 14 Strategies can be used concurrently, for example Sun Shading works with all cooling strategies. Other Strategies might conflict with each other, for example Natural Ventilation usually implies low mass construction with large openings during the day, while High Thermal Mass construction usually is closed up during the day to hold the "coolth" from the previous night in the high mass walls and floors. Thus it is usually better to incorporate in the building one cooling strategy or the other, using the one that has the highest percentage of hours and is most compatible with the winter passive heating design strategy that was selected.

3.2.3 Solar irradiance

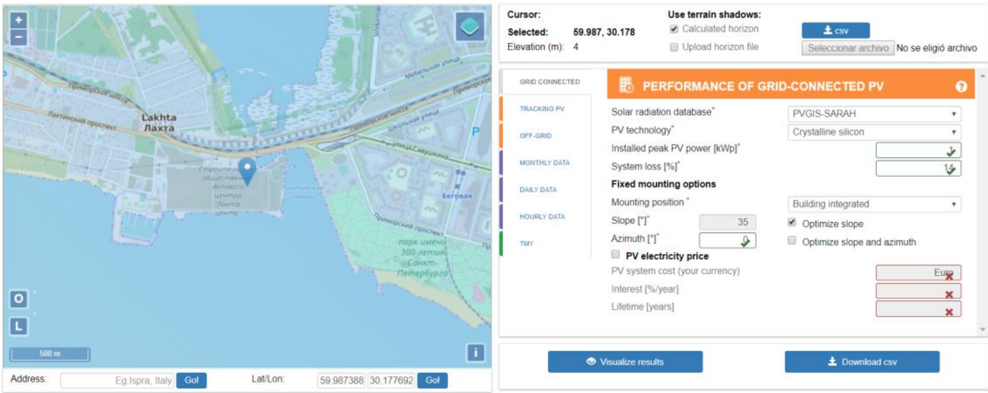
Solar irradiance (SI) is the power per unit area (W/m2), received from the Sun in the form of electromagnetic radiation. It can be captured and turned into useful forms of energy, such as heat and electricity, using a variety of technologies. However, the technical feasibility and economical operation of these technologies at a specific location depends on the available solar resource.

Using PVGIS, we calculated the electricity output for different PV technologies in the three different locations mentioned. Results can be found in Annex III and are discussed in the discussion chapter.

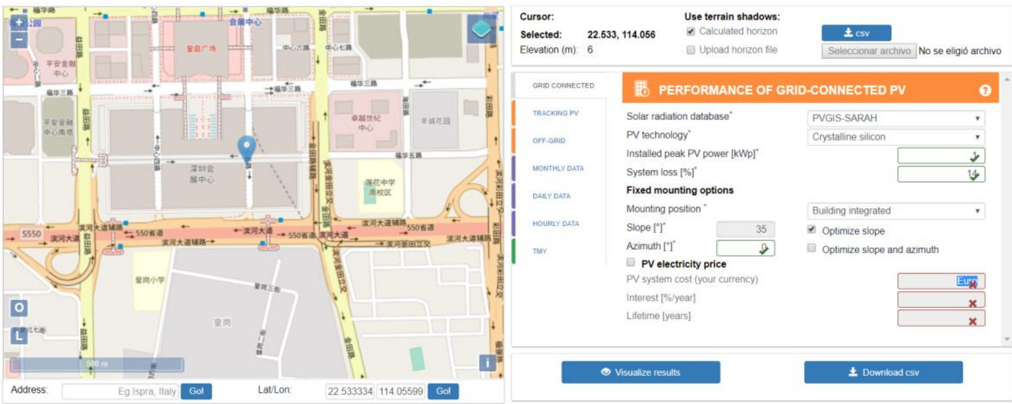
- BWTC (Manama, Bahrein)



- Lakhta Center (St Petersburg, Russia)



- Ping An Center (Shenzhen, China)



3.3 Evaluation

In order to evaluate the different climates, we located each skyscraper with its corresponding latitude and longitude.

Skyscraper	Latitude	Longitude
BWTC	26.239634	50.581545
LAKHTA CENTER	59.987388	30.177692
PAFC	22.533334	114.055994

Table 3. Latitude and longitude of the studied skyscrapers

The weather data can be found in detail in ANNEX I for each of the three regions.

3.3.1 Predesign

Before applying any of the active or passive measure, these are the psychrometric results we get for the three skyscrapers. Results can be found in ANNEX II.

The Table of Effective Design Strategies shows the number of hours and the percentage of time that falls within each strategy range. Changing the building design or default criteria will change these numbers.

A first look at the three charts gives us an idea about the comfort ratio we can achieve just by changing the clothes for each season and applying some solar shading strategies. The most comfortable building will be found in Bahrein and the less comfortable one in China probably due to the high humidity this country experiences in the selected region.

The results are similar and the use of passive active strategies is indeed required.

	Comfort indoors %	
	Comfortable	**Not comfortable**
Manama, BAHREIN	16	84
St Petersburg, RUSSIA	8	92
Shenzhen, CHINA	4	96

Table 4. Comfort indoors percentage

3.3.2 Design strategies

An evaluation of the results of the psychrometric chart has been carried out. Different building design strategies were tested by selecting or de-selecting any combination of the 14 options in this chart. These were the results explained:

- Manama, Bahrein

The best single cooling design strategy is direct evaporative cooling which accounts for 37.9% of the hours because Manama has a very hot dry climate. This strategy will be combined with sun shading which accounts for 22.9% of the hours. Conventional Air Conditioning is the only other option for cooling all of the hours that fall outside of these zones on the Psychrometric Chart.

On the heating side 23.3% of the hours would be comfortable indoors purely because of internal loads (lights, appliances, and people). Because it gets very hot in Manama which is surrounded by water in the winter 2.7% of the hours would be too humid for human comfort so some form of dehumidification would be required. This leaves us with only 10% hours that require Conventional Heating.

- Saint Petersburg, Russia

Even under the best of passive heating conditions at least 69% of the hours per year will require Conventional Heating in Saint Petersburg due to its mostly cold climate. This strategy will be combined with internal heat gain 20.6% of the hours to achieve big part of the comfort needed in winter. Cooling is not needed in this region, however natural ventilation and sun shading add 94 hours of comfort. The 1% left of not comfortable hours (53h) is placed when temperatures are a bit high and that could be solved with exterior activities.

- Shenzhen, China

In Shenzhen, two important things are important: Cooling and dehumidification because of the hot humid climate of the region. Fort that, we will need conventional cooling for the 38.4% of the hours and dehumidification for 24.1%. Internal heat gain will help the building when it’s cold for 23.9% of the hours and Sun shading of the windows in 18.1% of the summer time.

4. CASE STUDIES

In order to evaluate the sustainable strategies employed in different skyscrapers according to the climate zone where the constructions has been carried out and compare the relevant techniques towards efficiency; 3 different skyscraper projects have been studied in detail in 3 different climate zones:

- Tropical Hot Desert climate: Bahrain World trade Center (Manama, Bahrein)
- Moist Continental Climate: Lakhta Center (St. Petersburg, Russia)
- Humid Subtropical Climate: Ping An Finance Center (Shenzhen, China)

4.1 Bahrain World Trade Center

4.1.1 General information

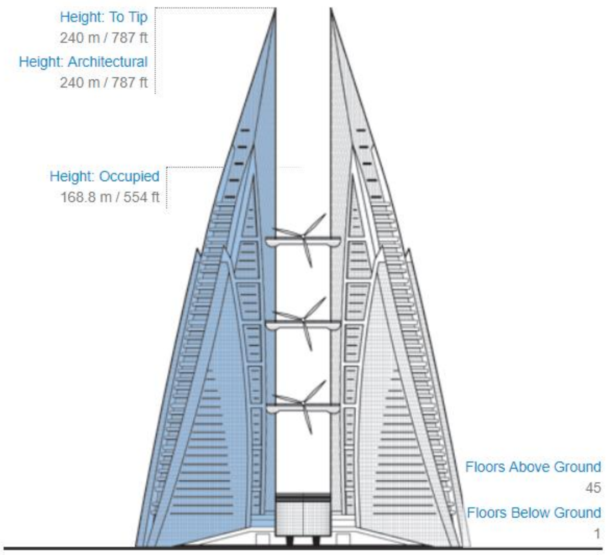


Fig. 26 BWTC (Source: skyscrapercenter.com)

Building location	Manama, Bahrain
Building type	Office
Year of completion	2008
Project size	16.500 m2
Total building costs	150 million $
Design & structural engineering	Atkins
Main contractor	Murray & Roberts

4.1.2 Concept

Bahrain, just like other nations of the Persian Gulf has a history closely linked with sea and maritime trade. The concept design of the twin towers was inspired by the traditional Arabian Wind Towers in that very shape of buildings harness the unobstructed prevailing onshore breeze from the gulf, providing a renewable source for this project.

The specific architectural forms of the Bahrain World Trade Center towers were born from using the nautical expression of a sail to harness the consistent onshore breeze, potentially to generate energy using wind dynamics, as well as to create two elegant towers for Bahrain, which would transcend time and become one of a kind in the world (Smith et al., 2007).

Fig. 27 The concept behind the BWTC (Source: Google Images)

4.1.3 Project description

4.1.3.1 Location and Climate

The Bahrain World Trade Center forms the focal point of a master plan to rejuvenate an existing hotel and shopping mall on a prestigious site overlooking the Arabian Gulf in the downtown central business district of Manama, Bahrain. Manama is the capital and largest city of Bahrain, with an approximate population of 157,000 people.

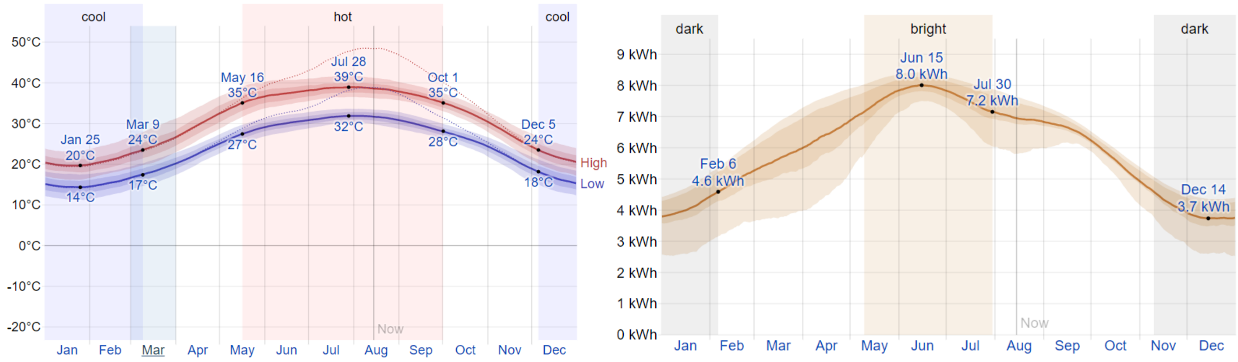


Fig. 26 Left: The daily average high and low temperatures in Manama. The thin dottedlines are the corresponding average perceived temperatures. Right: The average daily shortwave solar energy reaching the ground per square meter (Source: Weatherspark.com)

The climate type is of a subtropical desert and therefore it is hot and dry. Daily temperature variations are extreme. In Manama, the summers are long, sweltering, oppressive, and arid; the winters are cool, dry, and windy; and it is mostly clear year round. Over the course of the year, the temperature typically varies from 14°C to 39°C and is rarely below 11°C or above 42°C.

The brighter period of the year lasts for 2.6 months, from May 9 to July 30, with an average daily incident shortwave energy per square meter above 7.2 kWh. The darker period of the year lasts for 2.9 months, from November 9 to February 6, with an average daily incident shortwave energy per square meter below 4.6 kWh.

Rain falls throughout the year in Manama. The most rain falls during the 31 days centred around January 20, with an average total accumulation of 11 millimetres. The least rain falls around July 4, with an average total accumulation of 0 millimetres.

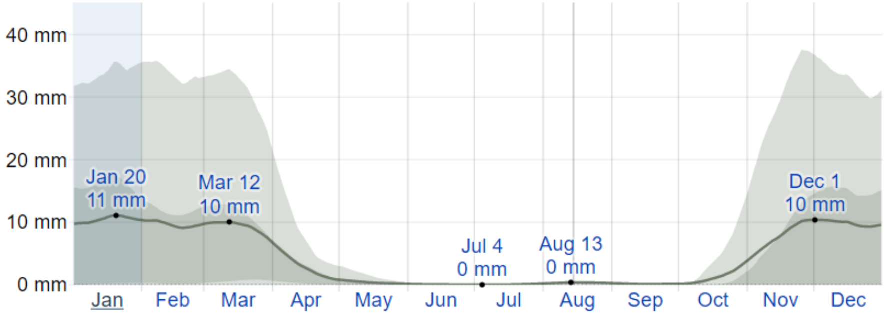


Fig. 27 Average rainfall accumulated over the course of a sliding 31 day period centred on the day in question. (Source: Weatherspark.com)

4.1.3.2 Sustainable strategies

<u>The turbines</u>

In its design, the BWTC takes advantage of the location to maximise the energy that can be captured from the sea breeze in order to cool bildings.

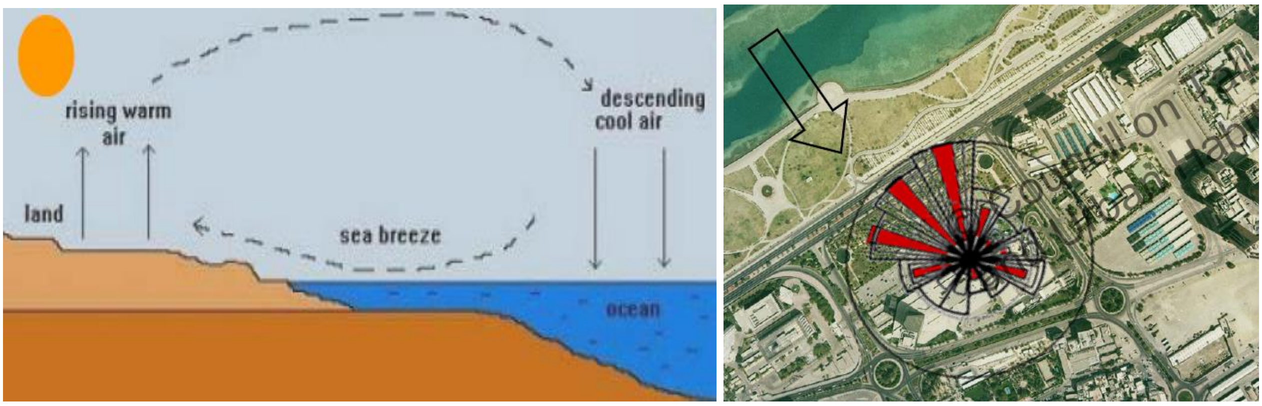


Fig. 28 Left: The progress of cooling from sea breeze. Right: Wind directions

Bahrain and Saudi Arabian land masses heat up during the early hours of the morning creating uplift and cool sea breeze and resulting in a consistent onshore sea breeze. The sea breeze effect creates a consistent North Westerly onshore breeze.

