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Analyzing passive solar strategies in the case of high-rise building

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A B S T R A C T

Nowadays, societies are not able to live without energy. After 1970's energy crises, energy has become a more serious issue and environmental protection is one of the most important considerations in countries' sustainable development. Different types of energies such as thermal, electricity and so on are used in people's daily lives. Many of these energy types are derived from sedimentary sources like oil, gas and coal, which are not interminable. So, one of the fundamental challenges of today's world is seeking renewable energy alternatives such as solar, wind, hydro, biomass, geothermal and so on, to replace the fossil fuels. This attempt should be done in all sections like transportation, industry, buildings and etc. Building section is one of the greatest energy consumer sectors. In this sector, high-rise buildings with their vast facades have a great potential to consume sustainable energies. For instance they can easily gain solar radiations. Thus, here, the emphasis has been put on the practices and attempts done to take advantages of solar radiation as an energy source in high-rise buildings.

Although there are many appreciable scientific solutions for energy efficiency problems, there are still huge gaps, especially negligence in analyzing the effectiveness of different passive solar strategy criteria, found in high-rise buildings as an imminent part of a new society. Therefore, the authors' main attempt is to understand how passive solar design strategies are implemented in the case study, the Frankfurt Commerzbank Tower. This has been done to obtain an environmental friendly pattern of high-rise buildings. This study is based on a theoretical approach supported mainly by the outcomes of literature review and case study analysis from the solar design aspects. The results of this research show that sustainable skyscrapers, which benefit from solar energy design, can be more energy efficient, using different solar passive strategies.

Contents

1. Introduction

In recent years, humans have not been able to live without energy. So, energy and environmental issues are becoming more

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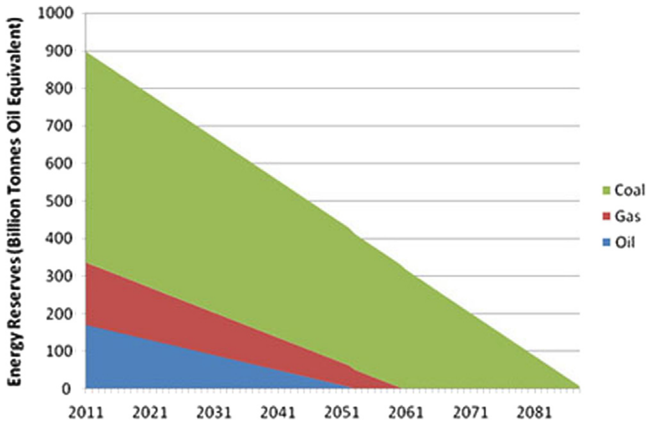


Fig. 1. World Energy Reserves from 2011 [4].

serious and the environment protection is one of the most important problems in the countries' sustainable development [1]. Energy is used in every aspect of people's daily lives to fulfill cooling and heating demands, producing domestic hot water supply and so on [2]. Most of the energy sources, including oil or coal-based fuels are coming from sedimentary organic substances. However, these energy reserves are limited and the fuel prices soar every day. It is proven that oil can be exploited just for about 40 more years. If the amount of gas production is increased in order to fill the energy gap left by oil, then those reserves will only remain for an extra 50 years and the coal for about 70 more years [3] (Fig. 1).

Pollution caused by building sector has a high percentage of the whole environmental pollutants and released gases have tremendous influence on the atmosphere. In other words, it is estimated that building section is responsible for about 40–45% of total delivered energy usage and only a little less than 50% of all CO_2 emissions [5]. While approximately above 30% of building-related CO_2 emission is attributable to the service sector. This amount is approximately 50% in the residential sector [5].

The question here is how to manage this great amount of consumption. The answer is not keeping on constructing gigantic power stations, consuming enormous amounts of energy sources in one hand, and making equally vast amounts of pollution on the other hand. However, in the case of nuclear power, the high toxic waste should be also considered and if fuel consumption continues at the present rate or follow an increasing rate we will undoubtedly face global vulnerability [6,7]. As building sector consume the great amount of energy, one of the most meaningful long term strategy for getting a handle on the world energy usage in building sector is to build constructions in such a way that consume the least possible energy.

In this study, the overall objective striven for is to find and introduce an alternative source of energy in the building sector. In this case solar energy as a permanent renewable source of energy has been analyzed in the case of high-rise buildings. In other words, the effect of utilizing passive solar strategies on the decrease of energy usage and total energy demands for cooling and heating the building—as an architectural point of view—is considered as the main objective of this research and the result could be a new definition of architecture and construction, so that, this branch of industry can supply the necessary contributions for sustainable and viable development.

1.1. *Learning from the past*

In ancient times, Romans and Greeks knew about the solar energy and were able to benefit from their knowledge. When the cost of wood increased and its availability was rare, they used the Sun as an energy source, which suited local conditions, eventually this kind of architecture, based on solar energy, was applied in Japan, China, and New Mexico. 2300 years ago Dositheius[1] made parabolic mirrors and Diocles[2] set out their geometric proof. In 1912–1913, Shuman[3] placed parabolic reflectors outside of Cairo, in the desert and was ambitious enough to cover 20,250 square miles of parabolic reflectors to obtain the same amount of fuel exploited in 1909. But, after the First World War, because of the enthusiasm towards oil and the death of the supporters of the project, things changed. In the late 19th and early 20th a group of experts stated that in order to avoid catastrophes, it was vital to harness Sun's energy [9].

Therefore, these days, as threats like pollutants and global warming were known, many countries tried to think of substitute energy sources such as solar energy or other renewable sources to be the pioneers in benefiting these sources. In early 1970s oil crisis appeared and caused some developments in the field of renewable energies. During this period, factors such as easy access to renewable energies, the high cost of oil and also the cost effectiveness assessments and conversion systems based on renewable energy technologies attracted the most attention. Moreover, recently, it has been found out that renewable energy sources and systems can have a useful impact on some essential environmental, technical, political and economic world issues [10].

1.2. *Research methodology*

There have been three different factors that motivated the author to do this research. First the matter of energy efficiency itself that tries to guarantee longer access of the next generation to energy resources. Secondly, this fact that architects have a really significant role in designing energy efficient buildings and finally the issue that high rise buildings deserve more attention in the field of energy efficiency.

Regarding to the above mentioned motives this research was done. It is based on a theoretical approach supported mainly by the outcomes of a literature review and case study analysis (descriptive research method). The method is used in order to gather information about the existing type and the amount of energy consumption in the high-rise building sector. So, at the first phase, it is a type of study, which is essentially concentrated on describing the degree and the condition of the current renewable energy usage situation in detail. On the other hand, it involves fieldwork and more especially literature review as a combination of two main phases, qualitative and quantitative methods of data collection.

2. Current situation

Buildings are generally the main energy consumer in urban context. They approximately consume 42% of the total world annual energy usage. This energy is mainly used for heating, cooling, providing electricity and air conditioning [11]. According to the data released from energy balances of the General Directorate for Energy and Geology [12,13], 30% of final energy is accounted by residential and services buildings and more than

[1] He was a Greek mathematician, engineer, physicist, inventor, and astronomer (287–212 B.C.). Although few details of his life are known, he is regarded as one of the leading scientists in classical antiquity [8].

[2] He was a Greek mathematician and geometer (240–180 B.C.). Diocles is thought to be the first person to prove the focal property of the parabola [8].

[3] Frank Shuman: (1862–1918) was an American engineer, inventor and solar energy pioneer noted for his work on solar engines, especially those that used solar energy to heat water that would produce steam.

