A Comparative Study of Design Strategies for Energy Efficiency in 6 High-Rise Buildings in Two Different Climates

Babak Raji¹, MSc          Martin J. Tenpierik¹, PhD          Andy van den Dobbelsteen¹, PhD
¹Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, the Netherlands

ABSTRACT

Due to the ever growing trend of urbanization and population growth, the construction of high-rise buildings is inevitable and will also continue at an ever increasing pace. However, typical high-rise buildings (the traditional template of a rectilinear, air-conditioned box) are not energy efficient in many aspects of their design. In this research the impact of architectural design elements on building energy performance will be studied through a combined literature review and case study research on 6 high-rise buildings with different degree of sustainability and located in two climate types, sub-tropical and temperate. The exterior envelope, building form and orientation, service core placement, plan layout, and special design elements like atria and sky gardens are the subject of investigation. This study found that a double-skin façade with automated blinds and operable windows besides a narrow floor plan, the correct placement of core services in regards to solar heat gains, and the application of vertical shafts like atria, which bring daylight and natural ventilation deeper into the plan, are the strategies that effectively can provide energy savings for tall buildings. However, when the building has this potential to use energy efficient design strategies, the real performance depends on how the building is used by the occupants. Designers should therefore take user behavior into account during the design stage.

INTRODUCTION

Urbanization, insecurity of resources and climate change are key challenges toward the future of cities (Dobbelsteen, 2012). As cities become denser and buildings become taller, sustainability may be at stake. Tall buildings are source-intensive due to the excessive scale and complexity of design (Cook, Browning, & Garvin, 2013). A wrong design strategy can lead to more energy consumption. This paper addresses design strategies that help a high-rise building to be more energy efficient in both a temperate and a sub-tropical climate. In order to have high performance tall buildings, first there is a need to reduce the building’s demand for energy and the most straight forward approach is to design them in a way that reduces their appetite for consumption.

METHODOLOGY

6 case studies with different degree of sustainability were selected from 2 climate types (temperate & sub-tropical). For each case, building-related energy performance data was collected through a literature review and contact with the energy consultants. This energy performance data of each group of buildings in one climate (3 cases) was compared to analyze the effectiveness of different design strategies for cooling, heating, ventilation and lighting in the specific climate type. Finally, energy-efficient design solutions were defined for both climates. The selection criteria for the cases were:

- Considered by one of the rating systems or standards as a high-performance building
- Availability of building-related energy performance data (metered or simulated)
- Newly constructed office building that has been occupied for two years with at least 15 floors

The difficulty with this kind of studies is that often the energy consumption data are neither measured nor
made publicly available. Therefore, it is always difficult to normalize all of the conditions between different cases. Sometimes, simulated energy data are the only source or internal conditions such as occupancy rate, building function and office equipment may vary among cases. Climate variations during different years can also influence the energy consumption. Therefore all of these conditions ideally should be accounted for when making the comparison. In this paper, the presented energy figures are delivered energy in kWh/m² of gross floor area, unless it is mentioned otherwise. For making the energy figures comparable, conversions were applied for some cases. The plan configurations and the energy performance data of the six cases are presented in Figure 1 & 2 respectively.

![Temperate Buildings](image1)

![Sub-tropical Buildings](image2)

**Figure 1.** Building orientation and plan configuration for the 6 buildings. Red color areas show the position of the service core and blue color areas present a vertical shaft like an atrium, a circulation void or an open void.

**Figure 2.** Energy performance data of the six cases. (S)=Simulated; (M)=Metered; the electricity consumption is just for lighting, pumps and fans. 1The EUI for the Commerzbank (Goncalves & Bode, 2010) and the Post Tower (S Reuss 2014, pers. comm. 19 May) were originally calculated based on the net floor area. To convert the figures from net to gross floor area an efficiency factor (net area/gross area) of 61% & 57% is considered respectively for Commerzbank and Post Tower. In addition a very small amount of the cooling load is combined with the electricity usage in Commerzbank building that should be negligible. 2The energy consumption at 30 St Mary Axe (N Clark 2014, pers. comm. 12 May) is simulated on two scenarios: a fully air-conditioned design on levels 16-34 and a mixed-mode design on levels 2-15. 3The energy consumption of the Liberty Tower (Kato & Chikamoto, 2002) is converted from primary energy to delivered energy with an average efficiency factor around 45.4% for power plants in Japan. 41Bligh Street (Yudelson & Meyer, 2013) building use a tri-generation system for combined cooling, heating and electricity generation. The
projected energy sources are gas and electricity. However, it is not clear how much is used to generate heat or lighting. 2Torre Cube (Wood & Salih, 2013) does not rely on an air-conditioning system for cooling, heating or ventilation. Therefore the energy consumption is zero in this building. The electricity consumption for lighting and equipment has not been published for this building. Therefore the predicted consumption is presented with a dashed line.