The turbines that were placed in the middle of both towers produce between ***11 and 15 percent of the total electrical consumption of the building***. This phenomenon is one of the successes of trying to resolve the world's first integration of turbines within a commercial tower structure.

Energy Yield:

Turbine 1: 400 MWh/year

Turbine 2: 430 MWh/year

Turbine 3: 470 MWh/year

Total: 1300 MWh/year

Equivalent carbon emissions 55.000 KgC p.a.

Energy generated: 15% of the electricity used by the towers.

Solar shading

- Buffer spaces were designed between the external environment and air conditioned spaces. Examples include a car park deck above and to the southern side of the mall which will have the effect of **reducing solar air temperature** and reducing conductive solar gain.

- Deep gravel roofs in some locations that provide dynamic insulation as a consequence of the gravel being heated by the sun and warm air percolating upwards against the direction of the heat flow.

- Significant proportion of projectile **shading** to external glass façades. Balconies to the sloping elevations with overhangs to provide shading where shading is not provided to glazing, a high quality solar glass is used.

- Extensive landscaping to reduce site albedo (ratio of reflected solar radiation to the incident one), generate CO2 and provide shading to on grade car parks.

Water consumption

Dual flush WC and electronic taps with excess water flow restrictors.

Connection to the district cooling system that will allow an order of magnitude improvement on carbon emissions since in Bahrain efficient water cooled chiller are not allowed due to water shortage, whereas the district cooling solution will involve sea water cooling/heat rejection and much improved levels of energy conversion efficiency.

Dual drainage systems that segregate foul and waste water and allow grey water recycling to be added at later date.

4.2 The Lakhta Center

4.2.1 General Information

The Lakhta Center is a Large Scale Project in Primorsky District – Saint Petersburg consisting of a modern business center exercising a wide range of public functions with a developed public transport infrastructure. It was implemented as a pilot project of an integrated development of the area and the construction of a mini city inside Saint Petersburg: A sustainable district for life and work (Nejad, 2014). It is aimed at increasing the level of business activity in the city and the North-western region as a whole.

The supertall skyscraper is a 462 meters office tower. The five-pointed star's floor plan rotates 0.82 degrees per storey. The floor slabs are twisted around each other at this angle, so that each level has a different floor plan area and orientation. The project was completed by 2019 and is as for today the tallest building in Europe.

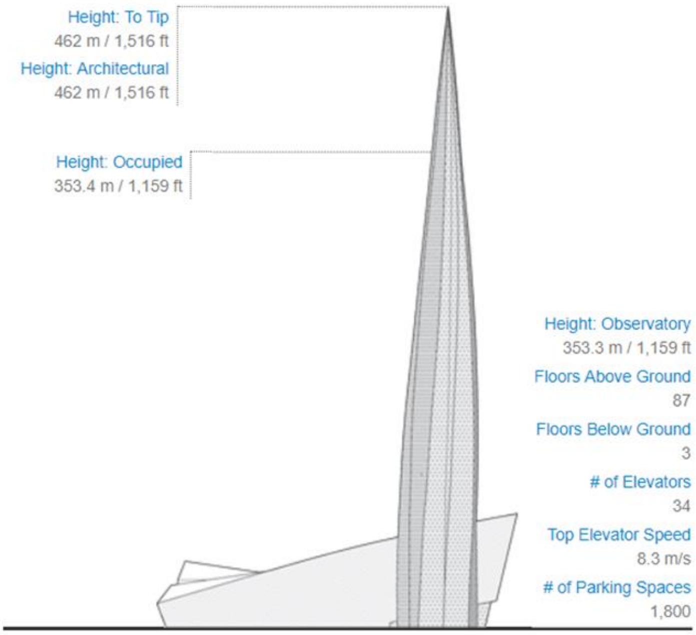


Fig. 29 Lakhta Center (Source: skyscrapercenter.com)

Building location	St. Petersburg, Russia
Building type	Office
Year of completion	2019
Project size	163.000 m2
Total building costs	1.77 billion $
Design & structural engineering	Gorprojekt
Main contractor	Renaissance Construction Company
Owner	Gazprom
Energy Label	LEED Platinium

4.2.2 Concept

Lakhta Center is built on the shore of the Gulf of Finland in St Petersburg. It embodies the aesthetics of the cold Baltic expanses of water. The Tower resembles an ice ridge, and the neighbouring multifunctional building resembles a split iceberg (Fig 31). The natural spire form of the Tower symbolizes the power of water, and its special glass facade makes the skyscraper change colour depending on the position of the sun, thus creating an impression of a living object (Lakhta center, 2017).

It is a theme of a lonely spire in the horizontal landscape which leaning base buildings symbolize the ship hull and maritime theme of wave-like bearing structures. An organic form of the building symbolizes the power of water, the flow of space, openness and lightness.

Fig. 30 The similarities between th tower of the Lakhta Center and the split of an iceberg

The tower shape represents a transition between dome and spire and it is proportioned similar to many Western European gothic and baroque cathedral towers.

According to the author of the architectural concept of the Lakhta Center, Tony Kettle (2017): “The flowing forms of water, the glinting spires of the Peter and Paul cathedral, the size of the sky canvas above the horizontal grain. My sense was very much to create something that was as light and elegant as the historical forms, capturing the changes in daylight in a similar way to that of the golden domes and spires.”

4.2.3 Project description

4.2.3.1 Location and climate

Ever since the project was first announced in 2005, the 462 meter tall tower of the Okhta Center (the first name of the project) has been the subject of fierce debate in the Russian city of St. Petersburg due to its location and height. Therefore, the project was cancelled in different occasions due to political motivations. The physical size of Gazprom's aspirations did not fit with the context of the city; its traditions and historical buildings.

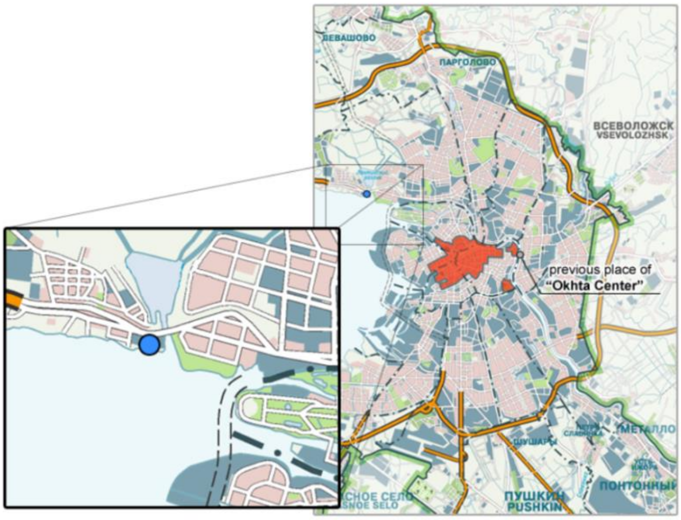


Fig. 31 Old and new location of the Lakhta Center

However, the elegant glass needle of the Lakhta Center finally emerged in the outskirts of Lakhta in Saint Petersburg, Russia. It is located at the exit of the city between the Gulf of Finland and Primorskoye highway. The construction of the highest skyscraper in Europe was not an easy task. One of the important factors to take into account during the planning, design and construction is the location and its climate conditions in order to build efficiently.

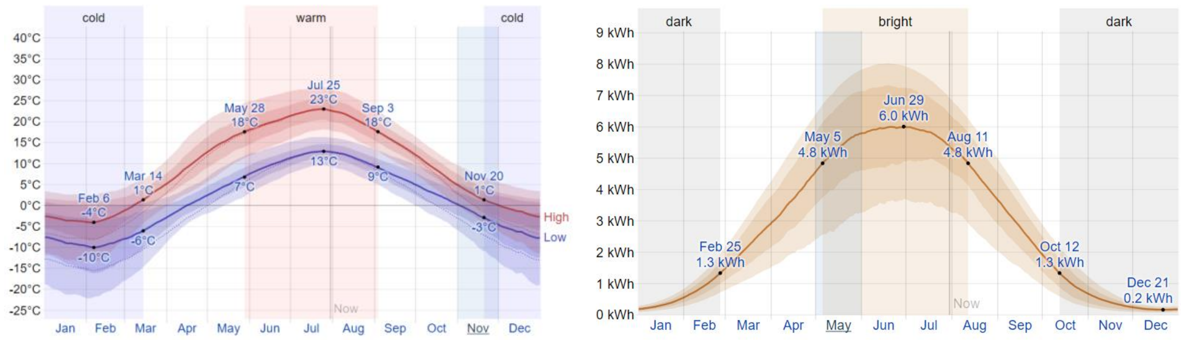


Fig. 32 Left: The daily average high and low temperatures in St Petersburg. The thin doted lines are the corresponding average perceived temperature. Right: The average daily shortwave solar energy reaching the ground per square meter (Source: Weatherspark.com)

In Saint Petersburg, summers are comfortable and partly cloudy and winters are long, freezing, dry and overcast. Temperatures typically vary from -10ºC to 23ºC (Fig. 33).

We are considering the total daily shortwave solar energy reaching the surface of the ground over a wide area, taking full account of seasonal variations in the length of the day, the elevation of the

Sun above the horizon and absorption by clouds and other atmospheric constituents. Shortwave radiation includes visible light and ultraviolet radiation. The brightest day of the year is June 29th with an average of 6.0 kWh, while the darkest day of the year is December 21st with an average of 0.2 kWh.

Saint Petersburg experiences significant seasonal variation in monthly rainfall.

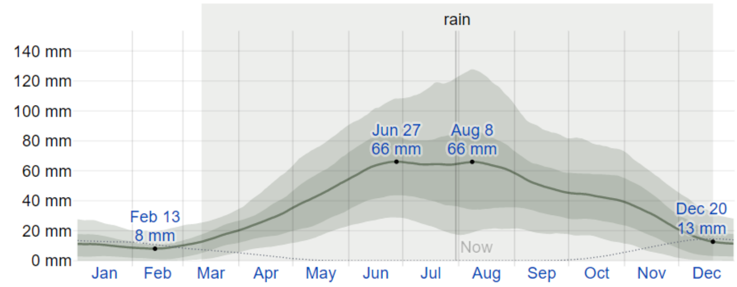


Fig. 33 Average rainfall accumulated over the course of a sliding 31 day period centred on the day in question (Source: Weatherspark.com)

4.2.3.2 Sustainable Strategies

Smart Façade

A 73.240 m² façade wraps around the 462-metre-high Lakhta tower which consists of unique structures and bent window units of 2.8m x 4.2m weighting about 740kg. The façade area is about the size of 14 football pitches. Its obelisk shape is enclosed by an innovative energy-efficient double skin façade, reflecting the sky and providing a dynamic visual movement of optical illusion caused by the three dimensional curvatures of its five twisted wings. In 2015, Josef Gartner from Gundelfingen was commissioned with the façade and spire.

The façade must follow the floor slight twisting as explained before which makes each floor a new challenge with a different area and orientation. In order to achieve this complicated geometry with smooth surface façade, cold-bent panes up to 40 mm thick were used. The Cold bent glass technology is a relatively recent development where an initially flat glass plate is bent into a curved shape at ambient temperature. This is considered to be an alternative to traditional sag bending process where the glass is heated beyond its softening temperature. It is an energy and cost efficient method that can be executed on site.

As an example, we have the area and perimeter of three storeys that illustrate the dynamic geometry of the tower:

Floor	Area (m²)	Perimeter (m)
5th	2.446	202
25th	2.684	214
73rd	1201	146

Table 5. Floor area and perimeter (Source: metallbau-magazin.de)

The lower part of the façade is angled outwards, and the skyscraper reaches its maximum width in the centre. Above this, the façade inclines inwards all the way up to the spire.

Natural ventilation

From the ground floor, the star's five points form the wings of the building with increasing height. Between the outer edges of these wings five atria are arranged, which are two storeys high. In the architectural design, these glass rooms are conceived as lounge areas; in building technology terms, they are buffer zones for temperature control: in winter as a heat buffer, in summer for natural ventilation.

In order to ventilate the atria in summer, two approx. 1.2 x 0.9 m casements per floor are integrated into the corner elements of the outer façade. On two sides of the room, four casements (about 1.2 x 0.9 m) per side can be opened. The corresponding four casements on the inner glass wall serve for ventilation.

The window casements are operated automatically via the building technology's central bus control system depending on wind speed and wind direction, because the control system is of course intelligently networked with wind sensor measurements and other weather information.

Glass panes

For the façade elements, only 2-pane insulating glass was used, consisting of white glass with sun protection coating. Special sun protection appliances were not commissioned; the glare protection was installed later on site. The large panoramic windows are mainly used for better use of daylight. The external façade's sound insulation is Rw=41 dB.

Since the inner and outer façades panes are coated differently, differences in reflection and transparency arise at the tower's five building edges. The WT1 façade type has panes with a light transmittance level (LT) of 59% and a total energy transmittance level (g) of 31%. This element type of the outer façade in the office area as well as the WT4 type of the inner façade are glazed with highly reflective panes for privacy. The interior should not be able to be seen.

The outer façade was glazed with double glazing: 1 x LSG made of 2 x 8 mm semi-tempered white glass facing outwards and a sun protection layer of Saint Gobain "Cool-Lite SKN 176 II".

Air space between the façade glazing layers provide at the same time heat insulation and natural ventilation which reduces heating and air conditioning costs.

All façades will be controlled by an automated environmental control system being part of the so called "Intelligent Building". Customized computerized automation system required of unprecedented complexity. Initial engineering, construction, commissioning and operation require highly specialized firms.

Operable openings

The greatest benefit they provide is ventilation. Operable windows can be equipped with motorized mechanical operators, which allow the opening and closing modes to be controlled. They can also be designed to activate automatically for smoke evacuation.