60% of the electricity that is consumed at the national level, that reflects in a greater weight in distribution of primary energy by sector and also a greater share of emissions of gases. A possible solution in building sector, which helps reduce energy consumption is designing buildings, which consume less energy, applying passive measures, particularly natural or hybrid ventilation in order to considerably reduce primary energy consumption [14].

The growing consumption of energy and environmental problems appearing every day have lead to great concern on the renewable energy (RE) and ecological environment control. Reports say that building industry is responsible for 34% of whole environment pollution, and 50% related to the energy consumed in building industry [11]. By developing our technology and applying specific methods we can have a friendly look toward ecology and have eco-buildings, which are more "environment friendly".

2.1. Energy and building sector

As an introduction, if the constructions are considered step by step, it becomes clear that there are many privileges in using renewable energies, not only as offering a snapshot of the energy future, which will greatly influence our whole lives. Furthermore, they will influence the way to construct buildings in the future. Many of the technologies are appropriate as so called 'embedded' systems, which are systems that may be independent of the grid and can be incorporated as stand-alone generators within buildings [7].

Energy system plays a main part in the society, economy, and the environment and the way they step toward development [15]. Both the conversion and the supply side of the contemporary energy system must change. A scenario suggested by IIASA-WEC[4], energy per GDP (the global energy intensity) is supposed to reduce by 0.8% to 1.5% a year until 2100 [16]. Another energy plan suggested by, the quantity of energy efficiency – megawatts – corresponds the entire supply of energy year 2100 [17], which is equal to 0.7% energy efficiency increase per year during the 21st century [18].

Unfortunately, nowadays, climate is changing. It is very likely caused by human activities and this shows crucial risks for a vast range of human and natural systems. The consideration of the climatic issues in the official education system began in the late 1960s [7]. Most probably the main reason for this neglect was the cheap price of oil and other fossil fuels before the energy crisis of the 1970s, which architects could easily reach the interior comfort level of their buildings without being responsible for considering the climate in their designs. After the energy crisis (1973), alternative sources of energy were pioneered with new legislation encouraging research and development to deal with the problem.

Furthermore, the addition of each ton of greenhouse gases leads to further changes and greater risks. In this case, buildings consume a huge amount of energy and these energies come from combustion of fossil fuels, which produce CO_2 in the process. It is also estimated that building section is responsible for about 40–45% of total delivered energy usage and only a little less than 50% of all CO_2 emissions [5].

In other words, it is believed that the energy consumed in buildings, both in construction and their usage section, leads to producing approximately 40% of the greenhouse gases [19]. Moreover, in industrial countries, about 40% of the total energy is spent for building needs and about 10% of energy usage is added to this amount for the materials' production, construction processes and the materials transportation [20]. It shows that, even today, they must be precisely managed in construction and running according to the principles of climatic aspects, energy efficiency and sustainability.

In general, 1000 kW h/m² or more can be consumed in office buildings for heating, lighting, computers and hot water per year. As shown in Fig. 2 the overall building energy consumption in Germany at 2007 was as follows; 25% of overall energy consumptions went to space heating, 9% to water heating 7% to lighting and appliances and 2% to cooking. According to this calculation, 43% of overall energy uses in 2007 in Germany related to building accounts, where the case study is located [21].

So, as energy efficient building and good design go hand-in-hand, principles like considering solar orientation gives an architect a great foundation on which to establish a more environmental-friendly architecture. Moreover, while designers and architects can fairly easily influence new building architectures by following some simple design principles, this study intends to explore one of the most complex and problematic issues facing humanity over the next century, which is finding the way to construct more sustainable and energy efficient high-rise buildings.

2.2. Energy efficiency and renewable energies

One of the fundamental challenges for the future is energy efficiency issue and taking an approach towards the nature [22]. In order to gain this purpose, there should be an attempt to find environmentally friendly energy supplies, which are both easily accessible and compatible with climatic conditions. Apart from new and more efficient technologies, which are currently used, more emphasis will be needed to be placed on reducing energy consumption and also on source requirements without diminishing either living standards or comfort level.

Energy efficient design includes not only engineering design but also other disciplines such as architecture. Unluckily, the main concern of high-rise building and skyscraper designers is building's function and low attention has been paid to their environmental impacts [23]. Thus, in order to gain environmental friendly design, which leads to economic efficiency as well, there should be a balance between function and paying attention to the effects of the building on the natural environment and vice versa. Architects and designers have to face these substantial challenges. Thus, the aim is achieving maximum overall comfort and living quality with the minimum energy and resource usage.

As it was mentioned, building sector is one of the biggest energy consumers and high-rise buildings are the inevitable part of this sector, which use enormous amount of emery as well. So, the issue of energy efficiency must be considered so seriously. For this purpose, first the energy consumption must be analyzed, This usage could be analyzed in different ways and building parts such as the thermal characteristics of a building (thermal capacity, insulation and so on), the air-conditioning installation, heating insulation and hot water supply, the built-in lighting installation, indoor climatic conditions and etc. Then decision making process can be done by applying various strategies like changing the building design, different material selection, changing construction system and so on [24], which due to the study limitations, some of these criteria are analyzed in the case study.

Other consequential matters, influencing energy systems and clarifying sustainability tendency are the energy efficiency issue and intensities progress towards sustainable development without sacrificing socio-economic growth. This development applies for the efficient energy end use, as a way of declining the amount of consumed energy [25]. Sustainable growth and renewable energy use must go along together. If governments designate subsidies for renewable energies, these type of energy will grow [26] but, as most subsidies do not last long, technologies should become

[4] IIASA-WEC: International Institute for Applied Systems Analysis – World Energy Council.

cost-competitive and sustainable commercial markets should be developed (Fig. 3) [27].

Certainly, one of the most critical threats to the planet ultimate security is based on the increasing use of sedimentary energy sources [29]. Supply and demand are the two main categories of energy regime, which are the present technological ways to combat against this danger. Consuming renewable sources is the main aim in the 'supply' section [30]. It should mainly limit the curbing demand of building and transportation.

Through converting natural phenomena into useful energy forms, renewable energy technologies generate marketable energies. The potential energy of sunlight and different energy forms, which are hidden in wind, photons, heating effects, plant growth, tidal force, the heat of the earth's core and falling water, are used by these new technologies to gain energy. As fossil fuels are generally diffuse and not fully accessible, the increased difficulties are solvable [10]. The researches and the developments in renewable energy resources and technologies have increasingly been done during the past two decades to solve the difficulties. Nowadays, renewable energy sources are produced more easily, cheaper and have more reliability and applicability. But, further developments are necessary in this field.

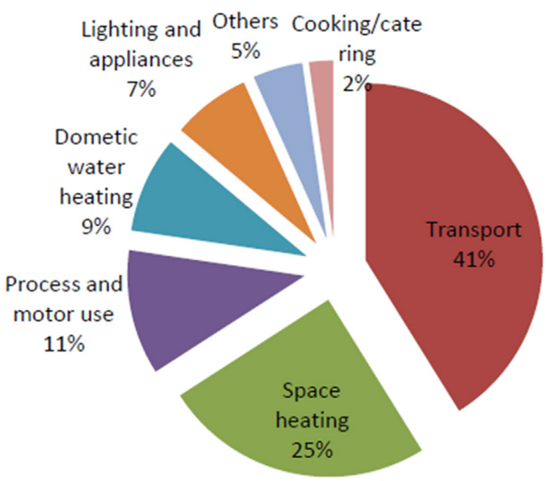


Fig. 2. Overall energy consumption in Germany 2007 [21].

