Analyzing Energy Efficient Design Strategies in High-rise Buildings with Reference to HVAC System

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Abstract: The Global Warming, Climate Change, Energy Depletion, and Carbon emissions are the greatest risks to humanity in the 21st century. Urbanization in many ways increases the lack of energy resources and demands more construction of high-rise towers for a better standard of living. Buildings are responsible for around one-third of global greenhouse gas emissions. With the emergence of the energy crisis, the rise of environmental consciousness, energy-saving measures, and sustainable buildings became a topic of attention. Due to advancements in technology, the design of high-rise buildings has come across various changes with large glass openings, sealed windows, and deep plans which increase the dependency on air conditioning systems (HVAC) thus increasing the demand for more energy consumption inside the building due to mechanical ventilation and air conditioning. In this paper, an attempt has been made to understand the strategies used for designing energy efficient high-rise buildings that can lower the heating and cooling load and thus increase the performance of the high-rise building. The research is based on a theoretical approach and qualitative analysis which is identified from the literature review and secondary case studies, Case studies selected for the study are office high-rise buildings which are sustainable skyscrapers and have achieved lower energy consumption in heating and cooling load compared to the typical office building which shows how an increase in natural ventilation and other architectural design parameters such as building envelop, form, orientation and integration technology like Building Management System (BMS) system can make it more energy efficient high rise building.
Keywords: high rise, energy efficiency, energy consumption, HVAC system, natural ventilation

1. Introduction

As cities cope with rapid population growth, adding 2.5 billion dwellers by 2050 and grapple with expansive sprawl, politicians, planners, and architects have become increasingly interested in the vertical city paradigm (Ali & Al-Kodmany, 2012). The high-rise buildings we see today are one of the results of the influence of science and technology which is measured as one of the trends in the development of high-rise buildings. As per NBC high rise building are 'A building up to 15m or above height'. A 'high rise building' or a 'tall building' is with a very small footprint, a small roof area, and a tall facade. The Council on Tall Buildings and Urban Habitats defines a tall building as "tall" based on its absolute height, its relative height to the surrounding, or its slenderness. The building heights of 200m, 300m and 600m as the thresholds for "tall", "supertall" and 'mega tall' status. Due to rapid population growth and massive urbanization, make a trend for the construction of high-rise buildings, which takes a lot of energy in various stages of construction, leading to the consumption of more non-renewable resources and carbon emissions. Therefore, a trend for producing energy from renewable resources, focusing on the energy performance of buildings making zero energy buildings or 'Net Zero Buildings' (Cangelli & Fais, 2012).

2. Factors Affecting the Energy Efficiency of High-Rise Buildings-

2.1 Architectural Factor

These are the elements associated with the design of the building. These elements include; constructing functions, spatial relationships, shape, height, and building envelopes (Figure 1). Building typology determines the variety of occupants and consequently has an instantaneous effect on energy consumption (Elotefy et al., 2015).

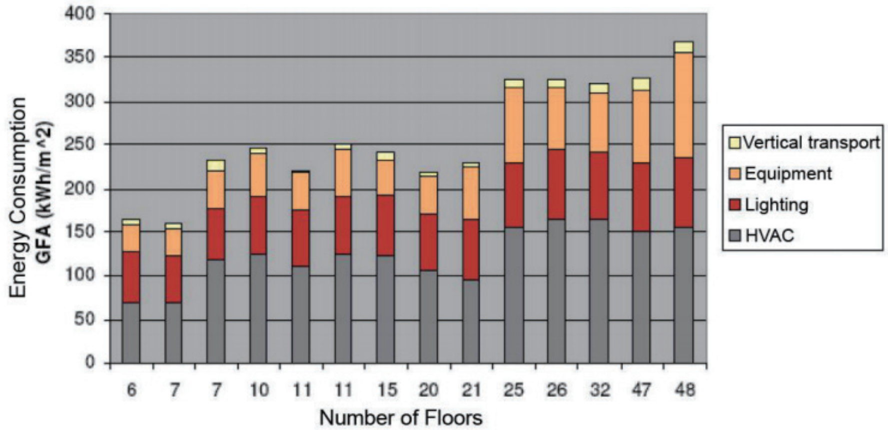

Figure 1. Energy consumption with a number of floors

2.2 Human Factor

They are the elements that relate to the person who owns the building, and the users. It includes 4 classes which might be the following: Laws and Regulations, Resident Behavior, Culture, and Economy.

2.3 Technology

The technology plays an important role in the energy efficiency of the building at various levels of construction and throughout the building performance. BMS (building management system) helps the building to operate automatically, controlling all the elements of the building to achieve more efficiency

2.4 Natural Factor

The natural factors such as climate impact the energy performance of the building and affect the heating and cooling load. At higher altitudes, the wind speed is which disturbs the opening of windows. Also at higher altitudes, high-rise buildings are directly exposed to the sun's radiation which increases the load of the HVAC system.

3. Energy Efficient Design Strategies

In this paper, the study aims to understand the strategies which are employed for the energy consumption on HVAC (heating and ventilation and air-conditioning) which take 30-33 percent and may vary on the climate of the region in the energy consumption of high-rise buildings which is more than any service in the building and also a study was done to analyze the strategies which will help in eliminating this energy consumption through mechanical ventilation and introduction of natural ventilation.(CTBUH Wood and Salib, 2013). Figure 2 shows the energy efficiency framework in high rise buildings and Figure 3 shows the average energy consumption in a typical rise-rise office building.