The natural ventilation, the high thermal insulation of the outer façade under Russian temperature conditions and the optimised use of daylight through special panes have contributed to the fact that the Lakhta tower has already received the LEED Gold pre-certificate in 2015. Compared to conventional skyscrapers, the complex will use up to 40 percent less energy thanks to energy-efficient heating, cooling and lighting.

4.3 Ping An Financial Center (PAFC)

4.3.1 General information

The Ping An Financial tower was built as a headquarter for the Ping An Insurance Group Company of China in Shenzhen. The Center represents a new generation of prototypical Asian Skyscraper: very tall, very dense and hyper-connected.

The main tower consists of 115 stories above ground and 5 stories below ground. It features 86 floors of Class-A office with the top three floors serving as an observatory and restaurant, coupled with ten-story retail podium. The office area is comprised of seven elevator zones at approximately 14 floors per zone. The tower is crowned by a domed atrium.

The design and planning of the project started in 2008 and the construction work began in 2010. The design of the building has included different sustainable strategies that will be described in this chapter.

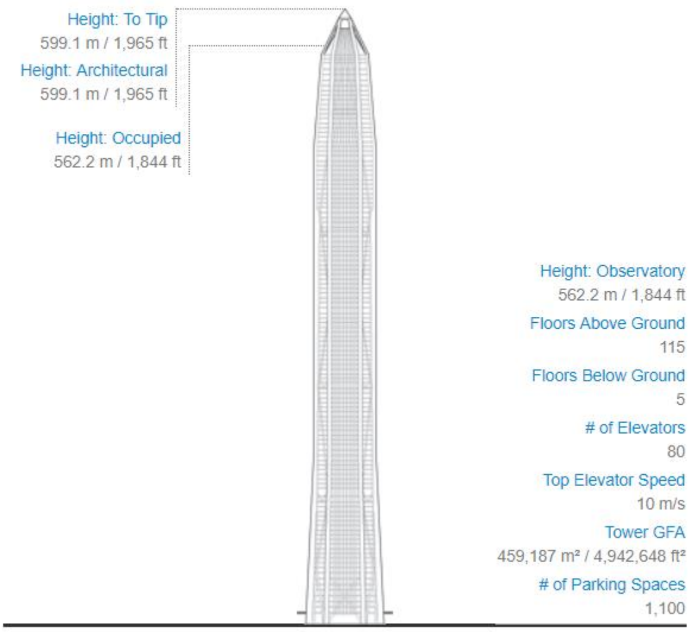


Fig. 34 PAFC (Source: Skyscrapercenter.com)

Building location	Shenzhen, China
Building type	Office
Year of completion	2017
Project size	18.932 m2
Total building costs	1.5 billion $
Design	Kohn Pedersen Fox Associates
Structural engineering	Thornton Tomasetti
Owner	Ping An Financial Center Construction & Development
Contractor	China Construction First Group Construction & Development
Sustainability	Arup
Energy Label	LEED Gold

4.3.2 Concept

Considering how important this tower's role is as a Shenzhen landmark is, different Chinese elements were introduced in the design of the project. For instance, the spire adopts the chamfered diamond folding; the observation deck adopts the accordion folding, like an opened folding fan showing grandiosity; and the podium façade integrates multiple different forms and angles that adds an artistic aesthetic feeling (Meng et al., 2016).

The PAFC exhibits similar traits than the innovative Shanghai World Financial Center (SWFC). SWFC has a compact shape as if unnecessary material were chiseled away; that silhouette contributes to its aerodynamic performance and structural efficiency. Similar to the PAFC which's compactness is one of tautness rather than compression. The concept consists of pulling the tower skyward rather than pushing it up from the ground (Malott, 2014).

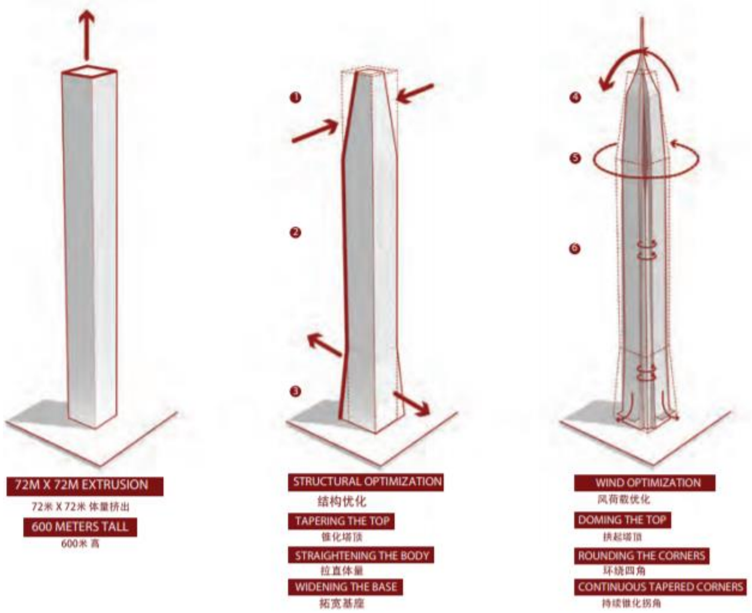


Fig. 35 The splayed base and tapered top along with tapered corners reduce wind load (Malott, 2014)

As figure 36 displays, ductile lines define a form anchored by gravity and pulled skywards to a point. Eight mega-columns firmly earthed at the tower's base converge in a spire rising to the top. The owners requested mainly a long term stable and safe tower (in Chinese, ping an literally means "peace and safety") which had conditioned the design of the tower. Wind tunnel studies demonstrated that the building's performance was greatly improved by recessing or stepping the tower corner profile; breaking up sharp corners in other words. The building profile transforms again at the upper fourth of the tower, where the main façades taper and the corners create a "rounded" octagonal-shaped floor to smooth wind flow around the corners. The reduced width of the tower at the top reduces the seismic loading (Malott et al, 2012).

In conclusion, regarding the concept of this tower; wind and seismic force components controlled the design of the building.

4.3.3 Project description

4.3.3.1 Location and Climate

Ping An Finance Center is located at the central business district of Futian in Shenzhen where is a coastal city in the south of China. Shenzhen is a city with warm, humid subtropical climate.

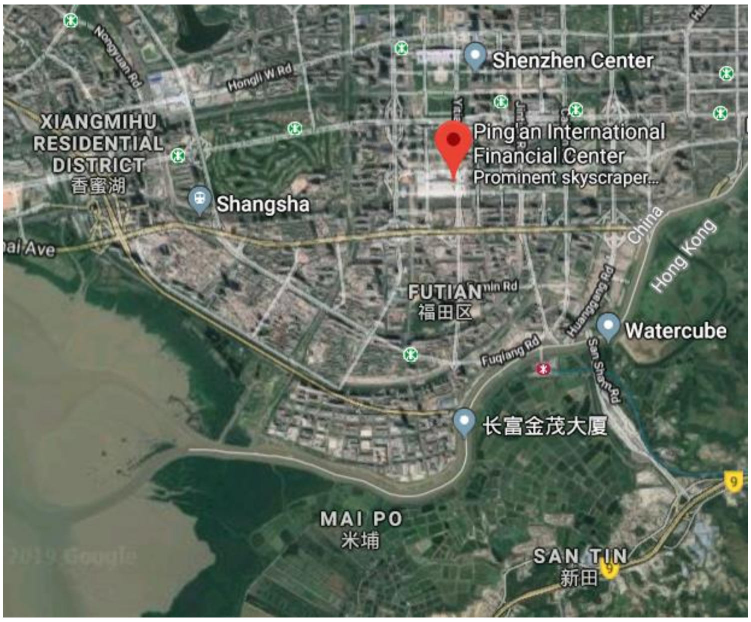


Fig. 36 The PAFC location in Shenzhen, China (Source: GoogleMap)

In Shenzen, the wet season is hot, oppressive and overcast while the dry season is comfortable, windy and mostly clear. Over the course of the year, the temperature typically varies from 13ºC to 32ºC.

The average daily incident shortwave solar energy experiences some seasonal variation over the course of the year. The brightest day of the year is April 30, with an average of 5,6 kWh. he darkest day of the year is December 17, with an average of 4.0 kWh.

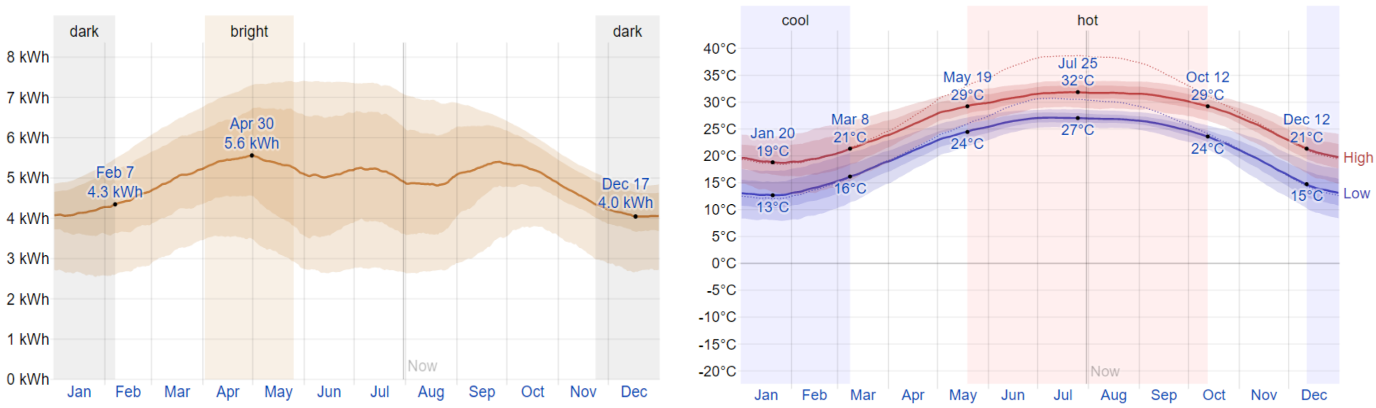


Fig. 37 Right: The daily average high and low temperatures in Shenzhen. The thin dotted lines are the corresponding average perceived temperatures. Left: The average daily shortwave solar energy reaching the ground per square meter in Shenzhen (Weatherspark.com)

Rain falls throughout the year in Shenzhen. The most rain falls during the 31 days centered around June 10, with an average total accumulation of 246 millimeters. The least rain falls around December 24, with an average total accumulation of 21 millimeters.

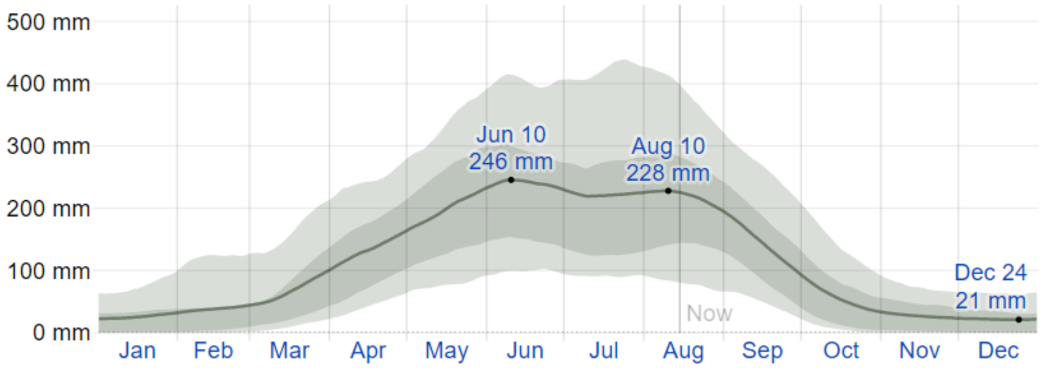


Fig. 38 Average rainfall accumulated over the course of a sliding 31 day period centred on the day in question (Source: Weatherspark.com)

4.3.3.2 Sustainable strategies

Water efficiency

The Podium roof is structurally designed to incorporate special **rainwater collectors** to reduce water consumption and operation of the green roofs (2500 m2), leading to **100% water saving for summer irrigation needs**.

The use of a recycled water cooling tower bleeds off grey water, which **reduces potable water use by 30%** but requires the structural design to provide additional openings in floors and structural walls, which needs to be coordinated closely within the design team from the beginning of the design process.

Energy efficiency

The building's façade is made up of glass, metal and stone. It is intended to be elegant and practical, using the minimal amount of material yet achieving the desired aesthetic effect.

Proper glazing selection and façade design. Glazing system with excellent thermal properties.

Results: Reduce solar heat and fabric gain, reduce air conditioning energy consumption.

Balanced solar heat gain and daylight penetration

Solar shading

Chevron-shaped stone verticals obtain functional external shading effect.

5. RESULTS & DISCUSSION

The evaluations we carried out in this dissertation had a lot of limitations due to lack of data. However we analyzed the BWTC in Bahrein, the Lakhta Center in Russia and the Ping An Center in China accordingly to their climates. As can be noticed, these three very well know skyscrapers are located in three different climate zones, which is the main factor that makes their design process in order to achieve the highest efficiency possible different.

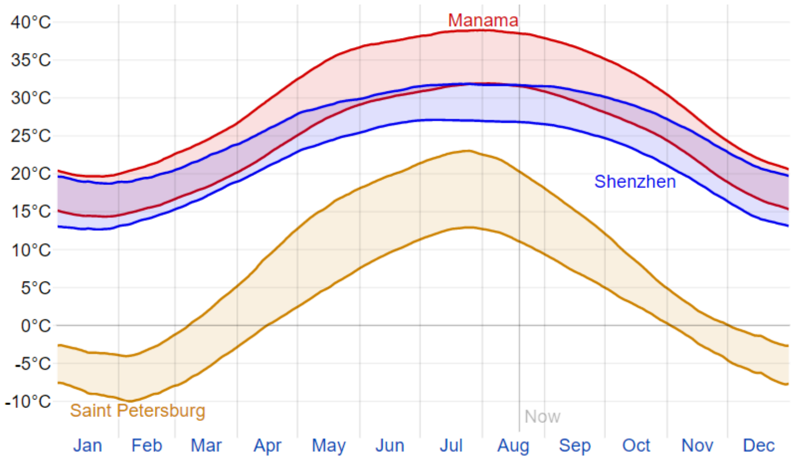


Fig. 39 Daily average high and low temperatures in Manama, Shenzhen and St Petersburg (Source: Weatherspark.com)

According to the 2030 palette guidelines; a resource for the design of zero net carbon, adaptable and resilient built environments worldwide, we analyzed the results of the charts and these are the strategies to adapt in each skyscraper in order to be sustainable:

- **Hot dry climate (BWTC: Manama, Bahrein)**

Window glazing and orientation

Provide enough north glazing to balance daylighting and minimize or eliminate if possible west facing glazing in order to reduce summer and fall afternoon heat gain. Using high performance glazing on all orientations should prove cost effective like Low E or low emissivity Glass that transmits visible light and blocks most solar heat and damaging UV light from getting in.