It is now believed throughout the world, that energy is an essential and primary factor in economic development and generating wealth. World population, consumption, industrial activities and similar factors have caused intensive problems and risks for the environment during the past two decades. Finding answers to these problems surely relates to sustainable development and in this case renewable energy sources seem to be one of the possible answers [31].

"Renewable energy is the energy, coming from natural sources such as solar radiation, wind, tides, rain, geothermal heat and so on, that are naturally replenished" [32]. In recent years, a lot of attention has been paid to renewable energy sources since sedimentary fossil fuels have been exploited too much and fuels crises have occurred, which encourage developed countries to welcome renewable technologies. As this kind of energy is renewable, it can be assumed as sustainable. In other words, it will never run out and it has minimal impact on the environment [33].

Renewable energy can be used everywhere in the world and is also an essential factor in development. In comparison with the fossil fuel it makes less pollution and is abundant in nature and is available everywhere [34]. It gains about 8% of the world's energy demand [35]. We can devote a share of 50% of the entire energy

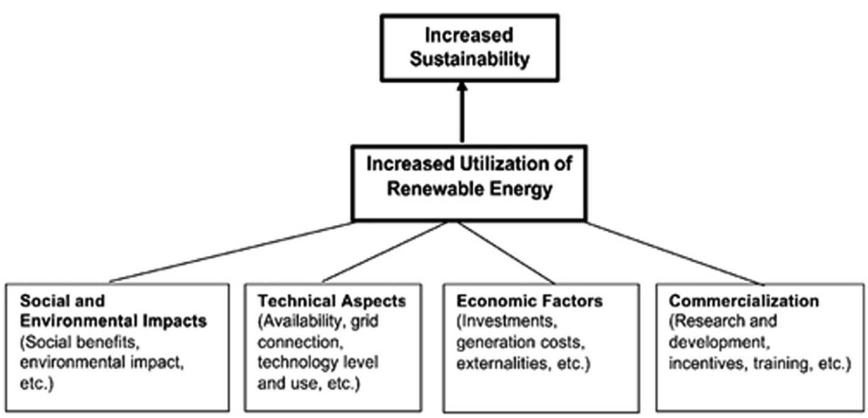


Fig. 3. Illustration about the major considerations (involved in the development of renewable energy technologies for sustainable development) [28].

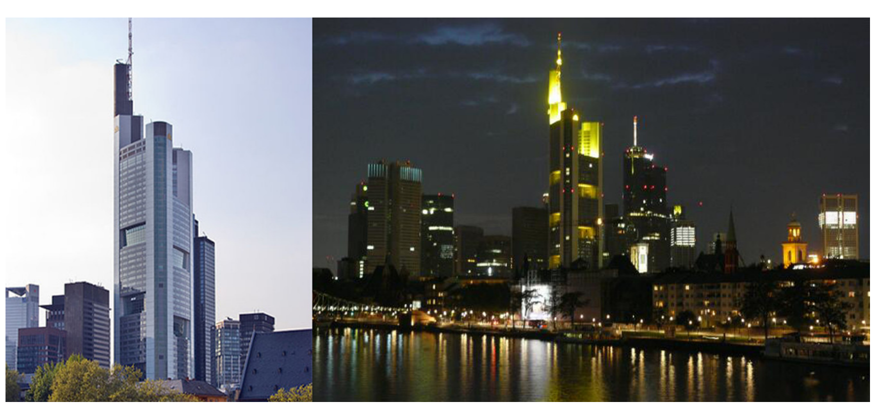


Fig. 4. The Frankfurt Commerzbank day and night views [44].

demand of the world to renewable sources if we apply proper policies and recent developments in technology, and use renewable energies such as solar radiation, geothermal, wind energy, biomass and the more traditional sources like hydro power [36].

It is obvious that increasing the consumption of renewable energy resources and also their integrated operation is an essential factor in obtaining the long-run purposes of energy. Buildings could be 'environmental friendly' and attain 'zero emission' by applying renewable energies as power sources [37]. Thus, studies on energy management and renewable energies play such a significant role in this process.

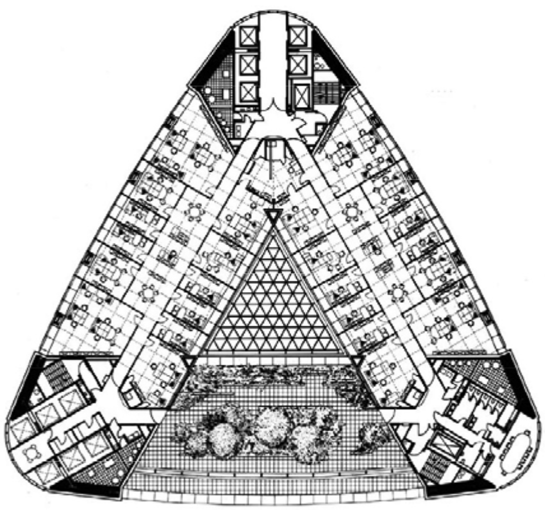


Fig. 5. The Frankfurt Commerzbank typical office storeys [45].

2.3. High-rise buildings

As population grows, more buildings are used as shelter and high-rise buildings gain inevitable importance. Accordingly, high-rise buildings had been more noticeable for such reasons as being more compact, which reduced land use and transportation being much safer against physical destructive phenomena, such as fire and earthquake, being more economical and so on. Therefore, each factor played a fundamental role in encouraging the growing population to move into high-rise buildings.

It is expected that world population become predominantly urban and grow by 2/3 in the next few decades. Regarding this population, high-rises can help a lot to face their incoming needs. The existing high-rises have a poor life cycle, about 50 years, 34% of their total costs relates to energy costs [38]. Artificial illumination is responsible for nearly 50% of high-rises energy use [38,39]. It is because of the current conceptual design methods used by the Architecture, Engineering, and Construction (AEC) industry. Early design decisions that determine the construction's future energy performance are commonly taken by architects, who develop and analyze few design options that respond mostly to architectural issues [40]. Therefore, the design post-rationalization currently performed by engineers leads to solutions with mediocre daylighting, and excessive thermal loads and energy demands. Better design methods are required to increase the energy efficiency of future high-rises buildings. A mere 10% improvement in the energy efficiency per household of the 4 billion additional people