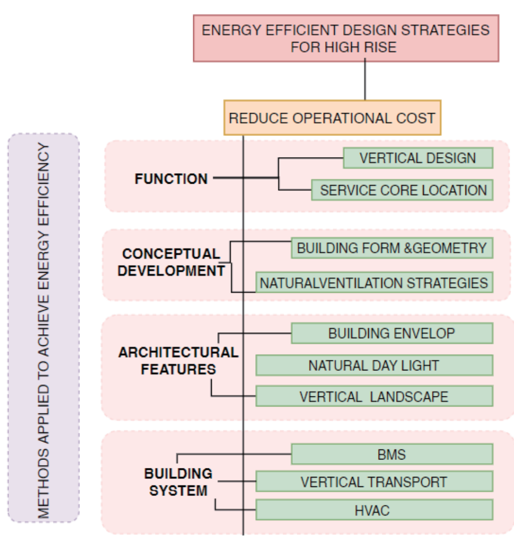

Figure 2. Energy efficiency framework in high rise buildings

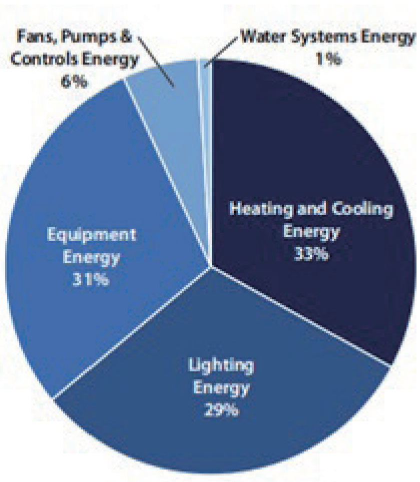

Figure 3. Average Energy consumption in a typical rise-rise office building

The energy efficient design strategies in high rise buildings are summarized as below:

3.1 Vertical design configuration

In a warm climate, the activities that require more energy for cooling load should be placed on the lower floor so that warm air above does not increase the energy consumption, while in a cold climate, a similar strategy to be adopted. In an area where a building is surrounded by skyscrapers the heat loss rate decreases with an increase in height, and then the function with high occupancy should be placed at a higher level, as shown in Figure 4 (Elotefy et al., 2015).

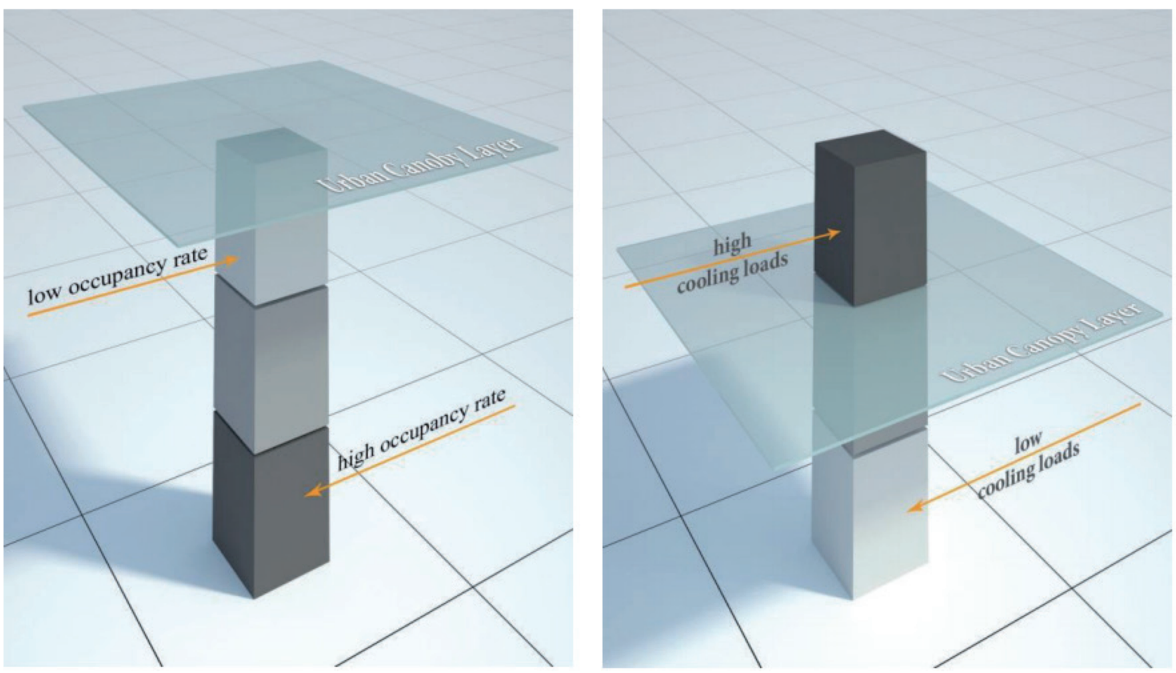

Figure 4. Vertical design configuration in high-rise buildings

3.2 Service core in high rise buildings

The location of the building service core plays an important role in the energy consumption of the building. The core located at the periphery of the building provides natural ventilation and light to all the services inside the core which reduce the dependency on artificial lighting and mechanical ventilation. The placement of the core is also done with an orientation of the building. The core in the west-facing facade serves as buffer space which reduces heat load, and also in temperate climates the core can be divided into two parts to increase the exposed surface area with natural ventilation and lighting

(Figure 5).