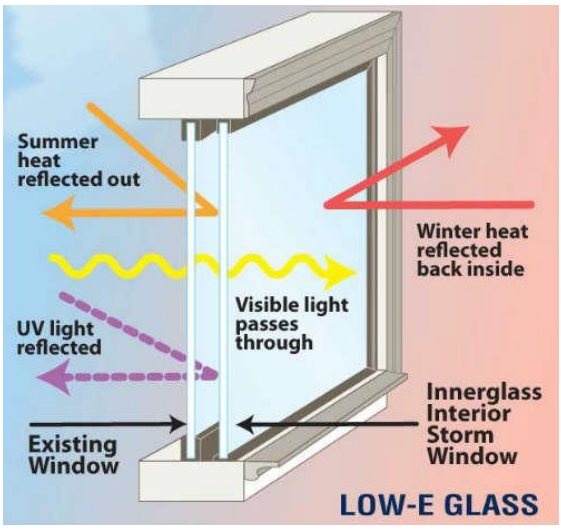


Fig. 40 The functioning of Low-E glazing (Source: Google images)

Ventilation

A good natural ventilation is important in warm weathers and it can reduce or eliminate air conditioning if windows are well shaded and oriented to prevailing breezes. To promote natural cross ventilation we can use louvered doors or jump ducts.

To produce stack ventilation, even when wind speeds are low, maximize vertical height between air inlet and outlet (open stairwells, two story spaces, roof monitors).

Passive Cooling strategies

- ✓ Window overhangs (designed for this latitude) or operable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning
- ✓ The use of ***ceiling fans*** or ***indoor air motion*** can lower temperature up to 2.8ºC or more.
- ✓ ***Light colored building materials*** and ***cool roofing*** with high emissivity to minimize conducted heat gains is recommended.
- ✓ In hot dry climates an ***Evaporative Cooler*** can provide enough cooling capacity (if water is available and humidity is low) thus reducing or even eliminating air conditioning.
- ✓ ***Earth sheltering***, ***occupied basements*** or ***earth tubes*** reduce heat loads in very hot dry climates because the earth stays near average annual temperature.
- ✓ Climate responsive buildings in hot dry climates used high mass construction with small recessed shaded openings, operable for night ventilation to cool the mass and enclosed well shaded courtyards, with a small fountain to provide wind-protected microclimates
- ✓ A radiant barrier (shiny foil) will help reduce radiated heat gain through the roof in hot climates.
- ✓ Humidify hot dry air before it enters the building from enclosed outdoor spaces with spray-like fountains, misters, wet pavement, or cooling towers.
- ✓ Raise the indoor comfort thermostat set point to reduce air conditioning energy consumption (especially if occupants wear seasonally appropriate clothing)

Passive heating strategies

- ✓ Heat gains from lights, occupants and equipment greatly reduces heating needs so keep building tight, well insulated (to lower Balance Point temperature)

This is one of the more comfortable climates , so shade to prevent overheating, open to breezes in summer and use passive solar gain in winter

- **Cold rainy climate (Lakhta Center: Saint Petersburg, Russia)**

Window glazing and orientation

Provide double pane high performance glazing (Low-E) on west, north and east but clear on south for maximum passive solar gain.

For passive solar heating face most of the glass area south to maximize winter sun exposure and design overhangs to fully shade in summer

Small well-insulated skylights (less than 3% of the floor area in clear climates, 5% in overcast) reduce daytime lighting energy and cooling loads

Windows can be unshaded and face in any direction because any passive solar gain is a benefit and there is little danger of overheating

Heating passive strategies

- ✓ Extra insulation (super insulation) might prove cost effective, and will increase occupant comfort by keeping indoor temperature more uniform
- ✓ Sunny wind-protected outdoor spaces can extend occupied areas in cool weather (enclosed patios, courtyards or verandas)
- ✓ Heat gains from lights, occupants and equipment greatly reduce heating needs so keep building tight, well insulated (to lower Balance Point temperature)
- ✓ Use compact building form with square-ish floorplan to minimize heat loss from building envelope (minimize surface to volume ratio)
- ✓ Insulating blinds, heavy draperies, or operable window shutter will help reduce winter night time heat losses if automatically controlled
- ✓ Pitched roof, vented to the exterior with a well-insulated ceiling below, works well in cold climates (sheds rain and snow and helps prevent ice dams)
- ✓ Locate storage areas or garages on the side of the building facing the coldest wind to help insulate
- ✓ High efficiency heaters or boilers (at least energy star) should prove cost effective in this climate
- ✓ Trees (neither conifer or deciduous) should not be planted in front of passive solar windows, but are OK beyond 45 degrees from each corner
- ✓ Organize floorplan so winter sun penetrates into daytime use spaces with specific functions that coincide with solar orientation

Ventilation

- ✓ Tiles or slate (even on wood floors) provide enough surface mass to store winter daytime solar gain and summer nighttime `coolth`

Climate responsive buildings in cool overcast climate used low mass tightly sealed, well insulated construction to provide rapid heat buildup in morning

Climate responsive buildings in cold clear climates had snug floorplan with central heat source, south facing windows and roof pitched for wind protection

- **Humid subtropical climate (Ping An Center: Shenzhen, China)**

Window glazing and orientation

Also in this climate, we will need high performance glazing on all orientations because they are cost effective (Low-E, insulated frames) in hot clear summers or dark overcast winters.

Minimize or eliminate west facing glazing to reduce summer and fall afternoon heat gain.

Window overhangs (designed for this latitude) or operable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning.

Climate responsive buildings in warm humid climates used high ceilings and tall operable (French) windows protected by deep overhangs and verandas.

Orient most of the glass to the north, shaded by vertical fins, in very hot climates because there are essentially no passive solar needs.

Ventilation

In wet climates well ventilated pitched roofs work well to shed rain and can be extended to protect entries, outdoor porches and outdoor work areas.

If soil is moist, raise the building high above ground to minimize dampness and maximize natural ventilation underneath the building

Long narrow building floorplan can help maximize cross ventilation in temperate and hot humid climate

Good natural ventilation can reduce or eliminate air conditioning in warm weather, if windows are well shaded and oriented to prevailing breezes

Screened occupancy areas and patios can provide passive comfort cooling by ventilation in warm weather and can prevent insect problems

Passive Cooling strategies

- ✓ Use plant materials (bushes, trees, ivy covered walls) specially on the west to minimize heat gain (if summer rains support native plant growth)
- ✓ A radiant barrier (shiny foil) will help reduce radiated heat gain through the roof in hot climates.
- ✓ Raise the indoor comfort thermostat setpoint to reduce air conditioning energy consumption (especially if occupants wear seasonally appropriate clothing)
- ✓ On hot days ceiling fans or indoor air motion can make it seem cooler by 2.8ºC or more, thus less air conditioning is needed
- ✓ Use light colored building material and cool roofs (with high emissivity) to minimize conducted heat gains
- ✓ High efficiency air conditioner or heat pump (at least Energy Star) should prove cost effective in this climate
- ✓ In this climate air conditioning will always be needed, but can be greatly reduced if building design minimizes overheating

Passive Heating strategies

- ✓ Heat gains from lights, occupants and equipment greatly reduces heating needs so keep building tight, well insulated (to lower Balance Point temperature)

Climate responsive buildings in hot humid climates used light weight construction with openable walls and shaded outdoor areas, raised above ground

- **Solar radiance**

Earth is bathed in huge amounts of energy from the Sun. Humans have always used some of the Sun's energy directly—for drying clothes and foodstuffs, for example. They've also utilized it indirectly—through photosynthesis to power the plant growth underpinning the agriculture that supplies us with food and the oxygen we breathe. And yet there is another way to use this abundant energy source: photovoltaic panels. These Photovoltaic solar panels absorb sunlight as a source of energy to generate direct current electricity.

According to the results of solar irradiance that we can see on the table below from the online tool PV-GIS (https://ec.europa.eu/jrc/en/pvgis), the BWTC can benefit from the highest electricity production due to the type of hot dry climate of its location; which is why using PV integrated panels in the building is a must to get clean energy.

	Electricity production [kWh]		
	Bahrein	**Russia**	**China**
January	130	12,6	88,5
February	130	30,7	71,8
March	148	68,9	88,3
April	141	95,4	88,1
May	151	116	94,9
June	148	115	93,5
July	150	121	115
August	153	98,3	110
September	153	65,5	105
October	152	35,8	107
November	127	11,6	92,9
December	130	6,97	95,2
TOTAL	1713	777,77	1150,2

Table 6. Electricity production of each location

This solar energy should be taken advantage of in order to generate electricity that can be used for heating or cooling specially in the BWTC and the Ping an Center.

All of the strategies mentioned above should be applied to the building design in order to get the most out of the climate we have and to make it as sustainable as possible.

6. CONCLUSIONS & FUTURE WORK

As earth population is growing in an exponential way and urban sprawl is increasing, cities are adapting a new way of construction: Skyscrapers. These vertical mega tall constructions save space and accommodate more workers compared to other office buildings. They have become nowadays essential and inevitable in urban cities. Nevertheless, this type of buildings are distinguished with their high energy consumption compared to other typologies since they rely mainly on mechanical heating and cooling. For this reason, it is important to achieve high energy efficiency and for that different areas of improvements were addressed in this dissertation including: Glazing, orientation and other passive strategies in different climate zones.

The first step to produce as much energy as a building consumes is lowering the amount of energy it takes to keep the building comfortable. Maintaining the right interior temperature, humidity and air quality often account for 30% or more of building energy use. But we can do that passively without demanding purchased energy. Designing passively means working with external weather conditions instead of fighting against it and that is the aim of this dissertation. The results have shown how the external weather and conditions sets the adequate passive strategies to follow.

For instance, comparing the results of the three different climates regarding glazing and orientation; the BWTC and Ping An Center seem to have similar characteristics. It is recommended for both dry and humid hot climates to face the glazing north and avoid west orientation in order to reduce summer and fall afternoon heat gains. As figure 40 have shown, temperatures in both Shenzhen and Manama are high during the whole year. On the other hand, in St Petersburg we need to face the glazing to the south due to the very low temperatures in order to gain some solar heat. Low-E glass which are high performance low emissivity panes are very much required in the three different cases to minimize the amount of ultraviolet and infrared light that can pass through glass without compromising the amount of visible light that is transmitted. It is also possible to use smart of switchable glass.

The most appropriate way to cool a space without any mechanical support is through the technique of passive ventilation. It is important to provide it as much as possible in all different climates but specially the dry hot and the wet hot ones. For both, windows should be well shaded and oriented in order to catch the breeze and reduce maybe even eliminate the use of air conditioning.

We have to shade the building but not forget to use the solar energy we get during the day to cool or heat the spaces. In hot climates, for Manama as well as for Shenzhen, 1710 and 1150,2 Kwh are generated per year. In cold climates like in St Petersburg, PV panels will generate less energy in the winter than in the summer due to the shorter days and less sunlight, but we still have to use that amount of solar energy we get.

Different passive cooling and heating strategies were mentioned in chapter 5 and should be followed in order to achieve the sustainable skyscraper we are aiming for. Each skyscraper should be studied according to its location and the climate zone it belongs to. A deep look and investigation into the climate conditions will help us know which strategies are best and which are not.

Regarding the passive strategies, we have the representation of the results on Fig 39. All three skyscrapers are using internal heat gain to heat the indoors and lower the heating consumption. We found a big difference of the % of natural ventilation comfort hours, since it doesn't add up much for the Ping An or the Lakhta Center but it helps in cooling the interior space in the BWTC. Sun shading will rise the comfort hours in Manama and Shenzhen since these two cities are exposed to more hours of solar radiation.

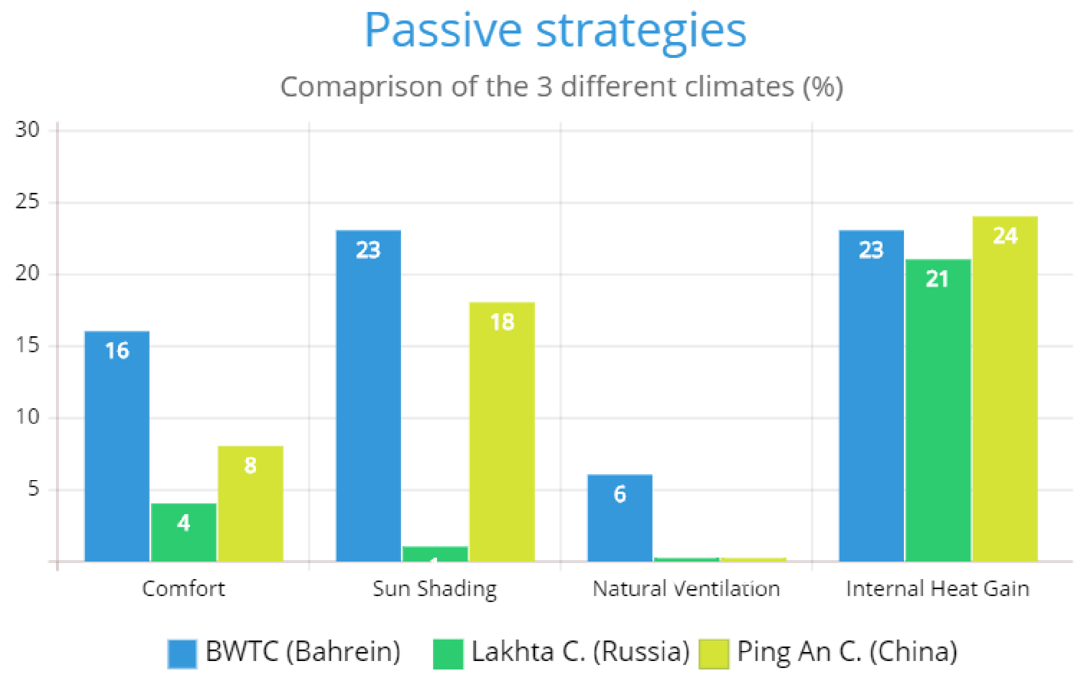


Fig. 41 Passive strategies comparison in %

In addition to these mentioned strategies, The BWTC is taking advantage of direct evaporative cooling as of 38% of the total comfort hours and only 3% of dehumidification differently than the Ping An in Shenzhen who needs 24% dehumidification due the high humidity level of the region.

