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Sustainable Tall Buildings: Summary of Energy-Efficient Design

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Abstract Tall buildings are frequently decried as unsustainable due to their excessive energy usage. Early skyscrapers used natural light and ventilation to facilitate human comfort and applied organic materials such as stone, glass, wood, concrete, and terra cotta for cladding and finishes. With the advent of fluorescent lighting, modern heating, ventilation, air-conditioning (HVAC) systems, and thermally sealed curtain walls, tall office buildings no longer had to rely on natural light and ventilation to provide comfort. Energy efficiency was not a significant factor when the operational costs of buildings were relatively inexpensive. However, today's skyscrapers must become more energy-efficient and sustainable due to energy crises and climate change. This paper highlights vital energy-efficient design principles and demonstrates with illustrative case studies how they are applied to tall buildings in various parts of the world. It shows how sustainable environmental systems do not act alone but are integrated with advanced curtain wall systems, sky gardens, and atria, among others, to regulate and sustain thermal comfort and conserve energy.

Keywords Energy saving, Daylighting, Natural ventilation, Intelligent technologies, Renewable energies

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1. Introduction

1.1. Background

Energy efficiency is among the most important contributors to the sustainability of tall buildings. Tall buildings inherently require large amounts of energy, typically from non-renewable fossil fuels, to run large boilers and chillers for mechanical heating and cooling and electrical systems for communications technology, lighting, and building management system (BMS). While conventional mechanical, electrical and plumbing (MEP) systems have become more efficient, sustainable tall buildings often augment them with alternative energy-efficient technologies integrated with other building components and systems to achieve high performance. Today, many architects are committed to designing the so-called "zero energy" buildings that are self-sustaining and require virtually no outside energy resources. This goal, while laudable, remains somewhat elusive. However, skyscraper designers can still achieve substantial reductions in energy consumption using a combination of conventional and alternative technologies.

1.2. Objectives and Scope

Collecting data on the annual energy consumption of a tall building may seem like a simple task. However, finding relevant data and evaluating and verifying tall buildings' actual energy efficiency performance is challenging (Ding et al., 2020). It becomes more complicated when we have to break down the energy used by each system, such as the heating, ventilation, air-conditioning, lighting, pumping, computing, elevators, etc., and the contribution of passive systems. Understanding fully the complex energy demands of tall buildings is elusive with many factors to consider, such as climate data, integrated building systems, and occupancies, to name a few. As such, due to the absence of needed data on buildings' actual energy performance, this paper does not evaluate the energy performance of tall buildings. Instead, it surveys and presents an overview of innovative ideas that lead to energy efficiency.

The paper aims to:

- Raise awareness of the importance of low-energy building design
- Summarize energy-based design principles
- Highlight key lessons on operational energy efficiency
- Examine exemplary, energy-efficient tall buildings

2. Energy-Efficient Design Principles

Three primary categories can be used to classify energy-efficient design principles, including Architectural Design

Concepts, 2) Mechanical, Electrical, and Smart Systems, and 3) Renewable Energy.

2.1. Architectural Design Concepts

The starting point of any design is to engage passive strategies, which aim to take advantage of what nature (sunlight, air, rainwater, etc.) offers for free to keep the building's environment comfortable, reducing the need for mechanical and electrical systems, such as HVAC. Passive design empowers natural ventilation and daylighting and improves thermal performance at minimal costs. Examples include using building materials of high thermal performance, boosting building insulation, integrating operable windows to facilitate natural ventilation, reducing lease span[1] and orienting the building to the Sun's seasonal paths to maximize natural light, employing landscaping features such as trees, plants, and water bodies to generate cool breezes, and integrating green roofs and living walls as a means of improving insulation and microclimate (Ali et al., 2008; Beedle et al., 2007; Hoseinzadeh et al., 2021; Yeang et al., 2007).

2.1.1. Façade Design

In tall buildings, facades are more towering and extensive than in ordinary buildings. Therefore, their design is paramount. Depending on the climate, costs, and height, architects choose between Single-Skin Façade (SSF) and Double-Skin Façade (DSF). The former is much cheaper and may work well in a moderate climate. SSF can benefit from integrating operable windows and shading devices to ensure comfortable interior environments. Also, double and triple glazing can improve thermal insulation. However, DSF could significantly save on cooling and heating in places with high-temperature fluctuation, especially for office buildings. DSF entails building a double façade with a cavity in between, ranging from several centimeters to a few meters. Larger cavities improve building insulation, empower stack ventilation, and facilitate walkable spaces used by a maintenance crew. Shading devices can also be placed in cavities. The outer skin could be a single layer of glass, while the inner skin could comprise double or triple layers. In both SSF and DSF, low-E glass (which contains a microscopically thin coating that is transparent and reflects heat) is used to improve thermal performance (Chew et al., 2022; Oldfield et al., 2009; Aminmansour et al., 2010).