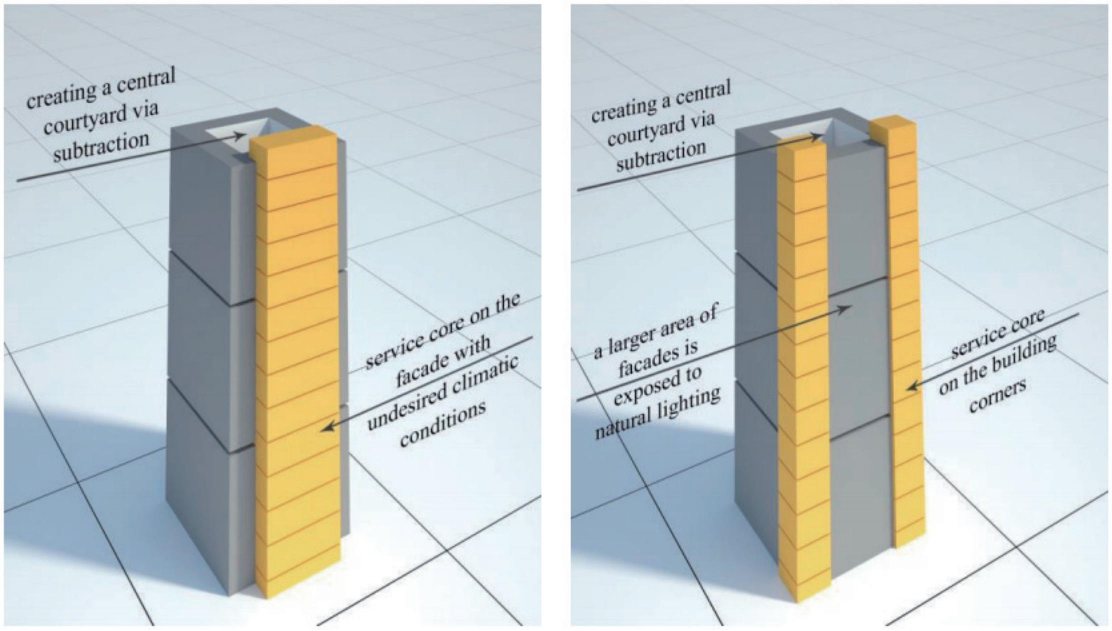

Figure 5. The location of service core in a high rise building

3.3 Conceptual development

Building Shape, Form, and Geometry: The degree of compactness, the ratio among the surfaces, and the quantity of the building, has a huge effect on power consumption. The more compactness, the better the power performance that may be done (Figure 6). The use of aerodynamic shapes reduces wind turbulence effect and waves around buildings, which reduce wind load on building shape and envelope. It additionally improves the natural ventilation. It additionally will increase the performance (Figure 7).

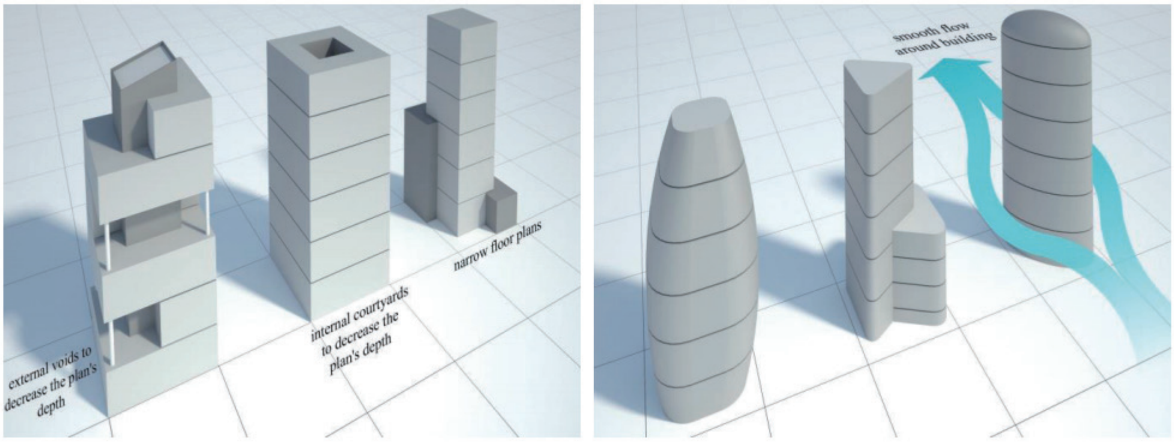

Figure 6. The impact of building shapes and aerodynamic form on energy consumption

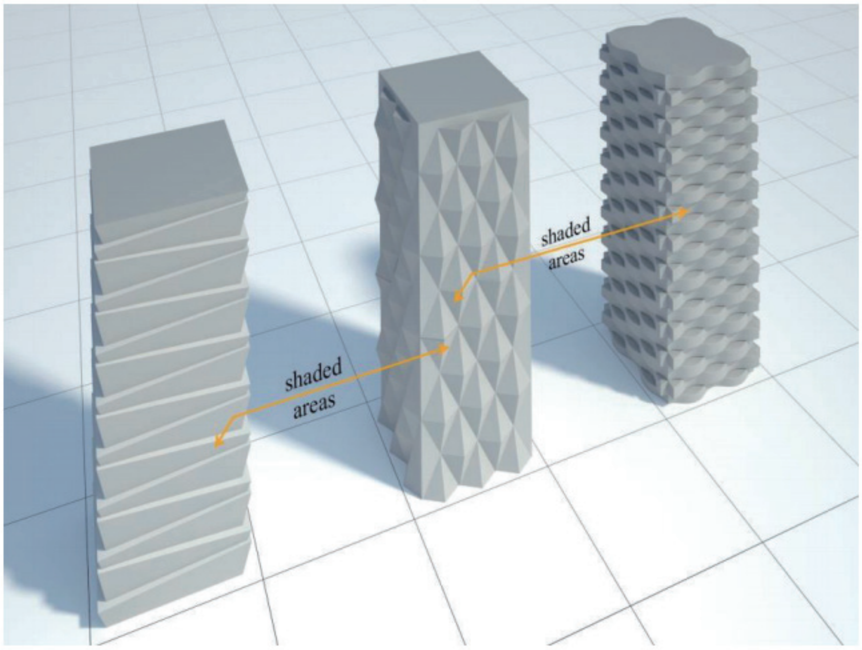

Figure 7. The impact of pattern on the building facade

3.4 Natural Ventilation in High-Rise Buildings-

Ventilation helps to make the indoor built environment healthier for the occupant. There are two types of ventilation in high-rise buildings natural ventilation and mechanical ventilation. A high-rise building cannot purely rely on natural ventilation, thus a hybrid type of system is used which is also called a Mixed-mode system which is works or changes over when external conditions are not favorable due to humidity, noise pollution, wind speed, or extreme cold or hot. Thus mixed-mode helps in the reduction of energy consumption of HVAC and space requirement for equipment.

4. Case Studies

4.1 Case Study 1: Commerzbank Frankfurt, Germany

The headquarters of Commerzbank is a 56-storey building, which is 259 m ecological tower located at Frankfurt, Germany (Figure 8). This office building was designed by Fosters and Partners and comprises of total area of 120,736 square metres. The building design responds to prevailing winds and solar orientation, to ensure optimum ventilation and daylight penetration.

Figure 8. The Commerzbank at Frankfurt, Germany

4.1.1 Key design features

A series of 4-storey sky gardens rotate every 120° up the entire building, providing not only ample space for the office users, but also provide daylight deep into the center of the building coupled with providing natural ventilation, with the open-able windows, to all office areas (Figure 9). The cooling is provided by chilled water ceilings, while heating is done in the perimeter radiant heating system. The windows are connected to the BMS to ensure that the mechanical ventilation only works when the windows are closed. Artificial lighting is connected to motion sensors and timers. The total annual period in which the building is naturally ventilated is 85%. (Foster partners).

Figure 9. The sky garden provides daylight deep into the centre of the building.