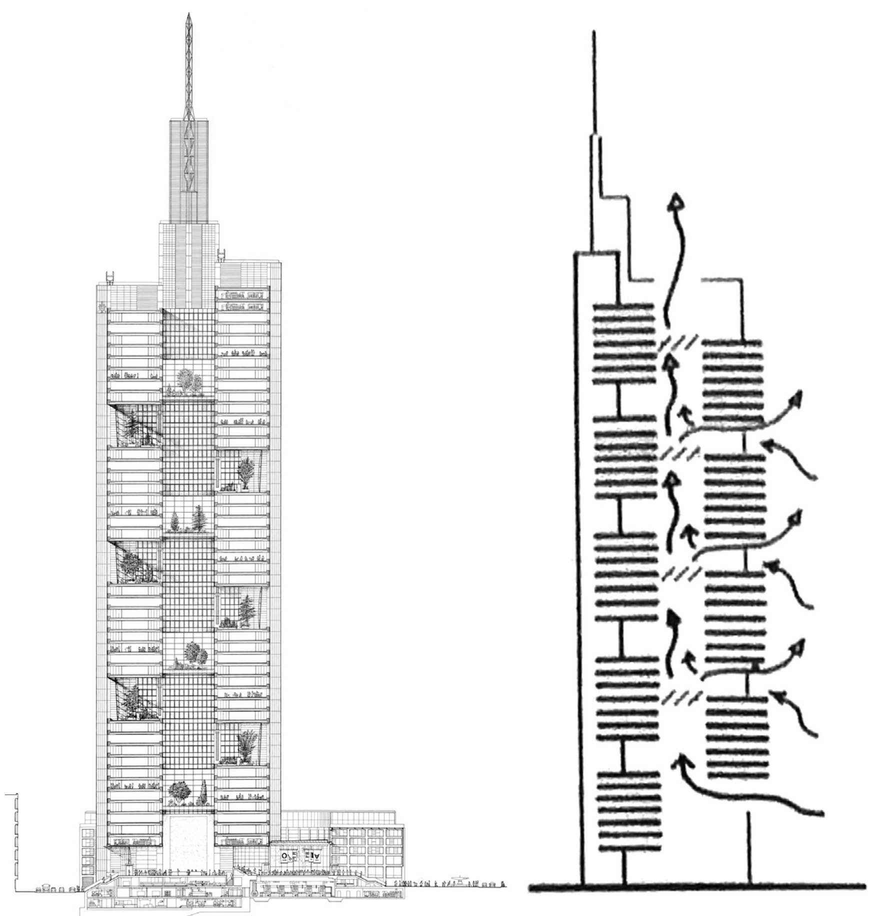


Fig. 6. The Frankfurt Commerzbank ventilation system [46].

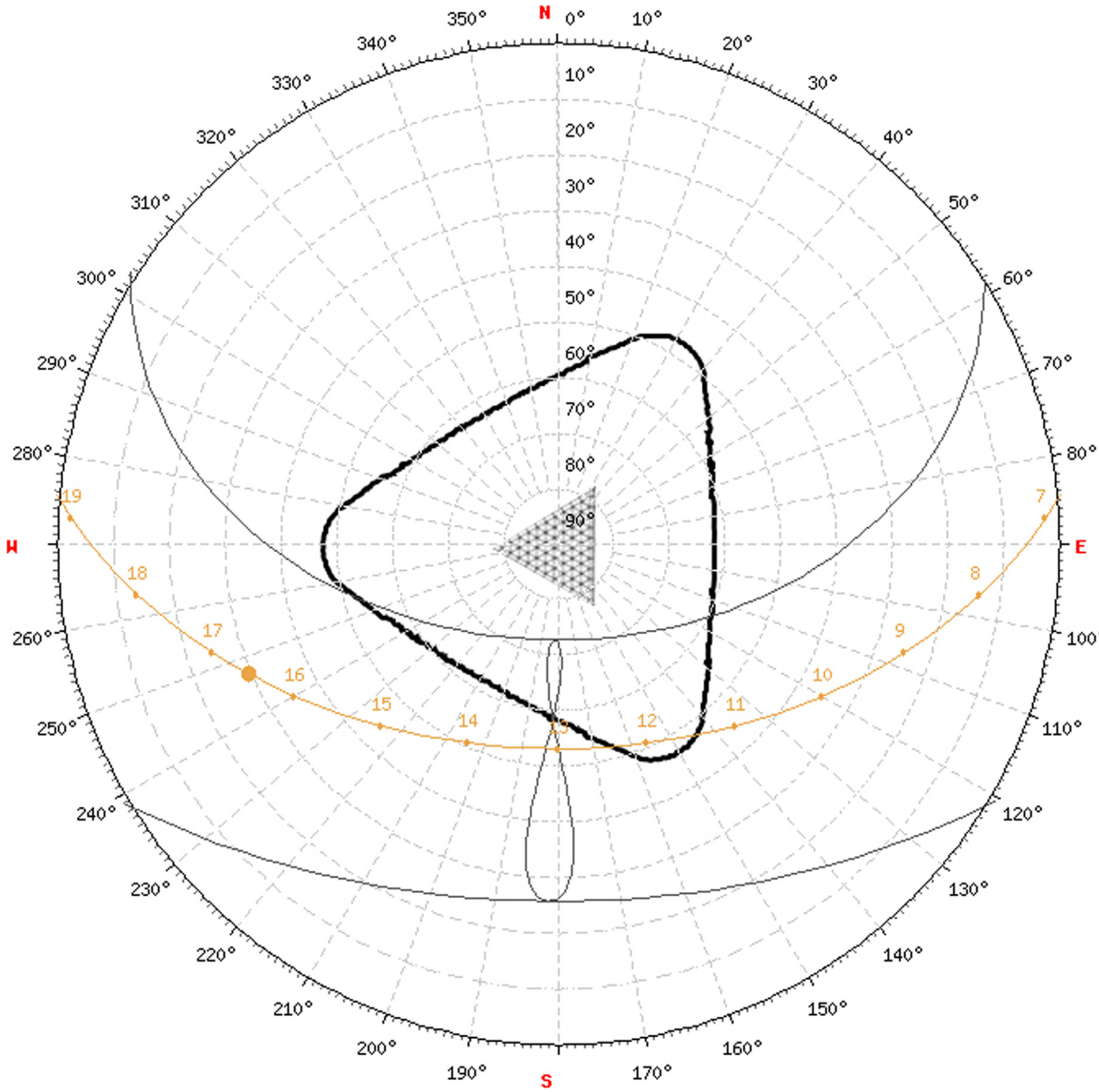


Fig. 7. Frankfurt Commerzbank Tower Sun Path [50].

would lead to annual savings of 10.1 million Btu × 1.4 billion households [40].

On the other hand, finding renewable energy sources is essential. Especially in high-rise buildings, which have an incredible potential for using sustainable sources such as solar energy, because of their vast facades, which provide a great area to benefit [41]. New design ideas are becoming common among pioneer architects and developers. Well-designed bioclimatic skyscrapers are to be related to their sites and to have energy efficiency. New constructions offer more comfort ability for their occupants during the whole year.

In other words, as a result of height, despite low-rise buildings, high-rise buildings are more directly exposed to the absolute impact of the environment such as solar radiations [7,19]. Apart from other low-rise buildings, high-rise buildings are the novel construction type possessing new technologies and of course they must certainly require special design and architecture premises. Therefore, justification for the immense consideration of this research is obvious.

However, unfortunately, since 1960s the development of high rise buildings, which has practically been energy efficient and respectful to nature, has deadlocked. However, after the 1973 energy crisis this attempt has started once more [42]. But, these days, although the importance of energy efficiency issue is apparent, it seems that the majority of architects still have limited interest in energy. In this case Sir Norman Foster's projects – as pioneer – have been very successful in designing high-rise buildings compatible with nature, as a case of solar designed constructions.

3. Case study analyses: the Frankfurt Commerzbank in Frankfurt am Mine, Germany

Norman Foster's high-rise buildings are equal to ambitious design. The Frankfurt Commerzbank was a meaningful progress as the first demonstrably ecological tower, which gains natural light and was organized in modules or villages of interior spaces (Fig. 4). This is a 56 floor building with the height of 259 m. The building encompasses about 80,000 m² of office space with a further 45,000 m² of other uses. It was one of the initial attempts to be an ecological building with regard to energy efficiency policy and natural ventilation in 1991. One of the main reasons of being green was, that the city policy was in favor of having an eco-high-rise building [43].