2.1.2. Service Core

The service core is often placed centrally in tall buildings to boost circulation efficiency. However, to decrease the cooling and heating loads, the service core or a multiple of it could be located near the perimeter of the building, amenable to high solar radiation exposure in a hot climate and cold wind in cold temperatures. For example, the National Commercial Bank in Jeddah, Saudi Arabia, places the service core outside to insulate the building from the hot, harsh sun. Similarly, Torre Reforma in Mexico City limits solar heat gain with its concrete shear walls (Ali et al., 2008, Memon et al., 2020; Tarboccuo, 2008).

[1]Lease span is the distance from the core face to the inside face of building enclosure, which is important for leasing.

2.1.3. Atrium

In the absence of technology, early tall buildings employed atria to facilitate natural ventilation and boost daylighting. To reduce energy consumption, today, atria can be employed. As early as 1967, John Portman integrated a magnificent atrium in Atlanta Hyatt Regency in Atlanta, GA. More recent examples of buildings include Zaha Hadid's Leeza SOHO (the world's tallest 190-m (623-ft) atrium) in Beijing and 1 Bligh Street in Sydney, Australia, by Ingenhoven Architects (McCall et al., 2017).

2.1.4. Building Materials

The thermal mass property of a material inside a building can help reduce temperature fluctuations, thereby reducing the heating and cooling demand of the building. Extreme hot and cold climate zones could better exploit the thermal mass property of the material. Using concrete for tall residential, commercial, and multi-use buildings can passively save energy in buildings. Other parameters, such as slab thickness and thermal mass distribution, could also be considered to demonstrate broader implications and benefits of thermal mass in different climate zones (Wimmers, 2017).

2.2. Mechanical, electrical, and intelligent systems

2.2.1. HVAC

Manufacturers of air-conditioning appliances have developed high-performance, energy-efficient appliances -- these have EPA-certified ENERGY STAR labels on them, for example. For any HVAC, the airflow distribution system is of vital importance. When the air distribution is well designed, it will result in energy efficiency and occupant comfort. The use of an underfloor air distribution system (UFAD) is one of the most efficient HVAC systems. It has several advantages over the traditional overhead system, such as raised access floors for environmental control and improved access to building services. It also improves the ventilation system causing high-quality airflow. Its layout reduces frictional losses in the system and a consistent temperature throughout the building (Gui et al., 2021; Al-Kodmany, 2018).

2.2.2. Cogeneration System

Also known as Combined Heat and Power (CHP), cogeneration system is a very efficient energy-saving technology. Also, its application is suitable for tri-generation systems. CHP allows concurrent production of heat, power, and, infrequently, chilled water for air-

conditioning. An advantage of it is that, unlike conventional systems, it averts transmission losses as electricity is produced near the point of use. The simultaneous generation of power and heat enables overall thermal efficiencies, reducing a significant amount of fuel. Efficiency and operational time are enhanced further by adding a boiler system or another heat storage medium. The generated electricity can be used by a facility or transferred into a public power grid. The heat energy can be utilized for heating water and producing steam. Consequently, this system reduces fuel consumption, costs, and CO_2 emissions (Aristodemou et al., 2018; Mahian et al., 2020).

2.2.3. Vertical Transportaion

Elevators consume considerable energy. Engineering advances and research have been making innovative means to improve their efficiencies. Examples include A.C. motors, gearless motors, regenerative drives, nano ropes, TWIN and double deck systems, and destination dispatching Systems. A regenerative elevator harnesses the power of descending cars to power ascending ones. The double-decker elevators in the Petronas Towers in Kuala Lumpur have doubled the ridership of single-decker elevators to improve energy efficiency. With the destination-oriented system, the building's tenants and visitors enter their destination floor at the central lobby booth and group them going to the same floor, thus reducing travel time. This arrangement saves energy and reduces the number of elevators, opening additional floor space for renting and other purposes (Al-Kodmany, 2015).