4.1.2 Natural ventilation strategy

The building has a triangular plan with a central atrium that runs the full height of the building but is divided into four segments, around which hang gardens and office spaces are there. The three corners of the triangle are the main structural elements and also a service core (Figure 10). The outward-facing office is directly ventilated due to a double-skin facade system which is made up of a solid sheet of laminated glass that deflects strong wind and rain. The cavity is ventilated at the top and bottom through continuous 125mm slots in the exterior facade. Small profiled strips are placed at the sills just above/below these ventilation slots to improve air circulation in the cavity (to capture the air flowing at the top or bottom of the front of the building and route it into the cavity) and avoid short-circuiting the air (Figure 11). The internal facade of the double skin facade consists of double-glazed hinged windows that open inward at the top with a maximum angle of 15°, thus allowing air from the cavity to flow directly into space (Figure 12). The inward-facing offices are ventilated by the increasing buoyancy of the stack in the central atrium, assisted by the wind moving from a windward garden to a leeward garden (Sev & Aslan, 2014).

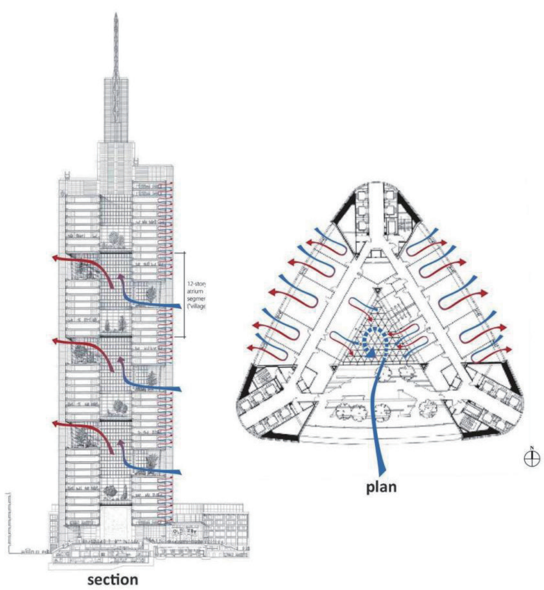

Figure 10. The plan and section of Commerzbank at Frankfurt, Germany

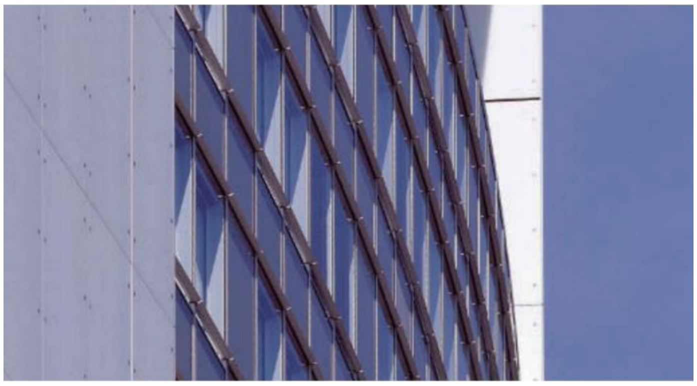

Figure 11. Detail of 125mm ventilation slot with aerofoil strip protruding top and bottom

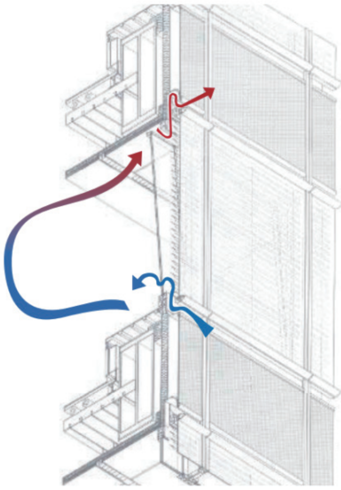

Figure 12. Double-glazed hinged window allows cool air from the cavity to flow inside

4.1.3 Energy performance

The BMS control unit controls the operation of motorized windows, shutters, cold ceilings, air conditioning and perimeter heating according to an 'intelligent algorithm' that changes modes for an optimal balance between occupant comfort and energy efficiency (Figure 13). While natural ventilation is achievable up to 80% of the year (+/5%), some areas of the building benefit from natural ventilation throughout the annual occupancy period (Goncalves 2010).

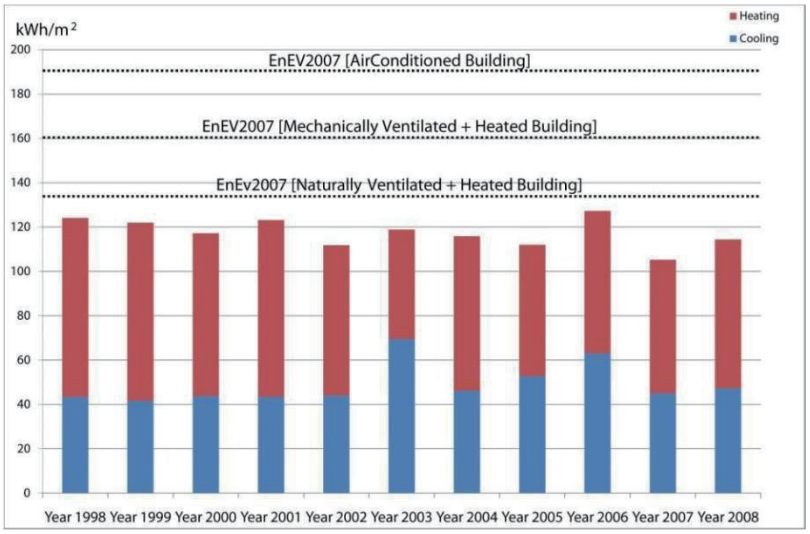

Figure 13. Annually energy consumption for heating and cooling

4.1.4 The HVAC system

The building was therefore designed with a Complementary Changeover system that alternates mechanical ventilation and natural ventilation on a seasonal (or even daily) basis. Overall, the building was designed to be ventilated naturally for about 60% of the year. be activated only in extreme conditions (i.e. when the wind is too strong or when the outside temperatures are too high or too low to allow the windows to open). On hot summer days, a water cooling system built into the office ceiling panels provides additional cooling (primarily for offsite occupant internal heat gains, as the air conditioning system provides cooling to the room), the air only at the design temperature of 26°C, but not lower. In winter, auxiliary heating is provided by thermostatically controlled panel radiators placed under the bay windows in the office areas (Figure 14) and under-floor heating in the sky gardens. (Davies & Lambot, 1997).