TEMPERATE CLIMATE

Cooling

Among the three case studies in the temperate climate, the Post Tower has the lowest energy use (from the grid) for cooling by around zero. Cooling is provided through thermally active ceilings and a decentralized supplementary fan coil system. Cold water from the nearby Rhine River and a sunk well is used as a source. Furthermore, the building is oriented based on the sun path with the long axis almost along east-west. The Commerzbank’s energy consumption for cooling is around 29.5 kWh/m$^2$. The building uses absorption chillers to generate cold water which is distributed through chilled ceilings. Natural ventilation throughout up to 80% of the year reduces the cooling need of this building. Both buildings have a double-skin façade with ventilated cavity and motorized blinds for solar control preventing excessive heat gains. Both buildings apply night-time ventilation and a BMS to control the operation of blinds and openings. The occupants can override this BMS to customize the climate to their desires. The Mary Axe building uses a decentralized air-conditioning system on each office floor. According to the simulation results, the cooling demand was lower when using natural ventilation in mixed mode zone compared to other one that was entirely air-conditioned. The total energy consumption of all of the 3 buildings is considerably less than of typical air-conditioned buildings.

Heating

Considering heating, the Mary Axe building has the lowest energy consumption. The air supply to the air handling units (AHUs) is provided by narrow slits between the glazing panels, then conditioned by the AHU and then distributed through adjusted ducts at ceiling level. Part of the exhaust air from the offices is used to ventilate the cavity inside the facade; therefore, in winter, the cavity will have a temperature similar to that of the indoor air, thereby reducing the heat loss through the envelope. Base on the simulation results of Mary Axe building, the heating demand is slightly higher when introducing natural ventilation into the building compared to a fully air-conditioned mode. The Post Tower can be ranked second best with an energy consumption for heating of around 30.8 kWh/m$^2$. The energy source is waste heat from electricity production (district heating). Furthermore, the deep cavity (120-170 cm) within the double-skin façade acts as a thermal buffer between the outdoor and indoor air. On cold winter days, fresh air firstly is warmed up in the double-skin façade before it enters the perimeter fan coil units; thus reducing the need for heating. The energy consumption for heating of the Commerzban is 42.5 kWh/m$^2$, higher than of the Mary Axe and the Post Tower. The energy for heating is provided by the local district heating network and is distributed through thermostatically operated radiators. The double skin façade of this building has the narrowest cavity (20 cm) among the three buildings. However, the window-to-wall ratio of this building is lower (around 58%) than of the other cases which are fully covered with glass.

Ventilation

All of the three cases use a mixed-mode ventilation strategy (natural ventilation + mechanical ventilation). However, the duration of natural ventilation is different throughout the year. With the help of architectural elements (central atrium and the sky gardens) and special plan configuration of Commerzbank, internal-facing offices can be naturally ventilated throughout the entire year. The outward-facing offices can also utilize natural ventilation up to 80% of the year. For the Post Tower, all of the working areas and communal spaces can be naturally ventilated with a combination of cross and stack ventilation. Only interior meeting rooms and conference halls are conditioned mechanically. The outer skin
of the façade is extended to create an aerodynamic form which increases the ventilation rate. In both projects, the double-skin façade is naturally ventilated and night-time ventilation is applied during summer. The office areas in the Mary Axe building are not ventilated directly through the façade. Fresh air first comes into 6 peripheral atria through small openings in the façade before this tempered air is distributed to the working stations. For the original design, it was predicted that the office areas could be naturally ventilated during 41-48% of the year. But with a change from owner occupation to multi-tenant occupation, most tenants rejected the energy-efficiency package with automated windows and choose for the year round air conditioning package instead (Wood & Salib, 2013). Because of the deep plan of this building, the central service core is mechanically ventilated. Besides, the cavity inside the facade is not ventilated with fresh air but with extracted air from the offices. Furthermore, the building does not use nigh-time ventilation.