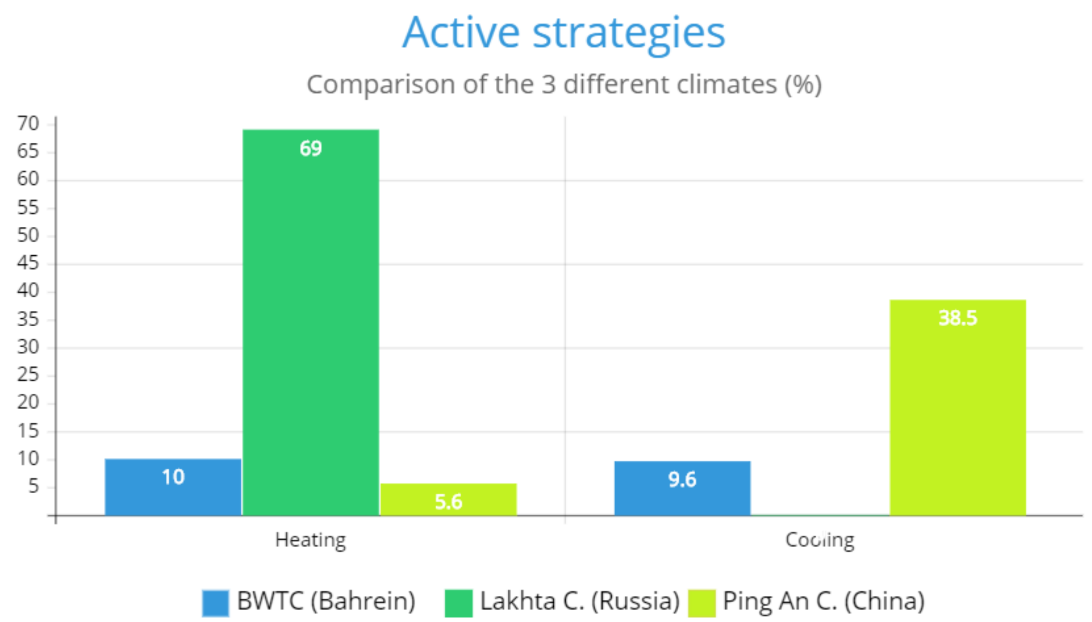


Fig. 42 Active strategies comparison in %

Regarding mechanical heating and cooling that will be needed we have to highlight the following results:

- The Lakhta Center doesn't require any cooling which will represent a high save of energy and money to the skyscraper. However 69% of the comfort hours can't be achieved unless we use a heating system. New passive strategies should be investigated to lower this high need.
- The Ping An Center will be needing almost 40% of cooling but only 5.6% of heating, while the BWTC needs 10% more or less cooling and heating which doesn't account for a lot of hours.

To sum up, energy preservation issue is feasible even in severe climatic conditions; either too hot, too cold, or too rainy. This question should be handled in an integrated way starting from the skyscraper location on the site, its orientation to the cardinal points, building configuration, possibilities of renewable energy sources usage and potential variations of energy consumption reduction methods.

In a near future, designers of the next generation of mega tall buildings will aim for "zero energy" design in an increasing way due to climate change and resource consumption. In this dissertation, climate was used to advantage and differ between the diverse case studies so the building becomes a source of power. It is very probable that high rise buildings will very soon even produce excess energy and transfer that excess to the city's power grid for other uses. This opens a new research window into the world of Zero energy plus skyscrapers that will be able in a future to generate energy for the smart cities we live in.

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ANNEXES

- Annex I: Weather data
- Annex II: Climate consultant
- Annex III : Solar irradiance

ANNEX I
Weather data

➢ **BWTC: Manama, Bahrein.**

Due to lack of data for this country, we chose a close one with similar climate conditions.
Location: {N 29– 13'} {E 47– 58'} {GMT +3.0 Hours}
Elevation: 55 m above sea level
Standard pressure at Elevation: 100.666 Pa
Climate type: Subtropical hot desert (Unbearably hot dry periods in summer, but passive cooling is possible)

Average Hourly Statistics for Dry Bulb temperatures –C												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	11.7	12.0	15.4	21.6	27.4	31.8	34.2	33.6	29.9	25.1	17.5	13.3
1:01- 2:00	11.5	11.4	15.1	21.2	27.0	30.7	33.1	32.8	29.3	24.6	17.0	13.0
2:01- 3:00	11.2	10.7	14.8	20.5	26.4	29.9	32.2	31.8	28.4	24.2	16.3	12.6
3:01- 4:00	10.9	9.8	14.4	20.1	25.7	29.1	31.4	30.9	28.2	23.6	15.8	12.4
4:01- 5:00	10.6	9.2	14.0	19.6	25.0	28.4	30.7	30.0	27.5	23.1	15.6	12.1
5:01- 6:00	10.2	8.7	13.7	19.3	25.4	28.8	30.5	29.2	26.5	22.6	15.2	11.9
6:01- 7:00	9.9	8.3	14.1	18.9	28.6	32.4	33.3	32.2	25.9	23.3	14.8	11.6
7:01- 8:00	10.8	11.3	17.1	21.1	31.4	35.7	36.2	35.5	28.0	26.2	15.2	11.4
8:01- 9:00	12.6	14.4	19.7	23.5	33.6	38.1	38.6	38.4	31.4	28.9	18.2	12.5
9:01-10:00	14.5	17.1	21.8	25.3	35.4	40.3	40.7	40.9	34.2	31.3	20.8	14.0
10:01-11:00	16.3	19.1	23.3	27.2	36.9	41.7	42.2	42.8	36.9	32.9	23.1	15.6
11:01-12:00	17.5	20.5	24.2	28.2	37.7	42.7	43.3	44.2	39.0	33.9	24.5	16.7
12:01-13:00	18.5	21.3	24.9	29.1	37.9	43.3	44.1	45.2	40.5	34.6	25.7	17.5
13:01-14:00	19.1	21.9	25.2	29.5	38.0	43.8	44.6	45.9	41.4	34.7	26.4	18.3
14:01-15:00	19.2	22.0	24.8	29.9	37.9	43.7	44.7	46.0	41.9	34.5	26.6	18.8
15:01-16:00	18.7	21.6	24.3	30.1	37.1	43.3	44.6	45.8	41.8	33.9	26.4	18.7
16:01-17:00	17.6	20.8	23.5	30.0	36.4	42.5	44.2	44.9	41.2	32.8	25.8	18.2
17:01-18:00	16.2	19.2	21.8	29.1	35.1	41.3	43.0	43.4	40.1	31.3	24.5	17.3
18:01-19:00	15.3	17.8	20.4	27.9	33.5	39.5	41.3	41.2	38.2	30.0	23.1	16.5
19:01-20:00	14.3	16.6	19.3	26.5	32.4	37.9	39.6	39.5	36.2	28.8	21.9	15.9
20:01-21:00	13.5	15.7	18.4	25.3	31.5	36.8	38.3	38.3	34.5	27.8	20.6	15.2
21:01-22:00	12.9	14.6	17.8	24.3	30.2	35.6	37.3	37.1	33.1	26.9	19.7	14.8
22:01-23:00	12.5	13.7	17.0	23.5	29.1	34.1	36.2	35.9	31.9	26.3	18.8	14.1
23:01-24:00	12.1	12.7	16.2	22.6	28.5	33.0	35.4	34.8	30.6	25.5	18.4	13.6
Max Hour	15	15	14	16	14	14	15	15	15	14	15	15
Min Hour	7	7	6	7	5	5	6	6	7	6	7	8

Monthly Statistics for Solar Radiation (Direct Normal, Diffuse, Global Horizontal) Wh/m²												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Direct Avg	4261	4258	4091	4080	4680	4289	6130	6904	6244	5695	4805	2859
Direct Max	8072	8641	8292	9391	7818	6981	8931	8110	8300	7977	6905	6057
Day	16	26	22	8	6	1	9	7	11	20	12	5
Diffuse Avg	1818	1573	2013	2319	3021	3292	2195	1672	1390	1106	1200	1454
Global Avg	3961	4259	5047	5960	7097	7416	7259	7063	6213	4971	4093	2951

Average Hourly Relative Humidity %												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	82	52	66	55	39	25	18	21	29	57	61	83
1:01- 2:00	81	53	67	56	41	27	19	22	31	56	62	85
2:01- 3:00	81	57	69	58	42	27	20	23	31	57	63	86
3:01- 4:00	81	57	70	58	43	29	21	25	31	57	64	86
4:01- 5:00	83	57	71	60	44	30	21	25	31	57	65	87
5:01- 6:00	84	56	73	61	43	29	21	26	32	58	66	88
6:01- 7:00	84	57	74	63	35	22	17	20	32	57	66	89
7:01- 8:00	81	49	62	56	28	18	13	17	28	48	66	88
8:01- 9:00	73	43	51	46	23	15	12	14	21	40	59	85
9:01-10:00	63	36	42	41	19	11	10	10	18	35	51	77
10:01-11:00	57	32	36	35	17	10	9	8	14	31	44	70
11:01-12:00	50	28	33	32	16	9	8	7	12	28	40	64
12:01-13:00	46	24	30	29	17	8	8	7	10	27	36	59
13:01-14:00	43	21	29	29	17	8	8	6	9	27	34	53
14:01-15:00	43	21	30	27	17	8	7	6	9	28	34	52
15:01-16:00	46	23	32	27	19	10	8	6	9	30	35	52
16:01-17:00	49	25	34	25	19	10	8	7	10	33	37	54
17:01-18:00	57	30	40	27	21	12	9	9	11	40	41	59
18:01-19:00	63	36	46	29	25	14	11	12	14	46	45	65
19:01-20:00	68	40	50	34	26	17	13	13	18	49	49	69
20:01-21:00	72	43	54	39	28	18	14	14	21	53	53	74
21:01-22:00	75	46	57	43	33	19	15	15	22	56	55	77
22:01-23:00	78	49	60	47	35	21	16	17	24	58	58	80
23:01-24:00	80	51	63	52	35	22	17	19	27	59	59	82
Max Hour	7	7	7	7	5	5	5	6	7	24	7	7
Min Hour	15	15	14	17	12	14	15	15	16	13	14	16

WEATHER DATA SUMMARY

LOCATION: **Kuwait Intl Airport, -, KWT**
Latitude/Longitude: 29.22° North, 47.98° East, **Time Zone from Greenwich** 3
Data Source: KISR 405820 WMO Station Number, **Elevation** 55 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	382	389	425	468	525	535	531	542	510	441	388	290	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	413	388	344	320	346	309	448	530	513	505	456	280	Wh/sq.m
Diffuse Radiation (Avg Hourly)	174	143	169	182	224	237	160	128	114	98	113	143	Wh/sq.m
Global Horiz Radiation (Max Hourly)	707	815	962	1015	1040	1028	993	1001	970	867	762	636	Wh/sq.m
Direct Normal Radiation (Max Hourly)	1910	984	936	959	866	814	1321	843	886	928	932	793	Wh/sq.m
Diffuse Radiation (Max Hourly)	672	445	852	842	851	727	650	511	692	534	614	553	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	3961	4259	5046	5959	7097	7415	7258	7063	6213	4970	4093	2951	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	4261	4257	4091	4080	4680	4288	6129	6903	6244	5695	4805	2859	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	1817	1573	2013	2319	3020	3291	2195	1671	1390	1106	1200	1453	Wh/sq.m
Global Horiz Illumination (Avg Hourly)													lux
Direct Normal Illumination (Avg Hourly)													lux
Dry Bulb Temperature (Avg Monthly)	14	15	19	24	32	36	38	38	34	28	20	14	degrees C
Dew Point Temperature (Avg Monthly)	8	2	8	10	11	9	8	8	9	15	10	10	degrees C
Relative Humidity (Avg Monthly)	67	41	51	42	28	17	13	14	20	45	51	73	percent
Wind Direction (Monthly Mode)	320	320	310	330	320	320	310	320	330	330	320	320	degrees
Wind Speed (Avg Monthly)	3	4	3	4	4	5	5	5	3	3	3	3	m/s
Ground Temperature (Avg Monthly of 3 Depths)	22	19	18	18	21	25	29	32	34	33	30	26	degrees C

- **Lakhta Center: Saint Petersburg, Russia.**

Location: {N 59– 58'} {E 30– 17'} {GMT +3.0 Hours}
Elevation: 4 m above sea level
Standard pressure at Elevation: 101.277 Pa
Climate type: Moist continental (Warm summer, cold winter, no dry season)