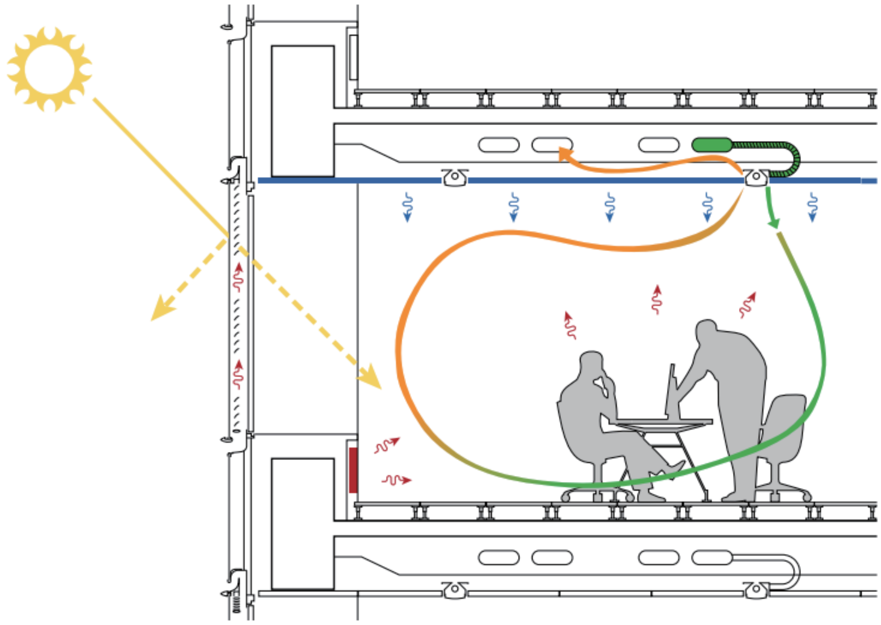

Figure 14. The HVAC system in the building both in winter and summer

4.2 Case Study 2: The Post Tower, Bonn, Germany

The 163 metre high Post Tower was designed by the German-American architect Helmut Jahn, who set out to design an office building for the 21st century, exemplary in terms of form, technology and environmental impact. It is a 42 storey office building, having a total built up are of 65, 323 square meters (Figure 15).

Figure 15. The Post Tower at Bonn, Germany

4.2.1 Natural ventilation strategy

The building is aerodynamically designed to create pressure difference which induces natural ventilation, for this a Computational fluid dynamic studies have been done to understand the wind flow and create cross ventilation from the central corridors from either side (Figure 16). The offices are ventilated through pivoting horizontal flaps which located in the outer skin of the double skin facade. Cross-ventilation draws the air through the offices into the corridor which is then exhausted into the nine-story atrium. Vents located at the top and bottom of the atrium facade contribute to the stack effect in the atrium, aiding in the exhausting of air from the building. Each office floor is cross-ventilated by bringing fresh air in from the double-skin facade and exhausting it into the sky gardens through vents in the raised floor system since the sky gardens are separated from the corridors with glazing (Wood & Salib, 2013). Additional vents at the bottom of each sky garden facade add cool air to aid stack effect within the nine-story space and vents at the top of each sky garden facade exhaust the air from the building (Figure 17).

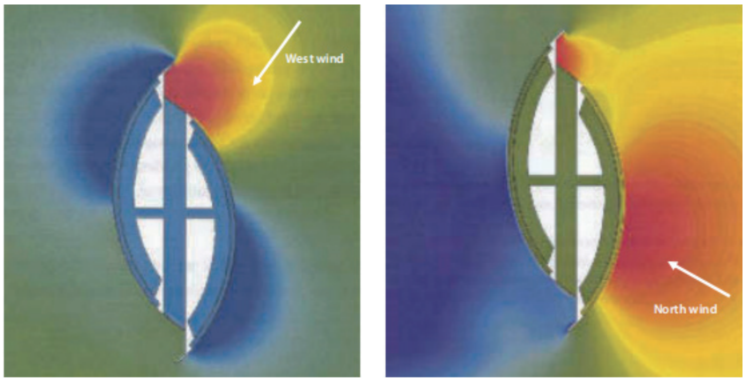

Figure 16. Computational fluid dynamic studies showing the effect of wing walls

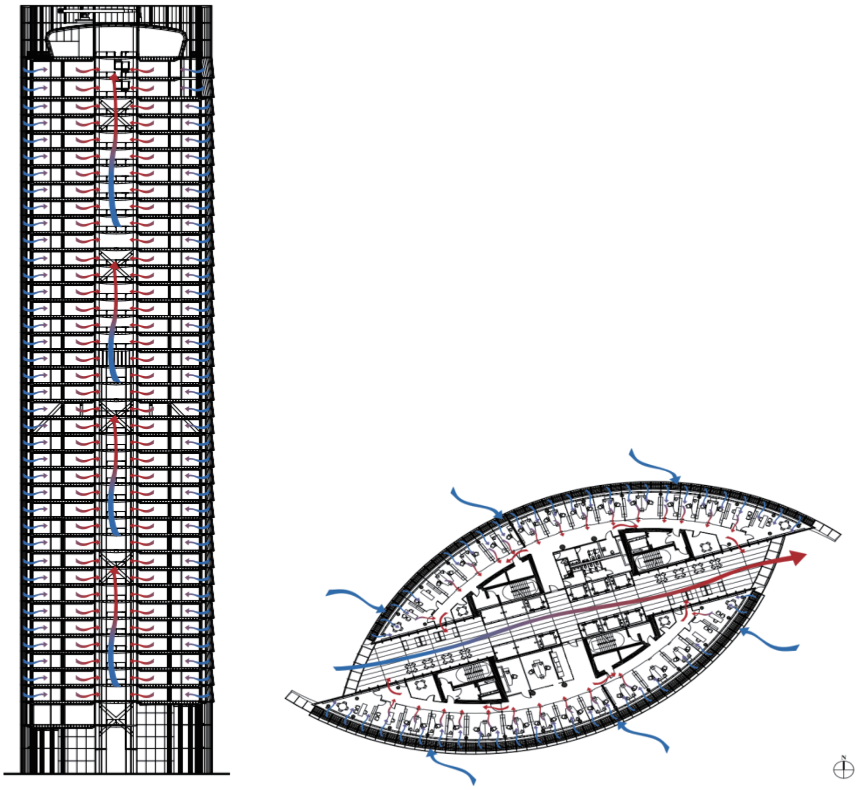

Figure 17. Plan and section showing cross ventilation and stack effect through the sky garden

4.2.2 Energy performance

The building was designed to use 65 kWh/m^2 for ventilation, heating, and lighting. The benchmark was an 83% reduction in energy consumption compared to a typical air-conditioned building and a 63% reduction compared to a 'good practice office building'. High-efficiency radiant panels, exterior solar shading, and the use of natural ventilation and decentralized mechanical conditioning effectively consumed 75 kWh/m^2 in 2003 (Figure 18). This is a reduction of 79% compared to a typical office building with air conditioning (Schuler, 2005).