**Lighting**

The Commerzbank has the highest electricity consumption (67.7 kWh/m²) among the case studies in the temperate climate. As it is not clear how much of this energy is used for lighting, it is difficult to determine the causes for this and might be derived from a prestigious design, more office equipment, higher number of occupants per square meter or architectural design features like window-to-wall ratio and plan depth. Considering the façade transparency, the Commerzbank has the lowest window-to-wall ratio of approximately 58%. This could mean that there is more need for artificial lighting. However, a full height central atrium and 9 spiral sky gardens bring a lot of natural light deep into the building interior. In the Post Tower around 85% of the working stations are located within 5 meters from the external façade. A considerable part of the office spaces therefore utilizes daylight reducing the energy demand for artificial lighting significantly. Furthermore, most of the meeting rooms and service spaces at the heart of the building are faced toward a central atrium and can therefore also be naturally lit. The office spaces can operate in stand-by mode when the rooms are empty. From the total electricity consumption, lighting is 6.2 kWh/m². In the Mary Axe building, the distance between the core and perimeter ranges from 6.4 to 13.1m depending on the floor size. This building thus has a deeper plan compared to the other cases. However, the problem of a deep plan is solved here with the help of 6 triangular atria along the building perimeter. All of the rectangular office fingers can be naturally lit from three directions. The big central service core should always be artificially lit due to its central placement. The total electricity consumption for lighting are respectively 26.4 and 29.1 kWh/m² for mixed-mode (levels 2-15) and fully air-conditioned (levels 16-34) zones.

**SUB-TROPICAL CLIMATE**

**Cooling**

Among the cases in a sub-tropical climate, Torre Cube has the lowest energy consumption for both heating and cooling (0 kWh/m²) because it does not depend on an air-conditioning system. Due to the mild climate in Guadalajara, buildings in this city can be naturally ventilated throughout the entire year if designed well. Solar radiation intensity, however, is very high in this area making sun-shading an essential additional strategy for passive cooling. Adjustable external screens protect this building from excessive heat gain in summer. The 1 Bligh Street building in Sydney is equipped with a hybrid tri-generation system that simultaneously generates heat, cold and electrical power. 500 m² of the roof of this building is covered with solar collectors that feed the absorption chiller to generate cold. Therefore, the building does not use electricity from the grid for cooling. Furthermore, the compact elliptical form has 12% less surface area than a rectilinear building of the same volume, thus reducing the heat gain/loss through the building envelope. In addition, a high-performance naturally ventilated double-skin façade with 60 cm cavity helps to reduce the heat gain through the envelope. However, there is some debate considering the land use and ecology of this building. The building’s orientation and configuration of plan are mainly derived from the urban grid and the desire to maximize the view, not from environmental concerns. While the service core
could have been used as solar buffer on the hot east and west side, it is placed on the south side (non-harbor side of the floor plate). The Liberty tower in Tokyo has an educational function, which because of high occupancy rates typically has a higher cooling demand than an office function. The building uses around 34 kWh/m² for cooling which is higher than the other two sustainable buildings. However, the 1 Bligh Street building’s dependence on renewable energy (solar energy) for cooling does not mean that the cooling demand of this building is less than of Liberty Tower. This building does not seem to be oriented environmentally. The majority of lecture rooms are facing (south)east whereas the opposite (north)west contains the majority of service areas. Vertical and horizontal concrete fins on the façade protect the openings from high solar gains in summer.

**Heating**

As mentioned before, Torre Cube has zero energy use for heating due to the mild weather conditions of Guadalajara. During the cold months (December and January) daily mean temperature is around 17°C. As a result, the internal and passive solar heat gains are sufficient to warm up the small interior office spaces. Liberty Tower’s heating load is around 40 kWh/m². The rectilinear shape of the building increases the surface area and therefore the heat gains/losses through the envelope. 1 Bligh Street building uses 73.7 kWh/m² gas to feed a gas-fired tri-generation system which generates electricity and useful heat. It is up to 50% more efficient compared to conventional grid-connected systems. From the waste heat, ‘free’ cooling and hot water can be generated. The office spaces are fully air-conditioned and separated from the atrium by glass walls. Extracted conditioned air from the offices is used to temper the naturally ventilated atrium. However building’s energy use for heating has not been published.