Average Hourly Statistics for Dry Bulb temperatures −C												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	-6.1	-6.2	-1.4	1.8	7.2	13.0	15.6	15.3	8.8	5.6	-0.5	-4.3
1:01- 2:00	-6.2	-6.2	-1.5	1.4	6.9	12.6	15.2	15.0	8.7	5.4	-0.5	-4.3
2:01- 3:00	-6.2	-6.1	-1.6	2.4	7.7	12.2	14.8	14.8	9.4	5.1	-0.6	-4.2
3:01- 4:00	-6.2	-6.1	-1.8	1.3	6.1	12.3	14.6	14.6	8.3	5.0	-0.6	-4.5
4:01- 5:00	-6.4	-6.2	-2.0	1.2	5.8	12.3	14.4	14.3	8.1	4.9	-0.7	-4.3
5:01- 6:00	-6.2	-6.2	-2.3	2.0	7.6	12.3	14.2	14.0	9.1	4.8	-0.8	-4.0
6:01- 7:00	-6.2	-6.3	-2.2	1.1	8.6	12.9	15.2	14.6	7.8	4.9	-0.9	-3.9
7:01- 8:00	-6.1	-6.3	-2.1	2.1	10.1	13.5	16.2	15.1	8.8	5.0	-0.9	-3.8
8:01- 9:00	-5.9	-6.4	-2.1	3.7	10.9	14.1	17.2	15.6	10.1	5.1	-1.0	-3.8
9:01-10:00	-5.9	-6.0	-1.6	4.8	12.9	14.8	18.0	16.4	11.2	5.5	-0.8	-4.1
10:01-11:00	-5.7	-5.7	-1.2	5.9	13.8	15.5	18.7	17.2	12.1	5.9	-0.6	-4.1
11:01-12:00	-5.5	-5.3	-0.7	6.4	13.2	16.2	19.5	18.0	12.5	6.3	-0.4	-3.7
12:01-13:00	-5.2	-5.0	-0.3	7.1	14.8	16.4	19.7	18.2	13.4	6.5	-0.3	-3.9
13:01-14:00	-4.9	-4.6	0.1	7.7	15.0	16.6	19.9	18.3	13.4	6.7	-0.1	-3.9
14:01-15:00	-4.7	-4.2	0.6	7.6	14.2	16.8	20.2	18.5	13.4	7.0	0.1	-3.5
15:01-16:00	-4.9	-4.5	0.6	7.8	15.4	16.8	20.3	18.5	14.0	6.8	0.0	-3.8
16:01-17:00	-5.0	-4.7	0.7	7.6	14.9	16.7	20.5	18.4	13.5	6.7	-0.1	-4.0
17:01-18:00	-5.1	-5.0	0.7	6.9	13.7	16.7	20.6	18.3	13.1	6.5	-0.2	-3.8
18:01-19:00	-5.2	-5.3	0.4	6.2	13.8	16.2	20.0	17.7	11.8	6.4	-0.3	-4.0
19:01-20:00	-5.3	-5.5	0.0	4.9	12.8	15.7	19.4	17.2	10.9	6.2	-0.4	-4.1
20:01-21:00	-5.3	-5.8	-0.3	5.2	11.7	15.2	18.8	16.6	11.1	6.1	-0.5	-3.9
21:01-22:00	-5.6	-6.0	-0.5	3.3	9.9	14.6	17.9	16.2	9.9	5.9	-0.6	-4.2
22:01-23:00	-5.7	-6.3	-0.7	2.8	8.8	14.0	17.0	15.9	9.4	5.8	-0.7	-4.3
23:01-24:00	-5.8	-6.5	-1.0	3.7	9.5	13.4	16.1	15.3	10.2	5.6	-0.9	-3.9
Max Hour	15	15	18	16	16	15	18	15	16	15	15	15
Min Hour	5	24	6	7	5	3	6	6	7	6	9	4

Monthly Statistics for Solar Radiation (Direct Normal, Diffuse, Global Horizontal) Wh/m⁄												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Direct Avg	337	1388	1873	2788	3693	3262	3851	3004	1392	816	355	253
Direct Max	2847	5313	6440	7321	6449	6594	7083	5994	4044	2974	1912	1463
Day	29	28	24	25	29	30	13	8	1	3	9	1
Diffuse Avg	176	536	1088	1760	2515	3254	2851	2223	1462	693	267	122
Global Avg	224	880	1808	3246	4865	5398	5331	3946	2140	962	325	148

Average Hourly Relative Humidity %												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	85	85	71	86	80	80	81	84	86	86	85	91
1:01- 2:00	86	86	71	87	83	82	84	84	87	86	85	91
2:01- 3:00	88	86	73	83	80	83	86	85	87	87	85	91
3:01- 4:00	85	86	73	89	85	83	86	86	89	87	86	90
4:01- 5:00	84	86	74	89	86	82	86	87	89	87	86	90
5:01- 6:00	88	86	75	85	81	82	86	87	89	88	86	91
6:01- 7:00	85	86	75	91	81	78	81	84	89	88	86	90
7:01- 8:00	84	87	75	89	76	75	77	81	88	88	86	90
8:01- 9:00	86	87	75	79	69	72	74	78	84	88	86	90
9:01-10:00	83	86	73	79	63	68	70	74	80	85	86	88
10:01-11:00	84	85	71	73	59	65	66	70	73	82	85	88
11:01-12:00	86	83	70	67	59	62	63	67	69	80	84	89
12:01-13:00	82	81	68	65	55	61	61	66	64	79	82	88
13:01-14:00	81	80	66	62	54	61	60	65	65	78	81	87
14:01-15:00	83	78	66	62	54	60	59	65	65	77	80	89
15:01-16:00	80	79	65	61	53	59	58	65	63	78	80	88
16:01-17:00	81	79	64	62	53	59	58	66	64	79	81	88
17:01-18:00	84	80	65	63	55	59	57	66	67	80	82	90
18:01-19:00	84	80	65	68	56	62	60	69	72	81	83	91
19:01-20:00	84	81	66	73	58	64	62	72	76	82	84	92
20:01-21:00	85	81	68	73	62	67	65	75	80	84	85	92
21:01-22:00	82	82	68	81	68	71	69	77	83	84	85	92
22:01-23:00	82	83	69	84	75	74	74	79	85	85	85	92
23:01-24:00	86	84	71	79	73	78	79	83	84	86	85	92
Max Hour	3	8	9	7	5	3	3	6	7	6	6	22
Min Hour	16	15	17	16	16	18	18	15	16	15	15	14

Weather data summary:

WEATHER DATA SUMMARY

LOCATION: **SAINT-PETERSBURG, -, RUS**
Latitude/Longitude: 59.97° North, 30.3° East, **Time Zone from Greenwich** 3
Data Source: IWEC Data 260630 WMO Station Number, **Elevation** 4 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	34	100	154	224	285	294	303	258	168	97	45	26	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	51	156	158	191	214	177	218	197	108	81	51	44	Wh/sq.m
Diffuse Radiation (Avg Hourly)	26	61	93	122	148	177	162	145	115	70	36	21	Wh/sq.m
Global Horiz Radiation (Max Hourly)	171	343	499	668	741	758	745	670	542	369	172	102	Wh/sq.m
Direct Normal Radiation (Max Hourly)	615	796	819	833	718	720	757	700	613	512	461	409	Wh/sq.m
Diffuse Radiation (Max Hourly)	85	165	273	390	402	431	420	419	311	196	108	57	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	223	879	1807	3245	4865	5397	5331	3945	2139	961	324	148	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	337	1387	1872	2787	3692	3261	3851	3003	1391	815	355	252	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	175	535	1087	1759	2515	3253	2851	2222	1462	692	266	122	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	3750	10708	16754	24464	31129	32358	33309	28414	18553	10698	4980	2873	lux
Direct Normal Illumination (Avg Hourly)	3208	12402	14389	18476	20940	17060	20723	18465	10097	6953	3395	2308	lux
Dry Bulb Temperature (Avg Monthly)	-5	-5	0	4	11	14	17	16	10	5	0	-4	degrees C
Dew Point Temperature (Avg Monthly)	-7	-7	-5	0	4	8	11	11	6	3	-2	-5	degrees C
Relative Humidity (Avg Monthly)	84	83	69	76	67	70	70	75	78	83	84	89	percent
Wind Direction (Monthly Mode)	270	240	150	150	270	270	0	0	210	270	290	270	degrees
Wind Speed (Avg Monthly)	3	2	2	3	2	2	1	2	3	2	2	2	m/s
Ground Temperature (Avg Monthly of 3 Depths)	2	0	-2	-2	0	3	7	11	12	12	9	5	degrees C

- **Ping An Center: Shenzhen, China.**

Location: {N 22− 32'} {E 114− 5'} {GMT +8.0 Hours}
Elevation: 18 m above sea level
Standard pressure at Elevation: 101.109 Pa
Climate type: Humid subtropical (mild with no dry season, hot summer)

Average Hourly Statistics for Dry Bulb temperatures −C												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	13.5	14.1	18.6	20.5	25.3	26.6	26.8	26.3	26.6	22.8	20.1	16.8
1:01- 2:00	13.1	13.9	18.2	20.2	25.3	26.4	26.5	26.1	26.5	22.5	19.8	16.6
2:01- 3:00	12.9	13.5	18.3	20.0	24.9	26.2	26.3	26.0	26.3	22.3	19.5	16.2
3:01- 4:00	12.8	13.3	18.3	19.8	24.7	26.0	26.1	25.9	26.0	22.0	19.3	15.9
4:01- 5:00	12.6	13.3	18.1	19.6	24.9	25.9	26.0	25.8	25.8	21.7	19.0	15.7
5:01- 6:00	12.7	13.1	18.3	20.0	24.7	26.4	26.6	26.3	25.9	21.9	19.2	15.2
6:01- 7:00	12.8	13.0	18.3	20.3	25.2	27.0	27.2	26.7	26.1	22.2	19.3	15.2
7:01- 8:00	12.8	13.2	18.3	20.7	25.4	27.5	27.8	27.2	26.2	22.4	19.5	15.5
8:01- 9:00	14.2	14.2	19.7	21.6	26.8	28.2	28.5	28.0	27.3	23.5	20.8	16.5
9:01-10:00	15.6	14.9	20.5	22.5	27.6	28.8	29.3	28.6	28.3	24.6	22.0	17.6
10:01-11:00	16.9	15.2	20.5	23.4	27.8	29.4	30.0	29.4	29.4	25.7	23.3	18.3
11:01-12:00	17.6	16.3	21.8	23.7	28.8	29.6	30.4	29.8	29.6	26.2	24.0	19.9
12:01-13:00	18.3	16.9	21.9	24.1	29.1	29.8	30.7	30.0	29.9	26.6	24.6	20.7
13:01-14:00	19.1	17.6	21.8	24.5	29.0	29.9	31.1	30.3	30.1	27.1	25.2	21.3
14:01-15:00	18.8	17.1	21.9	24.4	29.1	29.7	30.9	30.2	29.8	26.8	24.7	21.5
15:01-16:00	18.5	17.2	21.6	24.1	28.8	29.5	30.7	30.1	29.5	26.5	24.2	21.2
16:01-17:00	18.2	17.2	21.2	24.0	28.3	29.4	30.5	29.9	29.2	26.1	23.7	20.7
17:01-18:00	17.2	16.4	21.1	23.3	27.7	28.8	29.7	29.1	28.6	25.4	23.0	19.6
18:01-19:00	16.2	15.8	20.4	22.6	27.0	28.3	28.9	28.3	27.9	24.6	22.3	19.0
19:01-20:00	15.3	15.3	19.6	21.9	26.5	27.7	28.1	27.5	27.3	23.8	21.6	18.4
20:01-21:00	14.9	15.2	19.8	21.6	26.2	27.5	27.8	27.3	27.1	23.6	21.2	18.2
21:01-22:00	14.5	15.1	19.6	21.4	26.0	27.3	27.5	27.0	27.0	23.4	20.9	17.9
22:01-23:00	14.1	14.8	19.5	21.2	25.7	27.0	27.3	26.8	26.8	23.1	20.5	17.4
23:01-24:00	13.7	14.6	19.3	20.9	25.7	26.8	27.0	26.6	26.8	22.9	20.2	16.9
Max Hour	14	14	13	14	15	14	14	14	14	14	14	15
Min Hour	5	7	5	5	6	5	5	5	5	5	5	7

Monthly Statistics for Solar Radiation (Direct Normal, Diffuse, Global Horizontal) Wh/m⁄												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Direct Avg	2237	1476	1119	1384	1589	1870	2347	2405	2540	3287	2996	2788
Direct Max	6436	5876	4627	5791	6138	6157	5834	6951	6636	7487	6944	6584
Day	24	6	13	18	30	16	26	14	28	13	3	29
Diffuse Avg	1912	2313	2904	3221	3483	3415	3174	2995	2616	2153	1885	1757
Global Avg	3191	3268	3744	4299	4765	4879	4965	4822	4397	4256	3689	3294

Average Hourly Relative Humidity %												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	77	86	90	88	89	87	91	91	83	83	77	75
1:01- 2:00	79	80	88	89	83	88	92	92	83	84	79	71
2:01- 3:00	79	89	87	89	92	89	92	92	84	84	79	73
3:01- 4:00	79	91	88	89	92	89	93	92	85	84	79	74
4:01- 5:00	79	83	88	90	84	90	93	93	86	84	79	73
5:01- 6:00	78	91	94	88	92	87	91	91	85	81	77	78
6:01- 7:00	78	91	94	88	90	85	89	90	84	81	76	77
7:01- 8:00	78	83	85	87	82	83	86	89	83	80	74	70
8:01- 9:00	72	88	90	82	85	80	83	85	79	75	69	72
9:01-10:00	68	85	87	79	81	78	79	82	74	71	64	66
10:01-11:00	64	75	76	75	70	75	76	77	70	67	60	60
11:01-12:00	61	79	81	73	76	74	74	76	69	66	57	59
12:01-13:00	59	77	81	72	75	74	73	75	68	64	55	57
13:01-14:00	57	68	71	71	65	73	71	74	67	63	54	52
14:01-15:00	58	78	80	72	75	74	71	75	68	64	56	55
15:01-16:00	59	77	83	73	76	74	72	76	70	66	58	55
16:01-17:00	61	70	74	74	67	75	73	77	71	67	61	55
17:01-18:00	64	81	84	77	81	77	76	80	74	71	64	62
18:01-19:00	68	83	86	81	84	80	80	83	77	75	67	65
19:01-20:00	72	76	82	85	76	82	84	86	80	79	71	65
20:01-21:00	73	85	89	85	85	83	85	87	81	79	72	70
21:01-22:00	74	84	90	86	86	84	87	88	81	80	73	71
22:01-23:00	75	85	91	86	88	85	88	89	82	81	74	74
23:01-24:00	76	86	91	87	87	86	89	90	82	82	76	76
Max Hour	5	7	7	5	6	5	5	5	5	2	5	6
Min Hour	14	14	14	14	14	14	14	14	14	14	14	14

Climate Consultant 6.0 (Build 13, Jul 5, 2018)

File Criteria Charts Help

WEATHER DATA SUMMARY

LOCATION: SHENZHEN, -, CHN
Latitude/Longitude: 22.55° North, 114.1° East, **Time Zone from Greenwich** 8
Data Source: SWERA 594930 WMO Station Number, **Elevation** 18 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	296	292	314	342	363	365	375	378	362	372	337	309	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	208	132	93	110	120	139	177	189	209	288	273	262	Wh/sq.m
Diffuse Radiation (Avg Hourly)	177	206	244	256	265	255	239	234	215	187	172	165	Wh/sq.m
Global Horiz Radiation (Max Hourly)	763	803	929	959	942	962	917	918	899	882	814	719	Wh/sq.m
Direct Normal Radiation (Max Hourly)	804	773	728	754	744	753	774	795	816	892	825	825	Wh/sq.m
Diffuse Radiation (Max Hourly)	514	642	706	668	685	660	626	576	527	592	487	452	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	3190	3268	3744	4298	4764	4879	4964	4821	4396	4256	3688	3294	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	2237	1476	1118	1383	1589	1870	2346	2404	2539	3286	2995	2787	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	1912	2312	2903	3220	3483	3415	3174	2994	2615	2152	1885	1756	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	32461	32417	35288	38539	41169	41423	42682	42998	40951	41427	37059	33765	lux
Direct Normal Illumination (Avg Hourly)	19240	12318	8145	9844	9896	11478	14422	15561	17896	26023	25136	24105	lux
Dry Bulb Temperature (Avg Monthly)	15	15	19	21	26	27	28	27	27	24	21	18	degrees C
Dew Point Temperature (Avg Monthly)	9	11	17	18	23	24	25	24	23	19	15	11	degrees C
Relative Humidity (Avg Monthly)	70	82	85	81	81	81	82	84	77	75	68	66	percent
Wind Direction (Monthly Mode)	20	40	140	110	90	110	220	140	40	20	0	40	degrees
Wind Speed (Avg Monthly)	2	3	3	2	3	1	2	1	2	2	2	3	m/s
Ground Temperature (Avg Monthly of 3 Depths)	19	18	18	19	22	24	26	26	26	25	23	20	degrees C