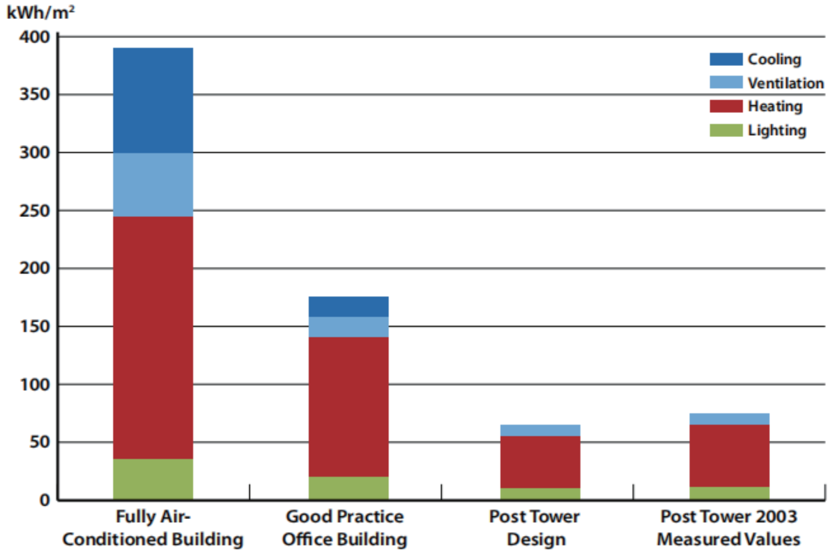

Figure 18. The energy performance of the Post Tower

4.2.3 The HVAC System

During the extreme periods of summer or winter, the thermal air conditioning of the offices is reinforced both by perimeter fan coils and by radiant ceilings. The perimeter fan coils are placed under the floor, adjacent to each other facade modules, and can be controlled individually in each office. The fan coils draw in the outside air from the double-walled facade and then heat or cool the air according to standard. During cold winter days, the air is heated in the double-walled facade (by supply of solar heat) before entering the fan coil of the unit. Additional conditioning is provided by exposed concrete radiant ceilings with integrated pipes that circulate fresh water (18°C) during summer and hot water (28°C) during winter. The Sky Gardens rely entirely on natural ventilation and are not mechanically ventilated. During most of the year, the only primary energy used for ventilation and general thermal conditioning is electricity to drive the water pumps for the radiant panels and the peripheral fan coils. During the cooling season, the fan coils and the radiant plate system both use an exchange of groundwater with cold water from the Rhine as a source of energy (Figure 19). This eliminates the need for additional cooling for the chillers. For heating, the energy source is district heating provided by the Municipality of Bonn, which is obtained from the waste heat produced by the production of electricity (Schuler, 2005).

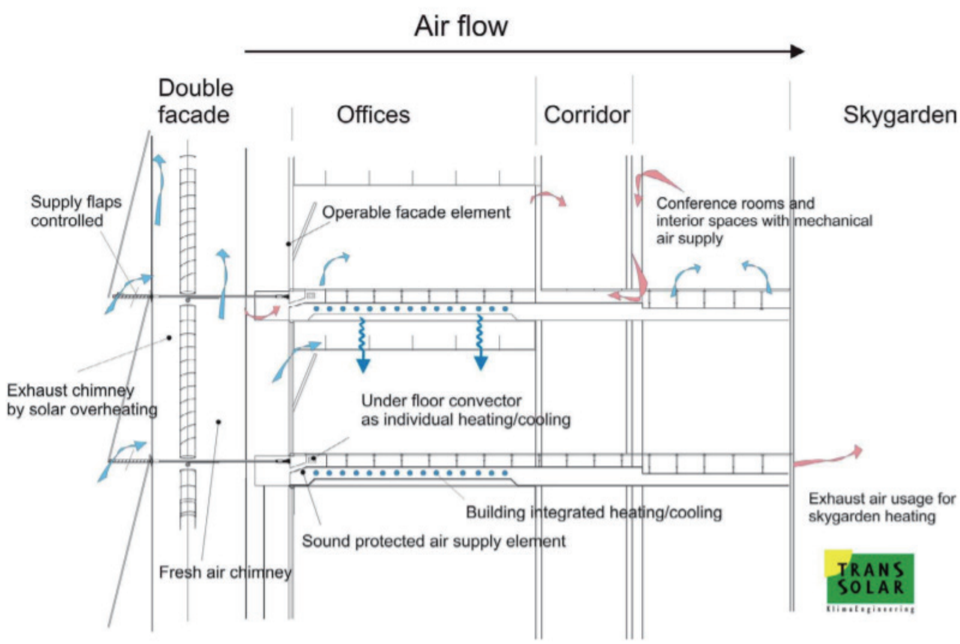

Figure 19. Sectional detail of the HVAC system of the Post Tower

4.3 Case Study 3: The 30 St Mary Axe, London

The 180 meters high 30 St Mary Axe is London's first environmental skyscraper having 42 floors. The architect of this iconic tower is Norman Fosters and Partners. It is located in the heart of the City of London; its distinctive shape is an instantly recognizable addition to the skyline and has already become a landmark in Europe's main financial hub (Figure 20). The tower embodies a very progressive strategic framework, with its streamlined shape that maximizes the amount of natural light and ventilation to significantly reduce the building's energy consumption. Equally important is its improved working environment with better views for everyone. A complete variety of sustainable measures manner that the construction will use 50% much less energy than a standard status air-conditioned workplace constructing. Fresh air is drawn up via the spiraling light wells to clearly ventilate the workplace interiors and minimize reliance on synthetic cooling and heating. The light wells and the form of the construction maximize herbal daylight, mild use of synthetic lighting fixtures and permit perspectives out from deep in the constructing.