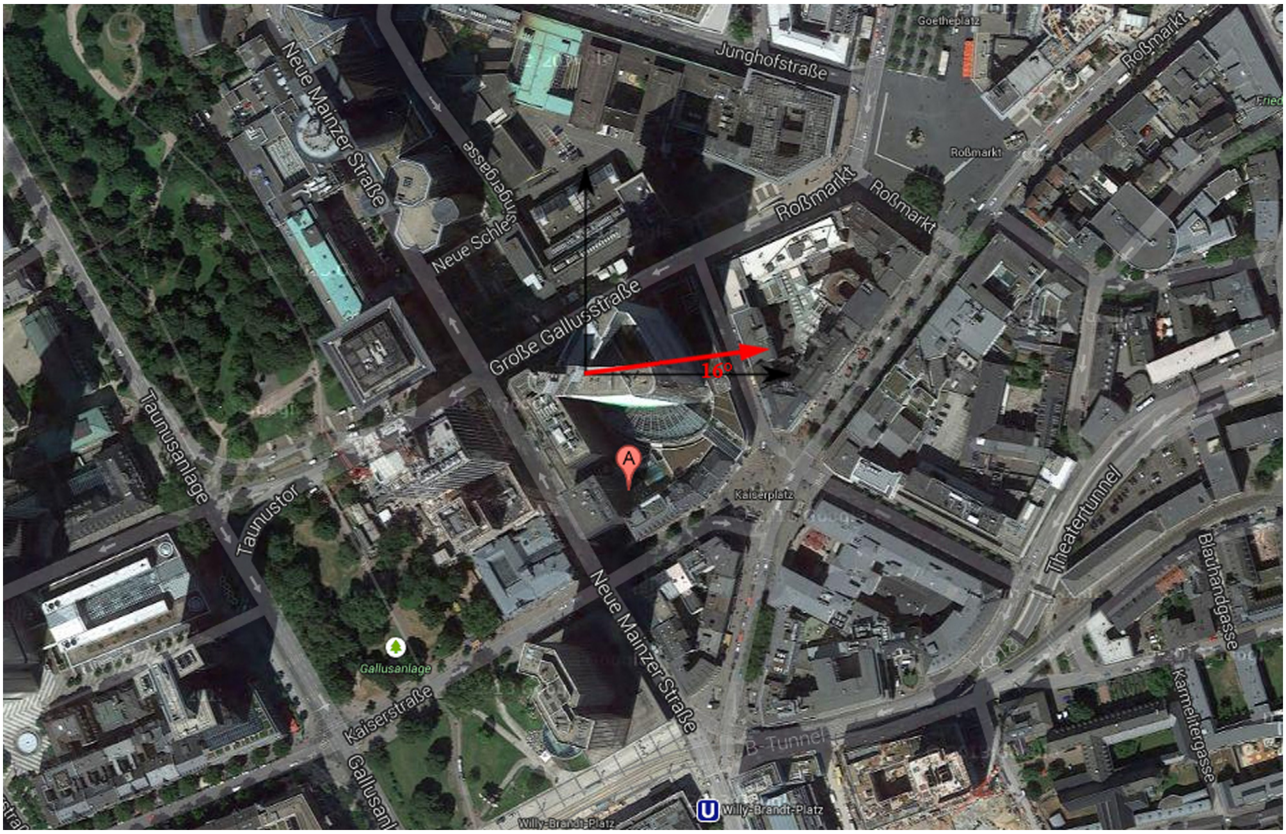


Fig. 8. Frankfurt Commerzbank Tower site orientation [50].

Fig. 9. Frankfurt Commerzbank Tower gardens [51].

Ignoring the necessity of supporting columns in gardens, the skyscraper, in contrast with the formal concrete was built with steel structure. However, the floors were constructed as a combination of steel beams and concrete slabs on metal panels. Apart from thick cores for vertical service movements, one of the fundamental principles of the building is the central void, which runs the full height of the building [45]. Related to that void, there is a sequence of gardens that help to improve both ecological aspect and good views for offices. So, the main idea was designing the triangular plan in order to move at all three corners.

However, in each floor, just two corners are offices and the other one is a garden (Fig. 5). But, the point is that gardens did not stay fixed on one elevation, they are nine, four storey gardens, which rotate all around the plan in such a way that all the offices are always in contact with one garden or another. Furthermore, ignoring the necessity of supporting columns in gardens, the skyscraper, in contrast with the formal concrete was built with steel structure. However, the floors were constructed as a combination of steel beams and concrete slabs on metal panels. This building has a double facade with adjustable solar shading, which will be discussed more.

These green spaces are part of the building total natural ventilation system. The fresh air comes in through the top of the gardens, and then moves up through the central atrium. Furthermore, the cross ventilation from the gardens in every three direction shows the adequate indoor air quality (Fig. 6).

It is estimated that the natural ventilation system will operate on average for about 60% of the year and the rest 40% of the year will be too cold, too hot, or too windy. With the automatic window system, the ventilation system will be down to 35% in comparison with the conventional fully mechanical air conditioned office

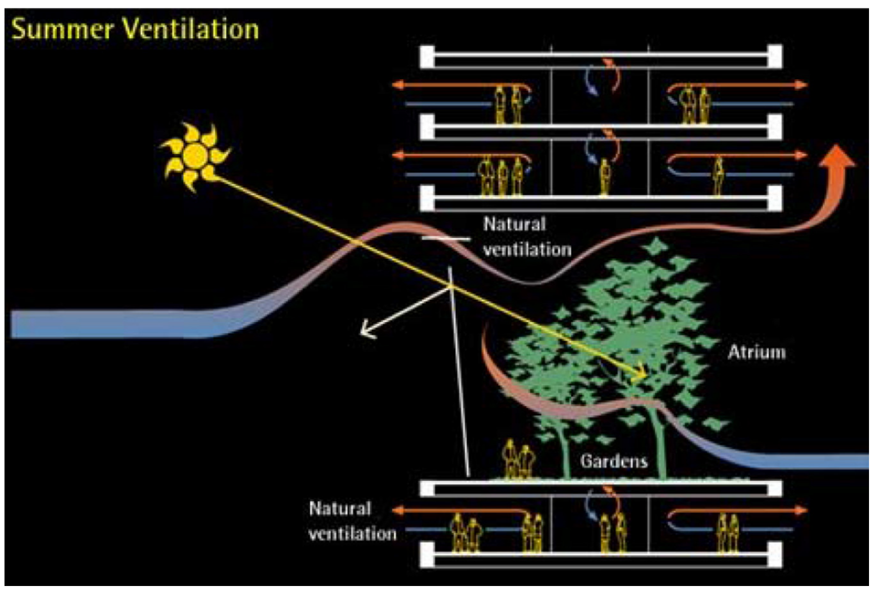


Fig. 10. Commerzbank Tower natural summer ventilation system [51].

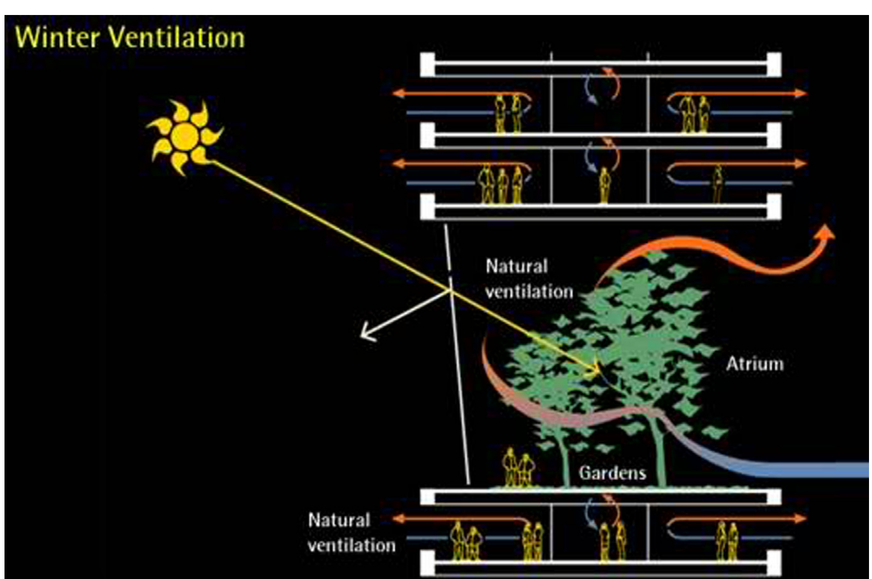


Fig. 11. Commerzbank Tower natural winter ventilation system [51].