**Ventilation**

1 Bligh Street has two strategies for ventilation. The communal heart of the building is naturally ventilated but the working areas are fully mechanically ventilated. Natural fresh air is provided through an opening on the ground floor and a sky garden on the 15th floor and is distributed on all floors by stack ventilation in a full height atrium. The building is designed in a way that the perimeter cellular offices may potentially use single-sided natural ventilation if the interior glass panels are replaced with operable ones. But the deep floor plate does not allow for cross ventilation. With the help of natural ventilation, the annual cooling demand at Liberty tower was reduced by 17%. Two architectural elements that effectively have improved this natural ventilation strategy are the escalator void and a wind floor on the 18th floor on top of the circulation shaft. CFD analysis has shown that the wind floor increases the air flow rate by 30% (Kato & Chikamoto, 2002). As the escalator void is not segmented, there is a risk of extreme stack effect and draft inside the building. Furthermore, the introduction of fresh air directly into the working areas might provide discomfort especially for the occupants sitting near the air inlets. In the Liberty Tower cool fresh air comes in directly through the inlets below the fixed windows. The inability of the occupants to control their operation (fully controlled by a BMS) may limit their comfort and may result in user dissatisfaction (cold feet). The Torre Cube building uses different architectural elements to provide both cross and stack ventilation. Fan-shaped office wings help to funnel the air across the working spaces before it is exhausted through a central open void. Three open spiral sky gardens lead to a higher air circulation in the void. However, without a CFD analysis it is not clear if the sky gardens have a positive or a negative effect on buoyancy in the central void.

**Lighting**

1 Bligh Street has a fully transparent façade. However, in 1 Bligh Street just 30% of permanent working stations are within 5 meters of this façade. Due to this deep plan (23.5 m from façade to central void), there are three working zones between the building perimeter and the atrium. A central atrium and transparent partitions are used to increase natural light penetration. Temporarily used spaces such as meeting rooms are placed in the mid-zone. The figures of electricity consumption for lighting, fans and ventilation has not been simulated but the total delivered electricity is around 32.1 kWh/m². Torre Cube’s
electricity use for lighting has not been published. Because of a central void, the office wings in this building receive daylight from two sides, which allows for a deep office plan of about 9-12.5m. The electricity use for lighting and pumps of Liberty Tower is around 55.5 kWh/m². Considering the façade transparency, the Liberty Tower and Torre Cube have compared lower window-to-wall ratio than 1 Bligh Street.

EFFECTIVE DESIGN STRATEGIES FOR HIGH-RISES

General design strategies for high-rise office buildings

Concerning plan configuration, it is important to place the permanent work stations close to the envelope to reduce the need for artificial lighting. Dividing the internal zone into areas with different temperature is another important strategy that can reduce the cooling/heating load of high-rise buildings. Office workers expect a high degree of comfort in their work stations but tolerate a little bit of discomfort in lift lobbies and communal spaces.

Plan form and building shape (or compactness) can influence the amount of heat gain/loss through the envelope. Circular and elliptical forms have an exposed surface area that is respectively 25% and 12% less than of a rectilinear building of the same volume. Furthermore, an aerodynamically curved form minimizes wind turbulence and downdraft at street level.

Furthermore, the effectiveness of natural ventilation and daylight depends strongly on how the openings and solar shading devices are controlled. The absence of a central BMS might cause problems in attaining the right adjustments for providing indoor comfort conditions and may increase the energy consumption. Smart occupancy sensors cut down unnecessary consumption for lighting, and mechanical ventilation. In cellular offices, it is important that occupants can override the BMS to ensure their individual comfort. Psychologically, occupants with more control over their environment are more tolerant to high or low temperatures. However, the BMS should automatically switch off the air-conditioning system if occupants decide to open the window.