Figure 20. The 30 St Mary Axe, London

4.3.1. Natural Ventilation Strategy

The curved aerodynamic shape of the building greatly facilitates the natural ventilation strategy. As the wind circulates around the tower, it accelerates, increasing the pressure differentials between the upwind and downwind sides for more efficient cross-ventilation, reducing downdrafts and causing less turbulence at street level (Figure 21). The circular arrangement greatly facilitates the natural ventilation strategy, increasing the pressure differentials between the upwind and downwind sides, inducing cross ventilation. Fresh air enters through the atria facing the wind and exits the atria facing the wind. Air also enters each six-story atrium and rises through the chimney effect. Each 'finger' of the desk thus receives fresh air from the adjacent hall. In addition to cross ventilation, the chimney effect is exploited through the overlapping spiral ear cups. Triangular-shaped windows placed on every other floor induce fresh air into the atrium where the air is tempered before being distributed in the offices (Figure 22). As each atrium wraps around the building, they take advantage of the high and low-pressure areas of the facade created by the wind currents circulating around the aerodynamic tower.

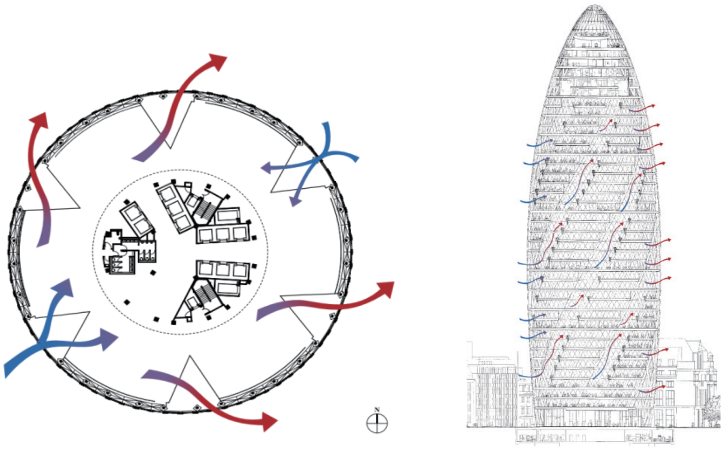

Figure 21. Plan and Section of 30 St Mary Axe

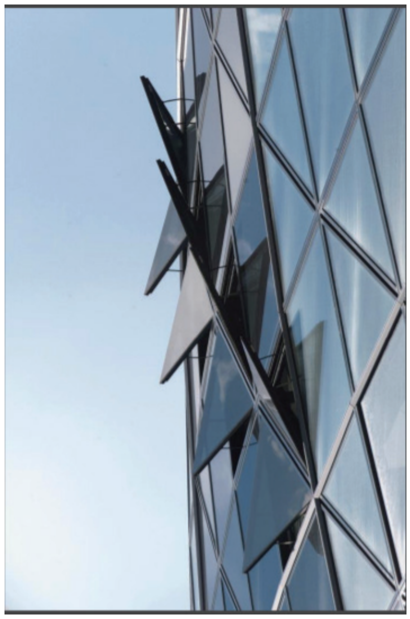

Figure 22. The external windows of 30 St Mary Axe

4.3.2 Energy Performance

At the design stage, an environmental assessment was carried out to determine the impact of the architectural design and the shape of the building on the natural ventilation strategy. The results indicated that the round and compact shape would have potentially resulted in 20% energy savings. Overall, the projected annual energy savings due to environmental design were between 30 and 50 kWh/m^2, compared to 250 kWh/m^2 for a similar fully air-conditioned office building in London, and the resulting reduction in CO2 emissions was between 30 and 50 kg CO2/m^2 per year. Studies have also shown a 60% reduction in suction typical of a rectangular building of equivalent volume. Predictive studies also found that the building's circular floor plan offered the possibility of longer periods of natural ventilation. Mary Axe can be ventilated naturally at 41 to 48% per year, depending on the outdoor climatic conditions and the layout of the open space office compared to the cellular one. of the year, while a cell arrangement with ventilation on two sides allowed natural ventilation for 48% of the year (Goncalves 2010).The results of the studies reveal that the building can be ventilated naturally for a longer period of the year with an office configuration maintaining the same standards of thermal comfort.

4.3.3 The HVAC system

The 30 St. Mary Ax is equipped with mechanical and natural ventilation to operate simultaneously as a complementary competitor system. However, when the outside conditions are too hot or cold, too windy or rainy, the building can be sealed, and the mechanical conditioning will be activated. The three upper floors of the tower (which house private dining and meeting rooms) are secluded and fully air-conditioned. The decentralized services on each floor separately (Figure 23). The air handling units (AHUs) contained in the false ceilings allow you to individually control each floor of the office or each "finger" of the office (divided by the halls). With air conditioning introduced and taken out floor by floor as needed, it allows the office environment to be easily

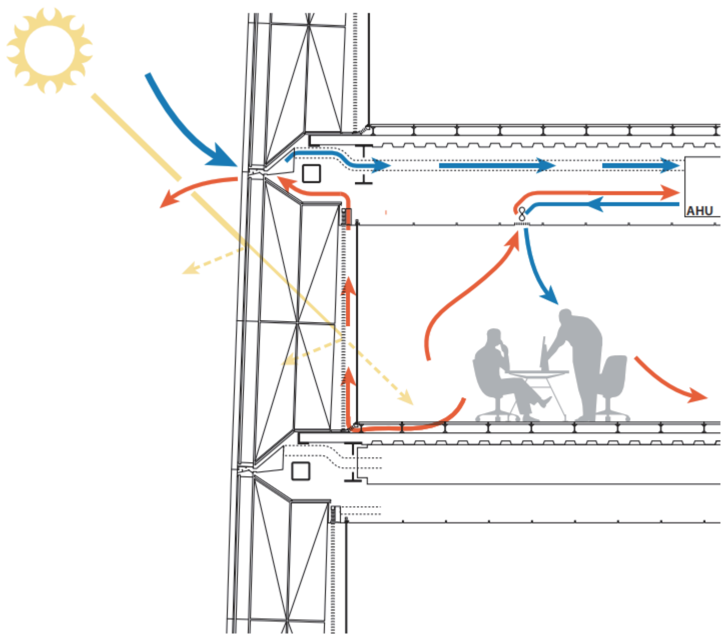

Figure 23. The HVAC system of 30 St Mary Axe

adapted and fine-tuned to user needs, thus optimizing energy consumption. (Massey, 2013)

5. Comparative Analysis

A comparative analysis of design strategies and energy consumption data for the three office buildings has been summarized as below (Table 1).