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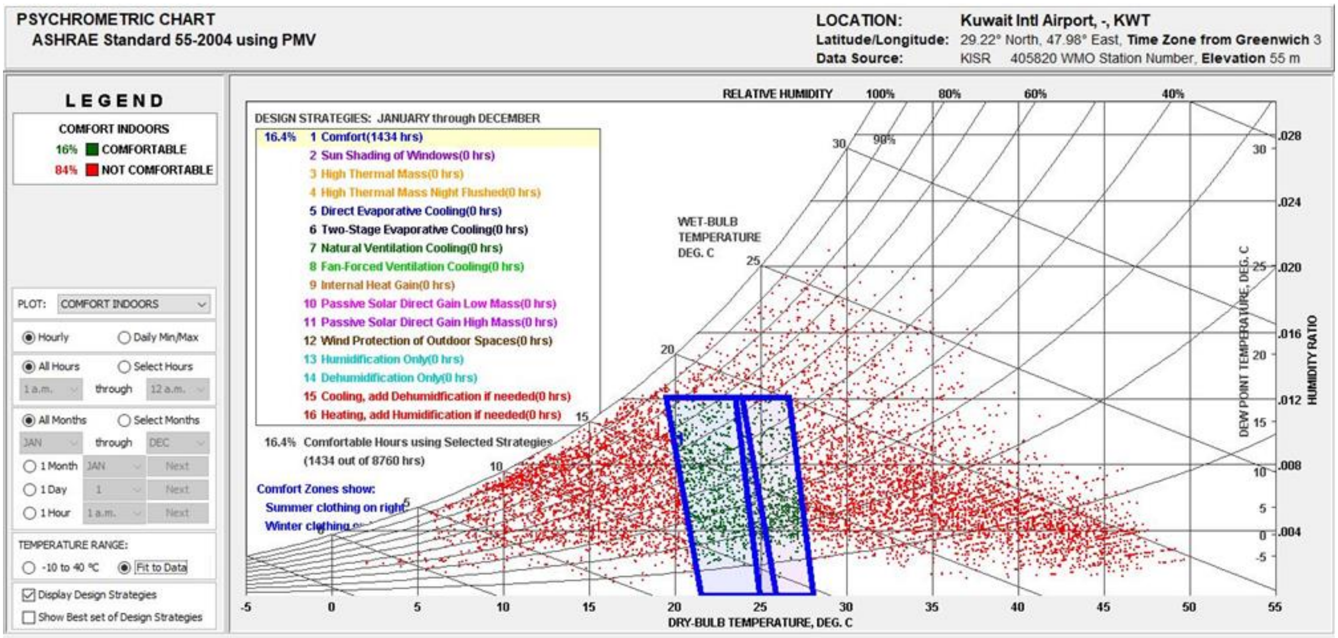
ANNEX II
CLIMATE CONSULTANT

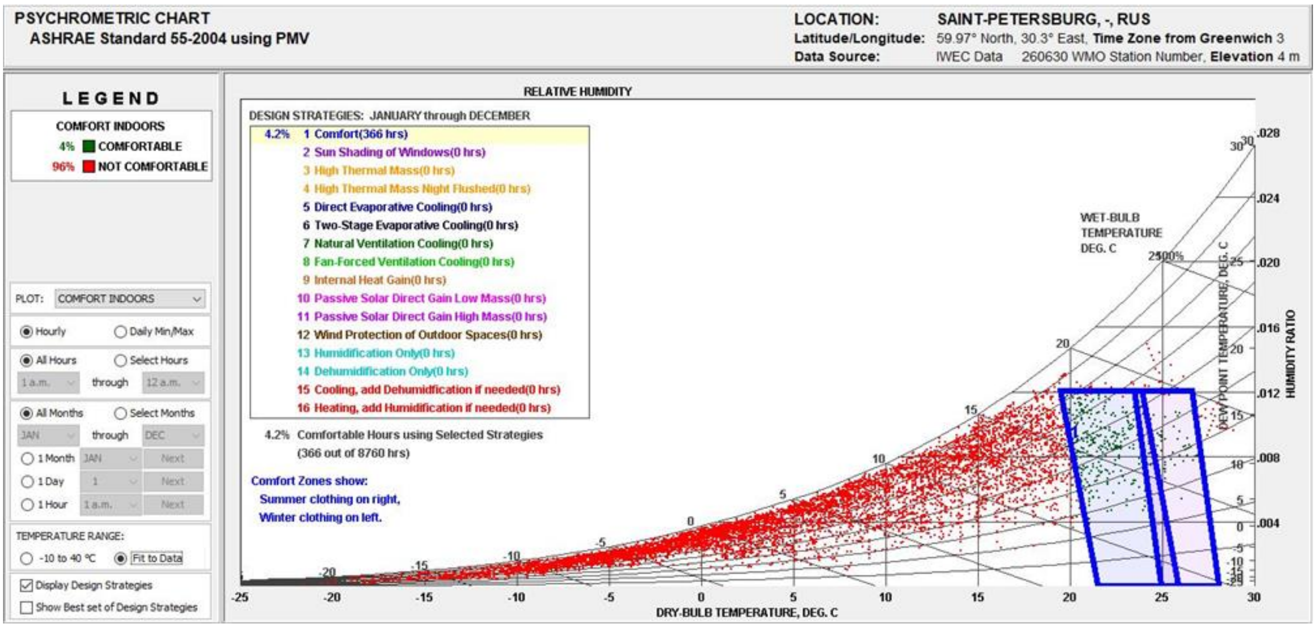
✓ PREDESIGN RESULTS

Once the weather data are introduce, these are the results we get once we desactivate all the active/passive strategies for the buidling. This way we can tell how many hours of comfort we have included just with the right sun shading of the windows which is included in the firt evaluation of the comfort hours of the building.

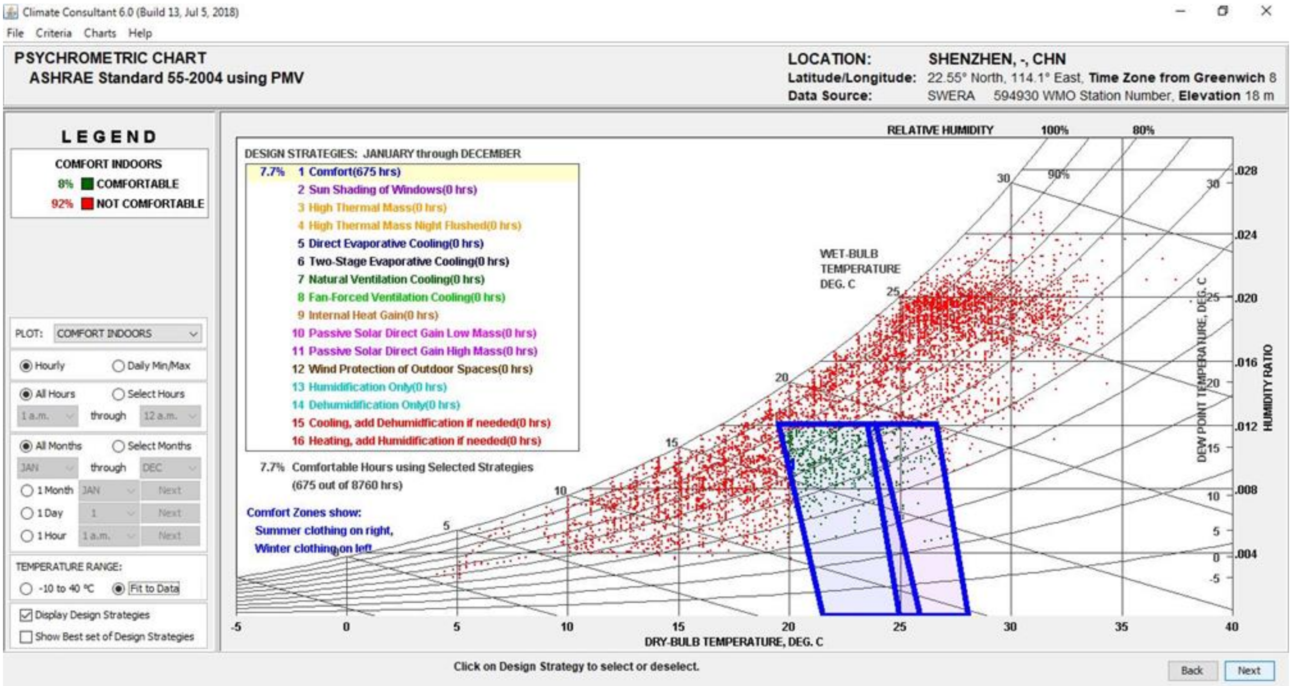
- BAHREIN



- RUSSIA



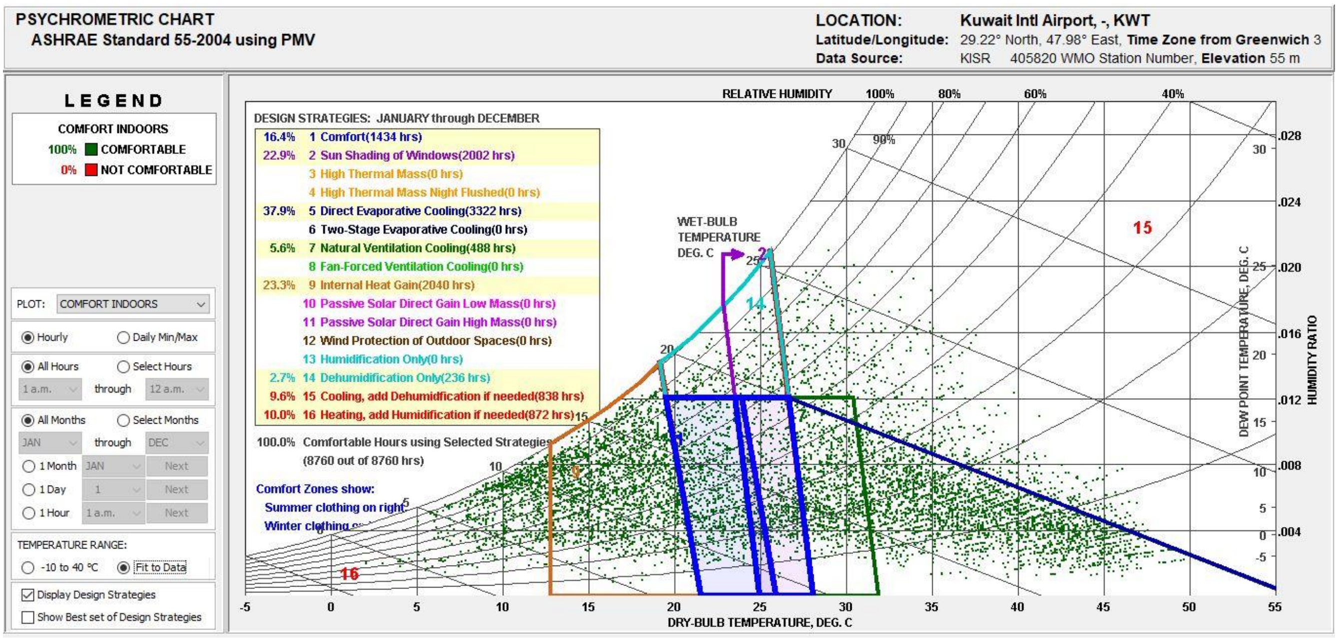
- CHINA



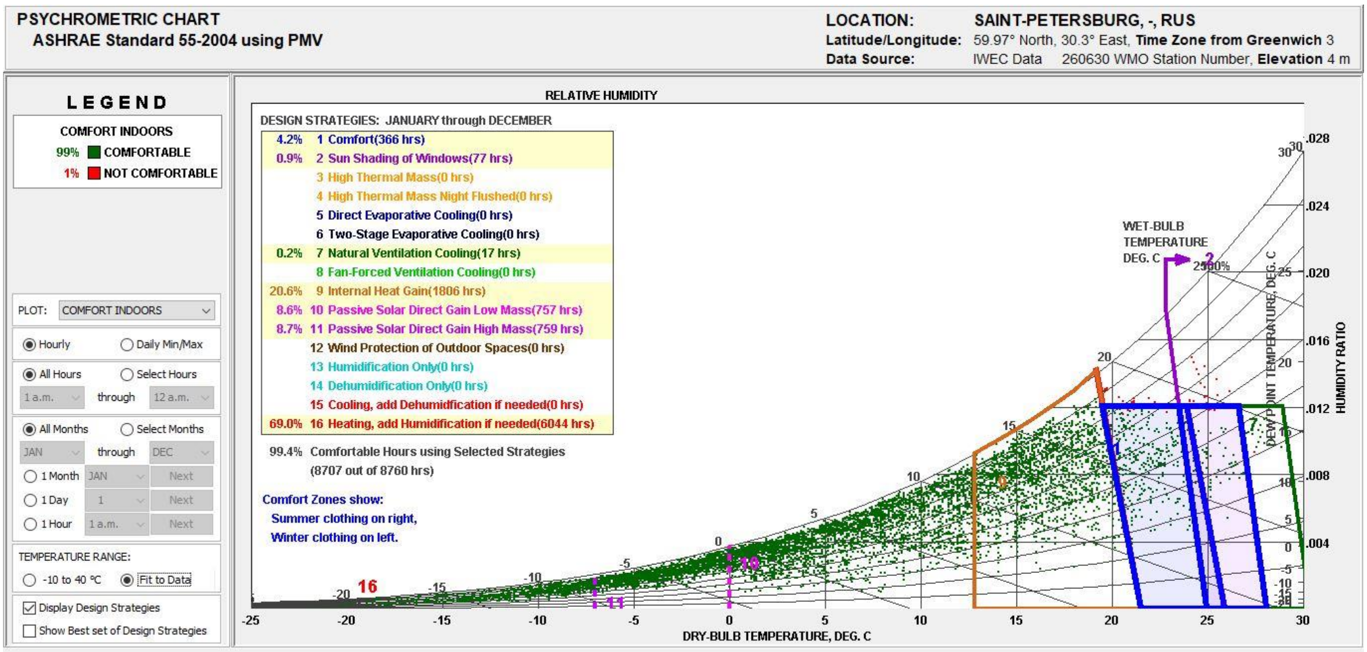
✓ DESIGN STRATEGIES SELECTED

We have 14 strategies that we will select according to our case study. However we have to take into account that passive strategies are always favoured. This helps us know how to operate with the building. The most effective strategies are chosen.