Design strategies for high-rise office buildings in a temperate climate

Façade transparency and plan depth are the two dominant factors with great influence on the electricity demand for lighting. A fully transparent façade is a common strategy in a temperate climate. However, it is important to provide a balance between the use of daylight, the solar heat gain in summer and the heat loss in winter. A double-skin façade with a deep cavity is an effective strategy for reducing the cooling and heating loads of high-rise buildings in temperate climates. A double-skin façade can act as a thermal buffer between the outdoor and indoor environment. Moreover, offices next to this façade can use natural ventilation for a longer period of time if fresh air first passes through the cavity in the double-skin façade before entering the offices. However, an effective ventilation strategy is highly needed inside this cavity especially during summer, otherwise the double-skin façade would act like a greenhouse and transfer a lot of heat into the building. Solar control devices within the cavity such as a motorized venetian blind allow for passive heating in winter, but prevent unpleasant glare and overheating in summer.

A mixed-mode (natural and mechanical) ventilation strategy can reduce effectively the energy demand for cooling and mechanical ventilation. Some architectural elements that can help the air intake, circulation and exhaust are sky gardens and vertical shafts like atria and circulation voids. When using a full-height atrium, there is a risk of high temperature differences and extreme stack effects and drafts. For controlling this excessive stack effect, a full-height atrium is usually segmented into smaller zones with lower pressure difference.

Design strategies for high-rise office buildings in a sub-tropical climate

In a sub-tropical climate, solar radiation intensity is high. Therefore the most effective design strategies are those that reduce the solar heat gain. Such strategies include limited façade transparency on the east and west side of the building, the placement of service cores on the hot sides (double-sided core on
east and west) and the extensive use of shading devices. Glazing type is usually double-glazing with low-e coating. Due to high solar radiation angle in these areas, it is also important to shade the roof surface and utilize energy generation systems like solar collectors or PV panels.

Placing the work stations along the north and south façade is a good strategy for reducing the electricity demand for artificial lighting. However, the size and position of openings should protect the occupants from direct solar radiation and glare. Using external shading and indoor blinds improves the quality of daylighting. As in a temperate climate, natural ventilation is also an effective solution for reducing the cooling demand in a sub-tropical climate. However, introducing humid outdoor air may reduce thermal comfort of the occupants as a result of which constant humidity control is an essential element of such a strategy.

CONCLUSION

Design strategies for tall office buildings were investigated through a comparative study of 6 high-rises in a temperate and a sub-tropical climate. The total energy consumption of all of the 6 selected cases are considerably less than of typical air-conditioned buildings. This research explained the most effective design strategies that sustainable high-rises using them to reduce the energy consumption for cooling, heating, ventilation and lighting in both climates as the summery is presented in Table 1. It is found that a double-skin façade with automated blinds and operable windows besides a narrow floor plan, the correct placement of core services in regards to solar heat gains, and the application of vertical shafts like atria, which bring daylight and natural ventilation deeper into the plan, are the strategies that effectively can provide energy savings for tall buildings.

| Table 1. Comparison of the design strategies and the energy performance for the six cases. |
|----------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **Temperate**                          | **Sub-tropical**                | **Design**                      | **strategies**                  |
| **Double-skin facade**                 | +                               | +                               | NA                              |
| **Deep cavity**                        | -                               | +                               | NA                              |
| **Ventilated cavity**                  | +                               | +                               | NA                              |
| **Natural ventilation**                | +                               | +                               | +                               |
| **Night-time ventilation**             | +                               | -                               | +                               |
| **Shading devices**                    | +                               | +                               | +                               |
| **Narrow plan**                        | +                               | -                               | -                               |
| **Energy recovery**                    | +                               | +                               | +                               |
| **Energy absorption**                  | -                               | -                               | +                               |
| **Environmental orientation**          | +                               | +                               | -                               |
| **Greenery systems**                   | +                               | -                               | -                               |
| **Annual EUI (kWh/m² gross floor area)** | 139.7 (kWh/m²)  | 63 - 73.6 (kWh/m²)  | 42.8 (kWh/m²)  | 129.5 (kWh/m²)  | 105.8 (kWh/m²)  | -0- Excluding electricity |
ACKNOWLEDGMENTS

We thank the architects and engineers who responded with case-study information specifically Mr. Nigel Clark, the technical director of HilsonMoran Company by providing detailed operation data of the Mary Axe building.

REFERENCES