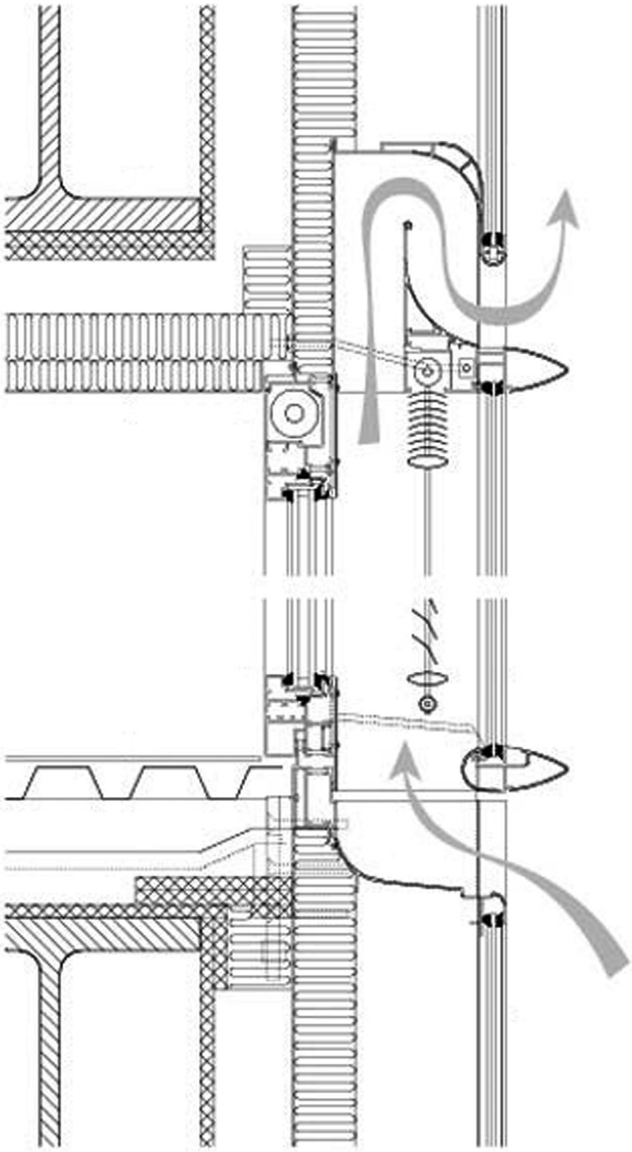


Fig. 12. Frankfurt Commerzbank facade system details [51].

high-rise buildings [47]. Therefore, very substantial energy saving is achieved.

3.1. Solar energy usage potential on high-rise buildings

This kind of energy can specifically be used in building sector as an energy source. However, this source of energy is considered as two parts:

- passive solar energy,
- active solar energy.

Although both strategies are important in building design, because of research limitation and case study considerations just the first one is analyzed in this study.

3.1.1. Passive solar design strategies

To take the advantage of solar design, the most basic response as mentioned before is the passive design. This type of design benefited from sunlight, almost without using active mechanical systems. This strategy uses solar radiations for heating, for instance, water, air, thermal mass, it may also cause air-movement used as heat exchange. Furthermore, the main objective of designing a passive solar construction is to benefit from the local climate. In this case, direct solar gain, indirect solar gain, isolated solar gain, thermal storage mass and passive cooling should be considered as passive solar design techniques in designing high-rise buildings. Thus, in this kind of solar design, constructions are considered to fully taking the advantage of solar gain without any intermediate operations. However, there are some conditions, which must be determined in order to access solar radiations. For example:

- Sun's position associated with building facades principles (solar altitude and azimuth),
- slope of the site and its orientation,
- obstructions, which exist on the site,
- over shadowing potential of outside obstructions elements.

3.1.1.1. Direct solar gain. This item mostly concentrates on the value of direct solar radiations, which are obtained in the living spaces. This type is an essential part of the passive solar design. A part of Sun's electromagnetic radiation is the sunlight, which is particularly visible – wavelengths between 390 and 700 nm – infrared and ultraviolet light [48]. Generally, whenever the clouds do not block the solar radiation, the gained combination of bright light and radiant heat, are called direct solar radiation. Otherwise, when it is blocked by whether clouds or other reflective objects, it is known as diffused light.

There are so many various factors and design features that are affecting this part. The main relevant ones are as follows; the construction's shape and layout, building's orientation, window's shape, size, orientation (daylighting), shading conditions and building's ventilation conditions [24,49]. In this part in order to analyze the effect of direct solar radiation, due to research limitation, the main attempt of the author is to evaluate the effect of the most meaningful factors, such as orientation, ventilation, daylighting and shading devices on the case study.

Therefore, in the Frankfurt Commerzbank Tower, the building architecture responds to predominant winds and solar orientation, to guarantee optimum ventilation and daylight penetration. The triangular shape of the skyscraper with the South-West orientation about 16°, cause it to benefit from maximum solar radiations and winds in all directions (Figs. 7 and 8).

Winter gardens, which directly gain solar radiations, spiral up around the atrium in order to become the visual and social focus for four-storey office clusters (Fig. 9). From outdoor views, these types of floating gardens in the sky, induce the sense of lightness and transparency to the tower simultaneously. Finally, they help the central atrium ventilation circulation, which is used as a kind of natural ventilation chimney, by providing fresh air and also light into it. Moreover, to make advantages of natural ventilation and daylighting, each office has operable windows (Figs. 10 and 11). It should be mentioned that, when the window is open, the ventilation, heating and cooling systems will be automatically shut off, which leads to more saving in energy section. Furthermore, it is estimated that the amount of saving in heating and cooling sectors in this skyscraper is nearly 20% [51].

3.1.1.2. Indirect solar gain. Its main purpose is controlling solar radiations, which are reached in an adjacent area that are not part of the building living space. Heat passes through windows into the building and thermal masses like masonry wall and water tank, trap and keep it and transmit it indirectly through conduction and convection to the building. At night, heat losses and slow response affect efficiency. Meanwhile, it should be mentioned that in this