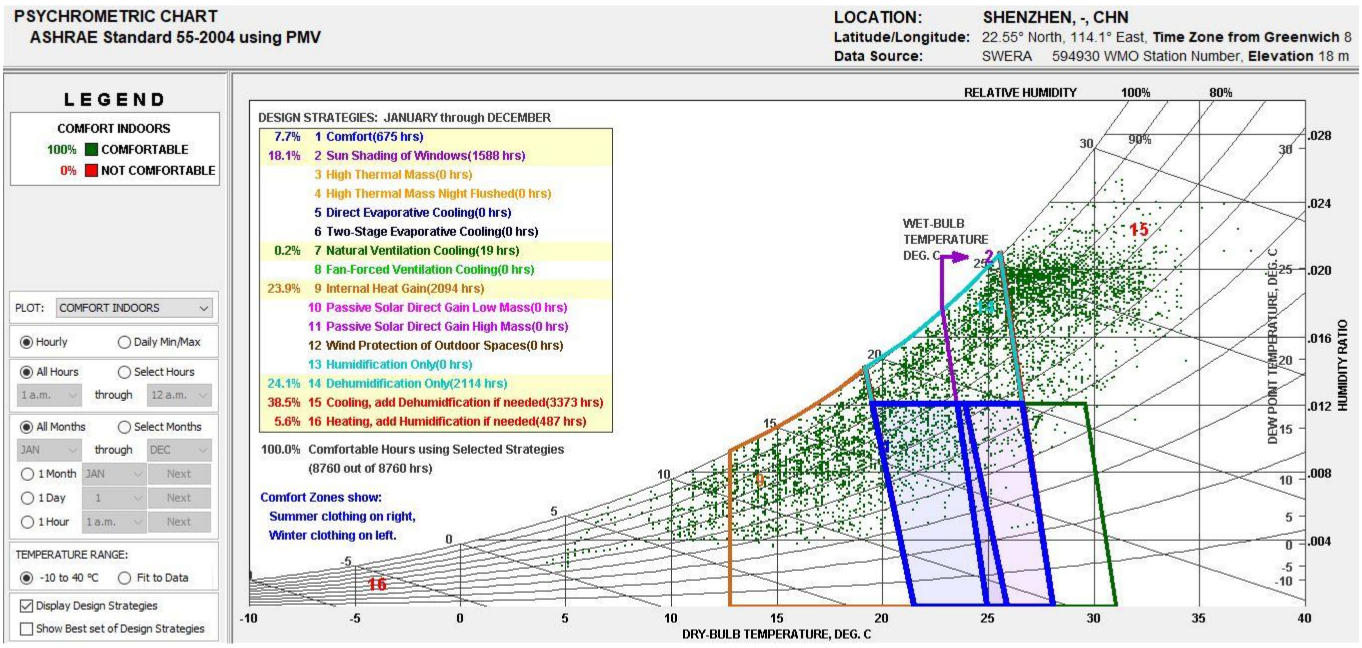
- BAHREIN



- RUSSIA



- CHINA



ANNEX III
SOLAR IRRADIANCE

Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

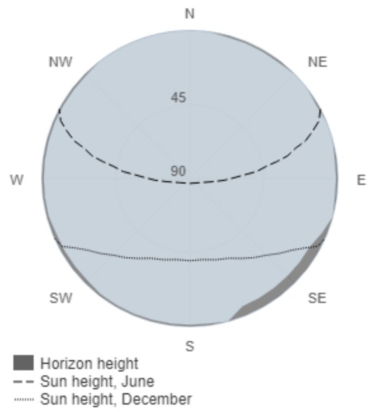
Provided inputs:

Latitude/Longitude:	26.240, 50.582
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed:	1 kWp
System loss:	14 %

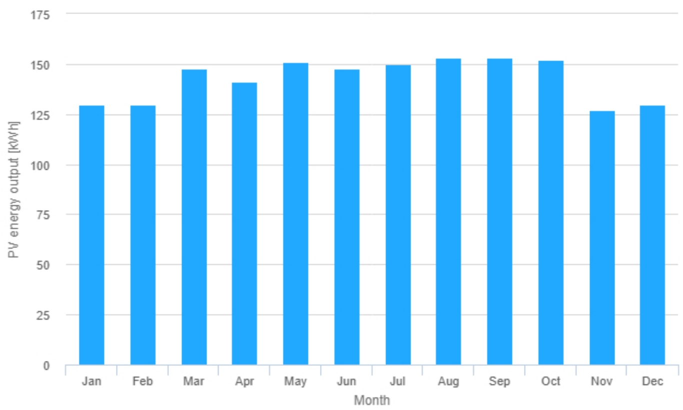
Simulation outputs

Slope angle:	26 (opt) °
Azimuth angle:	0 °
Yearly PV energy production:	1710 kWh
Yearly in-plane irradiation:	2400 kWh/m²
Year to year variability:	49.90 %
Changes in output due to:	
Angle of incidence:	-2.6 %
Spectral effects:	-0.5 %
Temperature and low irradiance:	-14.5 %
Total loss:	-28.7 %

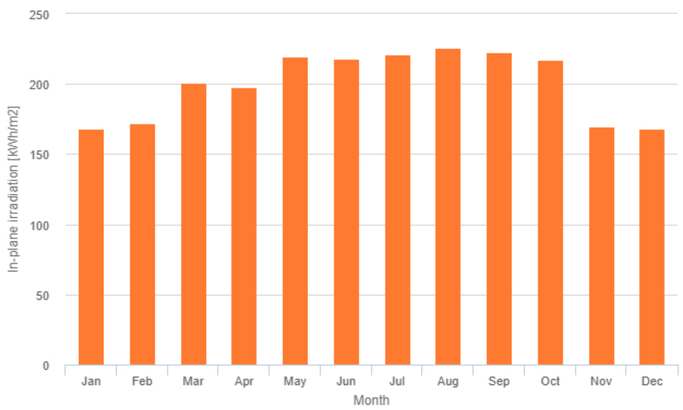
Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:



Monthly in-plane irradiation for fixed-angle:



Monthly PV energy and solar irradiation

Month	Em	Hm	SDm
January	130	168	11
February	130	172	12.2
March	148	201	11.7
April	141	198	8.35
May	151	220	3.4
June	148	218	2.66
July	150	221	2.59
August	153	226	3.12
September	153	223	2.35
October	152	217	4.84
November	127	170	8.59
December	130	168	12.8

Em: Average monthly electricity production from the given system [kWh].

Hm: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SDm: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Joint Research Centre

Report generated on 2019/08/01

Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

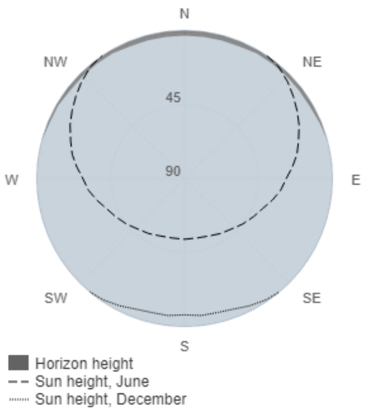
Provided inputs:

Latitude/Longitude:	59.987, 30.178
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed:	1 kWp
System loss:	14 %

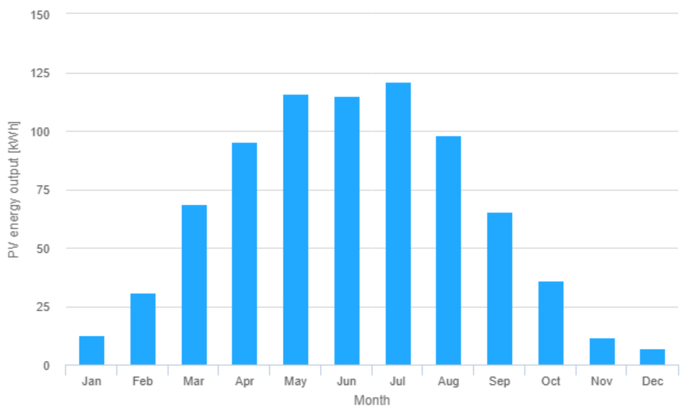
Simulation outputs

Slope angle:	41 (opt) °
Azimuth angle:	0 °
Yearly PV energy production:	777 kWh
Yearly in-plane irradiation:	1000 kWh/m²
Year to year variability:	247.00 %
Changes in output due to:	
Angle of incidence:	-2.9 %
Spectral effects:	? (0) %
Temperature and low irradiance:	-7.1 %
Total loss:	-22.5 %

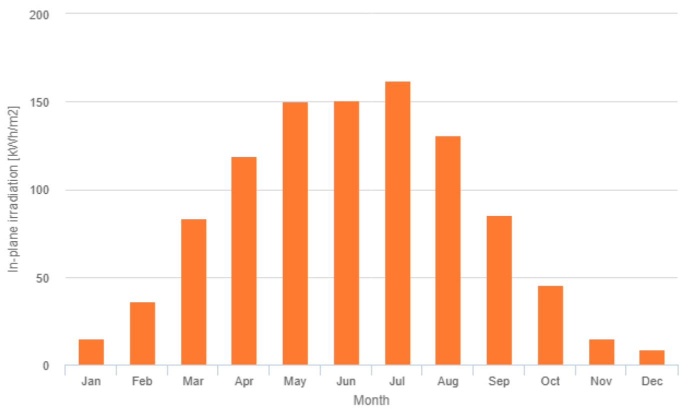
Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:



Monthly in-plane irradiation for fixed-angle:



Monthly PV energy and solar irradiation

Month	Em	Hm	SDm
January	12.6	15	6.3
February	30.7	36	19.6
March	68.9	83.2	29.2
April	95.4	119	33.7
May	116	150	39.4
June	115	151	37.7
July	121	162	40.4
August	98.3	131	34.9
September	65.5	85.1	23.1
October	35.8	45.6	15.8
November	11.6	15	4.28
December	6.97	8.81	2.58

Em: Average monthly electricity production from the given system [kWh].

Hm: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SDm: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Report generated on 2019/08/01

European Commission

Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

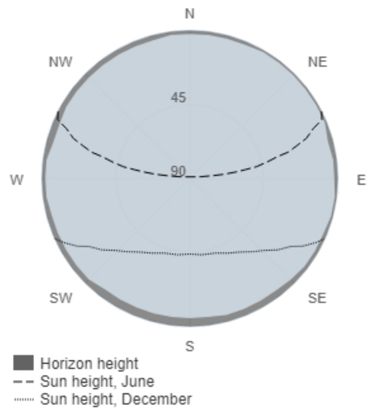
Provided inputs:

Latitude/Longitude:	22.533, 114.056
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed:	1 kWp
System loss:	14 %

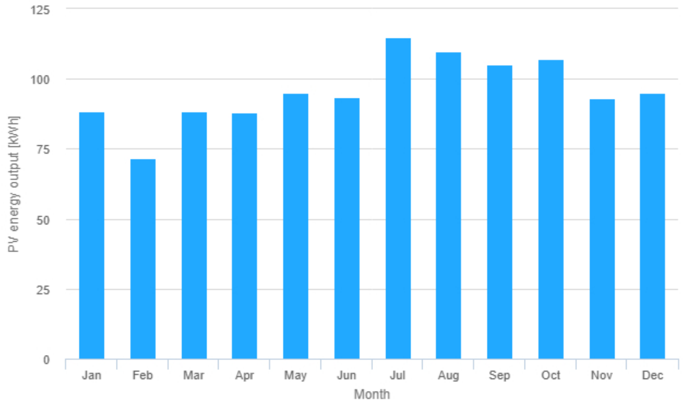
Simulation outputs

Slope angle:	20 (opt) °
Azimuth angle:	0 °
Yearly PV energy production:	1150 kWh
Yearly in-plane irradiation:	1550 kWh/m²
Year to year variability:	61.10 %
Changes in output due to:	
Angle of incidence:	-3 %
Spectral effects:	1.3 %
Temperature and low irradiance:	-12.3 %
Total loss:	-25.9 %

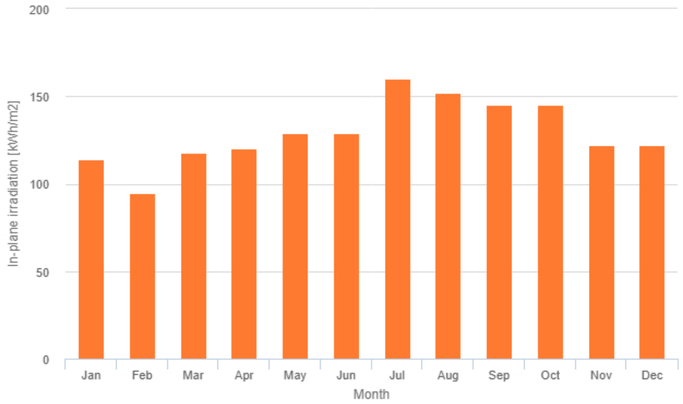
Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:



Monthly in-plane irradiation for fixed-angle:



Monthly PV energy and solar irradiation

Month	Em	Hm	SDm
January	88.5	114	22.6
February	71.8	94.4	12.2
March	88.3	118	14.2
April	88.1	120	13.5
May	94.9	129	10.8
June	93.5	129	12.7
July	115	160	7.85
August	110	152	9.83
September	105	145	5.95
October	107	145	12.3
November	92.9	122	15.2
December	95.2	122	16.7

Em: Average monthly electricity production from the given system [kWh].

Hm: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SDm: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Joint Research Centre

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