Table1. Design strategies and energy consumption data for the three office buildings

Name	Commerzbank, Frankfurt, Germany	Post Tower, Bonn Germany	30 St.Mary Axe, London
Height	259m	163m	180m
Floors	56	42	42
Gross Area	85500sqm	65323sqm	64470sqm
Plan Depth	16.5 meters (from central void)	12m from central corridor	6.4–13.1 meters(from central core)
Service Core location			
HVAC system	Water-based cooling system in the ceiling and thermostat radiant heating system in the wall periphery.	Decentralized A.C. through chilled water and hot water piping the concrete slab.	Decentralized A.C. system through AHU unit embedded in the ceiling for heating & cooling.
Mechanical A.C.+ natural ventilation	Mixed-Mode: Complementary Depending on weather conditions	Mixed-Mode: Complementary, Depending on weather conditions	mixed Mode: Complementary , Depending on weather conditions
Natural Ventilation Driving Force	Single sided and Stack Ventilation through 7-floor garden village space.	Cross and stack ventilation through the central corridor and atrium.	Cross and Stack Ventilation through connected atrium
Design Strategies to increase natural ventilation and decrease heating and cooling load	-Stepping sky gardens connected by segmented central atrium. -Façade -Small aerofoil sections above/below ventilation slots	-Central corridor divide in 9-story full height atrium as sky garden -Wing Wall -Aerodynamic form	Stepping atria which tempers air before being distributed to offices.
Double Skin Facade Thickness	Cavity Depth:200 mm	North façade-1200mm -south façade-1700mm	Cavity Depth: 1,000–1,400 mm
Greenery system	Segmented Central -Atrium and Stepped 4-Story Sky Gardens	Yes, three 9-story sky garden.	2-Story and 6-Story Stepped, Spiraling Sky Gardens.
Control of Openings	Automatically Controlled and Occupant Controlled	Automatically Controlled and Occupant Controlled	Automatically Controlled and Occupant Controlled
Night-time Ventilation	Yes	Yes	NO
Approx. % of year natural vent. can be used	80%	-	40%
Percentage of Annual Energy Savings for Heating and Cooling	63% compared to a fully air-conditioned German office building (measured)	79 % compared to a fully air-conditioned German office building (measured)	-
Typical Annual Energy Consumption (Heating/Cooling)	117 kWh/m^2 (measured)	75 kWh/m^2 (measured)	-

6. Conclusions

It is concluded that there are various impacts of high-rise buildings on the environment that need to be taken into account that has influenced the external surrounding of the building and also on its own internal environments. The research attempted to present the various impacts of high rise and further focused on the impact created due to HVAC systems in high-rise buildings. With the development of technology, high-rise buildings became sealed glass boxes with large openings and deep plans which increased the dependency on mechanical air conditioning, thus increasing the energy consumption of the building which is depleting the natural resources and releasing the greenhouse gas emissions from HVAC leading to Urban heat island and impact the environment, and with the mechanical ventilation also it affects the occupant comforts and creating various health issues such as Sick building syndrome and occupant comfort.

This paper focuses on the various energy-efficient design strategies that will make high-rise buildings more sustainable high-rise and reduce heating and cooling load thus increasing the performance of the building and also reducing the dependency on mechanical air conditioning systems as at higher altitudes of wind speed is high which restrict directly opening of windows in a high-rise building which needs to be designed for better energy performance. The extensive literature review and case studies of office sustainable high-rise buildings attempted to identify the design strategies that will reduce energy consumption on heating and cooling load with the addition of natural ventilation inside the building. In the case studies, it has been noticed that the annual energy consumption of the heating and cooling load is hitting less than the prescribed benchmark for fully air-conditioned and mixed-mode and has a high percentage of natural ventilation throughout the year which shows that the strategy used to have a major role in the energy efficiency of the building. The key elements which are identified from the case studies are that the building has a double skin façade, with a ventilated cavity, motorized blinds, an aerofoil section in the windows, a greenery system, night ventilation, and sky garden, additionally, the building is designed in such a way which induced cross ventilation and stack ventilation through used atrium and sky garden. The building is managed by the BMS (building management system) which regulates and controls all the opening and blinds and intake of fresh air and air conditioning system depending on the weather conditions and number of occupants which reduce the manual interference thus, increasing the energy efficiency of the high-rise building. The buildings. At the design stage, it has gone through energy simulations and a CFD model (computational fluid dynamic) study has been carried out to understand the solar radiation, and wind speed around the building so that it can be designed aerodynamically with the intervention of elements like "wing wall" in the Post tower and Wind Roof in GSW Headquarter which create pressure difference and induced cross ventilation. In order to reduce high-pressure differences inside buildings that develop stack effect the building has been segmented into sky gardens and atrium. From the literature review, it has been identified that building orientation, placement of service core, and building shape play an important role in the energy efficiency of high-rise buildings. In mixed typology, the building should be zoned, i.e. higher occupancy function should be placed on the lower floor in a hot climate and vice versa to reduce the energy demand of the HVAC system.

At last, there are various strategies that need to be incorporated in the high-rise building at various stages of design which will impact the overall energy efficiency of high-rise buildings not only on the HVAC system but also the overall energy consumption, thus reducing embodied energy and reducing the impact on the environment. Although there is a great susceptibility in the construction section, there is no doubt that architects have a huge impact. Architecture must be truly responsible for the present time and its special requirements for better efficient high-rise building, but a question arose whether we really need high-rise buildings, although there is a scarcity of land, which cannot be fulfilled with low rise building, the embodied energy consumed in the construction of high rise building cannot be called as sustainable building, this is the real challenge for the construction of high-rise in future with depletion of natural resources.

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