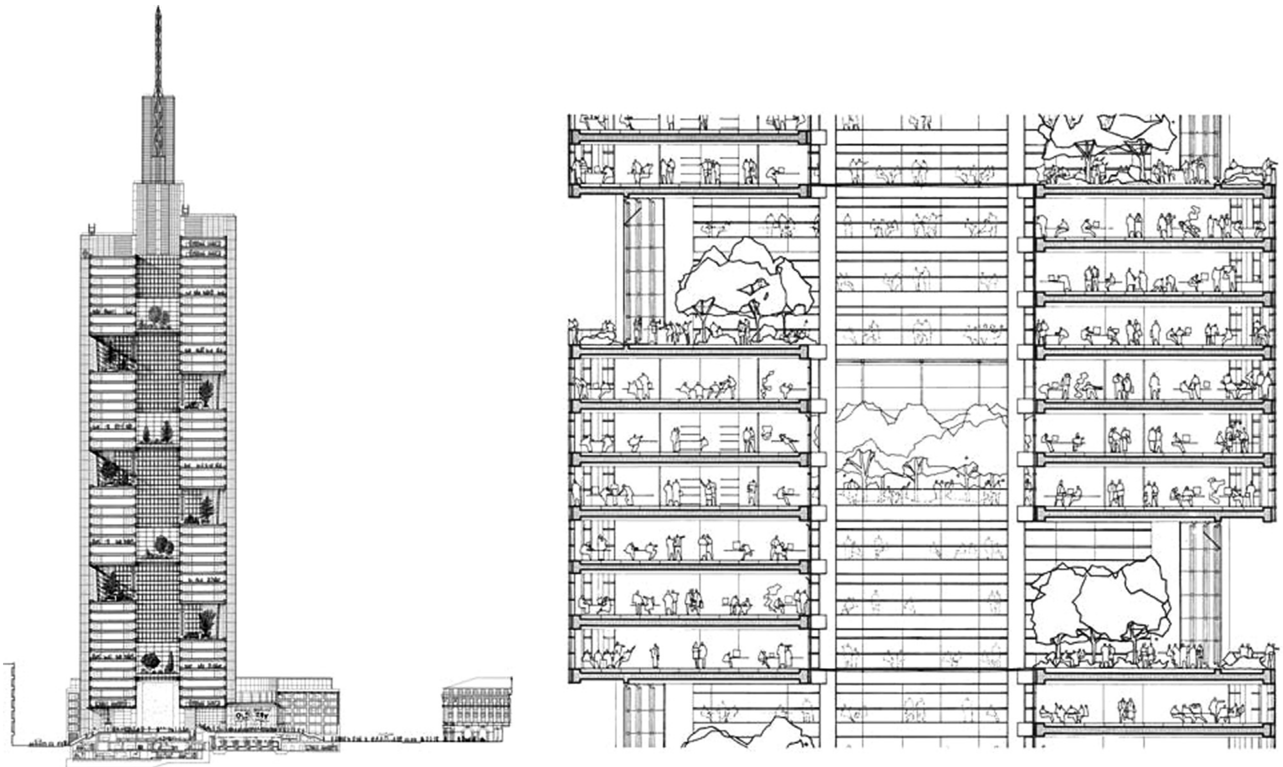


Fig. 13. The Frankfurt Commerzbank natural ventilation chimney [46].

Fig. 14. The Frankfurt Commerzbank Tower natural ventilation chimney supported by sky gardens [54].

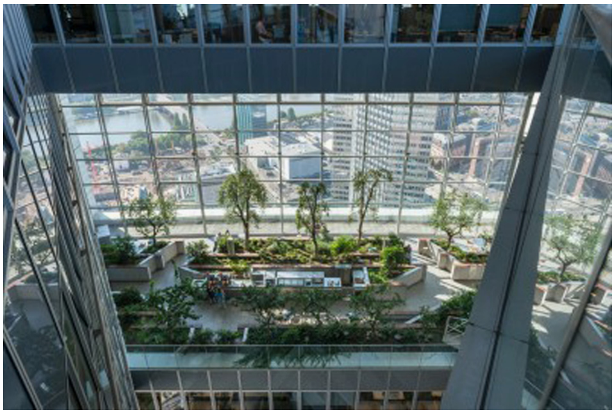


Fig. 15. The Frankfurt Commerzbank Tower sky garden (suggested place for using thermal storage mass flooring) [52].

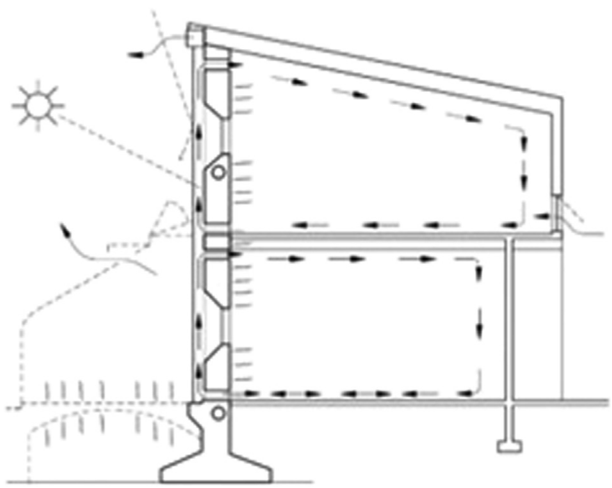


Fig. 16. Sketch of the Trombe Wall Principle [55].

building, most parts of the facades benefit from this effect and the parts, which cover the green spaces benefit from solar direct gain

The innovative facade system consists of three layers (Fig. 12). The inner layer, which is the main envelope, is a double-glazed hinged window. The outer layer is a fixed glass and the third layer is a cavity that lets the air flow inside at sill level and let it escape through a slot at the top of the window. Some blinds in the cavity cause the glare and solar heat gain in the office to reduce. Since these blinds are essentially external, unlike conventional blinds, they prevent heat from entering the building. Using this system makes it possible for the windows to be open even in driving rain or high winds. By improving thermal insulation properties of the windows up to 20% and natural ventilation the cavity caused Commerzbank to save 25–30% of the energy consumption [52].

3.1.1.3. Isolated solar gain. As it was explained, this factor focuses on passively transmit solar radiation heat to the indoor spaces by benefiting a fluid, such as air or water through natural convection or forced convection. There are so many methods and elements in order to benefit from the isolated solar gain. However, the most important one in high-rise buildings is using solar chimney and its effect. Passive solar energy heats the air through convection, which helps to improve building's natural ventilation.

Solar chimney or thermal chimney can simply be described as vertical shaft, which is utilizing solar radiations in order to gain the natural stack ventilation, especially through high-rise buildings. In other words, a solar chimney is one way to improve the building natural ventilation by using convection of air heated by passive solar energy. In its simplest form, the solar chimney consists of a black-painted chimney. Thorough the day, Sun radiations heat the solar chimney and the air within and makes it ascend. So, new air replaces it at the bottom of the chimney and causes cooling and ventilation [53]. The main point of solar chimney use is more beneficial in comparison with a wind-catcher in order to provide ventilation on hot windless days.

By considering vents on top levels of construction, natural air ventilation can be obtained. In other words, this system allows the warm air to go upward to the building exterior; while it leads the cool air to come down to the lower levels simultaneously. It is obvious that in order to have a better circulation, solar chimney must be built at least a little higher than the roof level. It should also be constructed on the south facade, which gains the most amount of solar radiation and this effect can be improved by benefiting a glazed surface on that side of the building. The size of the heat absorbing surface which can be used on the opposing side is more important than the chimney diameter.

In this case, the Frankfurt Commerzbank can be analyzed as a successful case study. Each office is benefiting from operable windows, which helps natural ventilation of the building almost throughout the entire year. As it was mentioned, four-storey gardens, which are located at different levels and directions, are actuated to provide fresh air into the central atrium, act as a natural ventilation chimney for the building. Moreover, central atrium and the triangular shape of the building plan helped to create a zone with negative pressure, which itself caused the building's natural ventilation (Fig. 13).

In this case, this high-rise building was designed in order to be naturally ventilated for approximately 60% of the year, with the mentioned gardens being helped by natural ventilation process. This attempt was expected to decrease building energy demand by up to 45% compared to an ordinary mechanical air conditioned office systems. Accordingly, post-occupancy studies have illustrated that this skyscraper in the reality consumes about 20% less energy than it was predicted, and this amount has been declining each year, since 2000. This is undoubtedly due to the building users, who benefited natural ventilation 85% of the year, while the designers had calculated 60% [52].

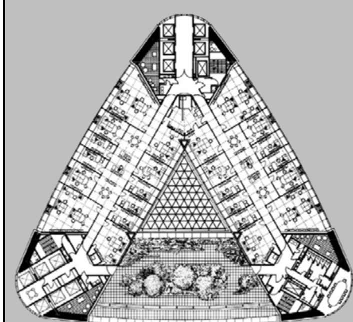
Furthermore, sky gardens are another important way of improving human enjoyment from the building, while simultaneously decrease the tower reliance on mechanical ventilation systems (Fig. 14). They are also a privileged social gathering space and provide fresh oxygen and absorb CO_2. This idea could be applied to any other building and decrease energy consumption up to 45%, like Commerzbank [52].

3.1.1.4. Thermal storage mass. It is not possible to benefit from the solar radiations every moment. Therefore, in these situations, thermal mass or heat storage can be a good solution. Unfortunately, this case is not meaningfully benefited from the effect of heat storage masses in its design. However, it must be noted that, in the Frankfurt Commerzbank as a case of ecological architecture, while this skyscraper makes so many positive gestures in order to be environmental friendly, still there is the possibility of going further.

Although a lot of natural light enters the building, there is no efficient thermal massing or other ways to store this free heat and give it to the building through radiation. Another way to lessen energy consumption is making garden floors of stone or tile instead of reflective surfaces. However, the weight of the above materials must be considered as a significant matter in designing high-rise buildings (Fig. 15).

In this case, in double skin facade system design, a transparent layer can be positioned in front of solid wall with a high thermal mass, which provides thermal insulation. Therefore, a considerable amount of solar energy is stored in the wall (Fig. 16). Solar beams

Table 1
The Evaluation of the Frankfurt Commerzbank Tower.

Passive Solar Energy in High-Rise Building						
Case Study				Frankfurt Commerzbank Tower		
Basic Information		Passive Solar Design Strategies				
		Direct Solar Gain			Indirect Solar Gain	
Passive Design High-Rise Building		Orientation	Standard Angles		3 Layers Facade System	Fixed Glass
			Actual Angles – Axies	South-West Direction		
Climate Zone	Temperate		Actual Angles – Angle	16°		
Function	mixed-use complex (Bank)		Orientation Consideration	----		
Location	Frankfurt / Germany	Shading Devices	Type	Not Applied		Cavity Layer Between them
Height	259m		Standard Size	Other Consideration: Sky Gardens		
Area	125,000m²		Actual Size			
		Daylighting	Consideration	Vast Transparent Windows		Double-Glazed Hinged Window
				Sky Gardens		
		Ventilation		Operable Windows		
		Effectiveness		More Than 20% Energy Saving	25-30% Energy Saving	
		Isolated Solar Gain		Thermal Storage Mass		Passive Cooling
		Central Atrium (Natural Ventilation Chimney)	Supported by:	Currently Employed: Not Applied	Active Solar Technology	Not Applied
			Operable Windows			
			Four-Story Gardens	Potential to Use: Using Thermal Mass Material in Facade System		
Effectiveness		About 45% Energy Saving		-----	-----	

pass through the transparent layer of thermal insulation and are absorbed by the dark surface wall; here 95% of the gained solar energy is converted into heat. While the transparent thermal insulation has been constructed in such a way that really prevents any heat loss, the solid wall absorbs the heat and gives it off to the neighboring rooms after 6–8 h [55].

The typical transparent thermal insulation materials include polymethyl methacrylate (PMMA), polycarbonate (PC) and glass. Very recently, cardboard honeycomb structures and sawn ‘wooden slats’ have been used [55]. Therefore, in order to select building elements, which are considered from performance requirements, knowledge acquisition and representation, ‘Building Elements Selection System’ (BES) can be used [56].

The table given below summarizes the effect of using passive solar strategies design in the Frankfurt Commerzbank Tower, which can be compared with ordinary high-rise buildings that do not benefit from these types of strategies.

4. Conclusion

As time passes, human beings gradually obtain a deep understanding of the reasons for their existence on earth, become aware of this fact that they must live responsibly and become conscious of their duty towards the environment as well. Nowadays, the necessity of living and thinking about energy efficiency in order to save inheritance and resources for our children and the next generations is mostly approved. This refers to every aspect of the natural environment and also building section. In order to create and develop sustainable society, one possible alternative is to consider saving energy necessity in the construction section. Although there is a great susceptibility in the construction section, there is no doubt that architects have come upon this issue late.

Architecture must be truly responsible for the present time and its special requirements. Meanwhile, high-rise building architects should follow up natural patterns and try to make a balance between the natural environment and human beings. This is in order to teach the profundities and beauties of the environment and also illustrate the physical and spiritual embodiment of human dignity. Thereby, the re-consideration of organic architecture should consider solar energy, could present new freedom of thought and also an expression of hope for the future in every aspect of life.

In this case, the Frankfurt Commerzbank was chosen from ‘Sir Norman Foster’ works as a role model in order to find the proper pattern for developing other cases, especially in developing countries. It has formed a new type of energy efficient skyscraper and has attracted worldwide attention. It also contests the widespread supposition that tall buildings and constructions are innately energy-inefficient and harmful to the environment. This high-rise building is iconic, and entirely deviates in major ways from customary buildings. It benefits the rules and principals of energy efficiency in skyscrapers, simultaneously combines the building construction and landscape in a dominant way throughout the entire structure.

Thus, to find new alternatives for building energy consumption, this study tried to analyze the way solar radiation can be considered as a source of renewable energy in order to reduce the high-rise building's energy demands compared with the use of fossil fuels. The research began with the hypothesis that simple solar design strategies have a significant effect on decreasing the total annual high-rise building energy consumption. However, sufficient attention has not been paid to them. So, in order to fill the gap caused by not being a proper evaluation of different aspects of solar energy in high-rise buildings, the research has reviewed the concepts and knowledge system of utilizing passive solar strategies on designing high-rise buildings.

Therefore, in brief, for analyzing the direct solar gain; orientation, shading devices and daylighting are considered as the main critical criteria. So, in the Frankfurt Commerzbank Tower, by 16° oriented to south-west direction and benefiting sky gardens and also the big size of transparent windows, which both lead to better ventilation, the amount of energy saving increased to about 20%. In order to understand the effect of indirect solar gain, the different multiple façade systems are analyzed. In the Frankfurt Commerzbank Tower triple layer facade system has a meaningful effect on the buildings' energy demands. So, the result illustrates that energy reduction is about 25–30% in this case (Table 1).

The next factor is isolated solar gain, which is better to be said the solar chimney effect. Thus, in this section, in the tower, central atrium is used as type of natural ventilation chimney, which is supported by operable windows and some kinds of green spaces as well. According to the analysis, the above factors can reduce about 45% energy usage in Frankfurt tower. Although this high-rise building has not benefited from the thermal storage mass capacity, it can gain this character by changing the green spaces floor with some kind of thermal mass storage materials. However, as the material weight is a meaningful factor in designing high-rise buildings, the more practicable suggestion is to apply these types of considerations in the facade system design.

Finally, high rise buildings and skyscrapers because of their vast facades benefit a great potential of gaining solar radiation. Analyzing the case study that benefits solar passive strategies reveals that applying these strategies has a meaningful effect on reducing annual energy demands. We can apply and adapt these strategies to high-rise buildings by using thermal storage mass, direct, indirect and isolated solar gain.

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