2.2.4. Intelligent Systems

Contemporary tall buildings use many sophisticated "smart" or intelligent technologies and systems that include high-performance curtain walls controlling and regulating daylight and ventilation, high-efficiency HVAC systems that provide thermal comfort in different seasons and climate zones, as well as other energy systems like PV panels, geothermal heating and cooling, and wind turbines. These systems can be combined with sky lobbies, sky gardens, and atria, creating indoor microclimates and informal human interaction within tall buildings (Ding et al., 2020).

2.3. Renewable Energy

2.3.1. Wind turbine

Wind can be used as an energy source at higher heights of tall buildings where wind speed is powerful. Tall buildings can be shaped to funnel wind into a zone containing wind turbines. Examples include the Bahrain World Trade Center (BWTC) in Manama, Bahrain, and Pearl River Tower, Guangzhou, China. However, fewer tall buildings have incorporated wind turbines due to generated noise, structural stability concerns, high maintenance, and small return on investment (Škvorc et al., 2021).

2.3.2. Photovoltaic

Photovoltaic (PV) cells convert light into electrical energy. Commercial PV cell performance has been steadily improving depending on the type of cell and density to permit the transmission of sunlight. Furthermore, PVs are being integrated with other materials such as glass. Applying PV technology for high-rise buildings can be significant as these structures offer direct sunlight if neighboring buildings do not overtower them. The disadvantage of PV technology is the massive power required to produce them, the source of which is fossil-based fuels. Moreover, strict management and recycling assessments are needed to produce toxic and flammable gases containing phosphate and cadmium (Al-Kodmany, 2018).

2.3.3. Geothermal

Geothermal energy is one of the most plentiful renewable energy resources. Because tall buildings are most often built deep into the ground, this form of energy can be extracted to support the functioning of the building. The Linked Hybrid in Beijing, China, employs 660 geothermal wells that descend about 100-m (328-ft) deep. The geothermal wells cool the complex in summer and heat it in winter, eliminating the need for boilers or electrical air conditioners. Generally, it is a good practice to consult the geothermal energy map (Elghamry et al., 2020).

2.3.4. Fuel Cells

Another source of renewable energy is the fuel cell. A fuel cell is an electromagnetic device that generates electricity like batteries, which can be considered an electrochemical internal combustion engine. It is a reactor that combines hydrogen and oxygen to produce electricity, heat, and water. An example is the 4 Times Square in New York City, which employs two 200-kW fuel cells utilizing natural gas to generate power. The cells provide 100% of the nighttime electric demand without combustion, and hot water and carbon dioxide are the only byproducts. Similarly, One World Trade Center Tower is partly powered by 12 hydrogen fuel cells, which produce 4.8 megawatts of power. Notably, the waste heat output from the fuel cell system is used for hot water and heating, amounting to 70,000 BTUs [(British Thermal Unit), equivalent to 20.1 kWh (kilowatt-hours)] of high-grade heat and 500,000 BTUs (147 kWh) of low-grade heat. Currently, its cost is high, but with future mass production, it is bound to go down (Ali et al., 2008; Blaylock et al., 2022).

3. Case Studies

This section reviews case studies of tall buildings that feature energy-efficient design. First, it concisely identifies critical energy-saving features in a dozen projects, representing Europe, North America, South America,

Table 1. It highlights critical built projects that observed energy-efficiency design. It lists projects based on continent and region chronologically. (Compiled by authors)

Continent/ Region	#	Building Name, Location, Year of Completion, Number of Floors, Function, and Architect	Critical Energy Feature	Thumbnail Image
Europe	1	GSW Headquarters, Berlin, Germany 1999 22 Office	Solar shading Double curtain wall Automated environmental controls Natural ventilation Thermal flue Daylighting Shallow leas span	
	2	Post Office Tower, Bonn, Germany 2002 41 Office Murphy/ Sauerbruch Hutton Jahn	Solar shading Combined heat and power Geothermal energy Double curtain wall Automated environmental controls Daylighting Natural ventilation Radiant floor slabs Sky gardens	
	3	KfW Headquarters, Frankfurt, Germany 2010 14 Office Sauerbruch Hutton	Solar shading Combined heat and power Geothermal energy Double curtain wall Daylighting Natural ventilation Radiant floor slabs	
North America	4	4 Times Square, NYC, USA 2000 43 Office Fox & Fowle Architects	Solar shading Combined heat and power Geothermal energy Double curtain wall Automated environmental controls Wind turbines Photovoltaic panels Fuel cells Daylighting Natural ventilation	
	5	New York Times Tower, NYC, USA 2007 52 Office Renzo Piano	Solar shading Combined heat and power Geothermal energy Double curtain wall Fuel cells Daylighting Natural ventilation Sky gardens	
	6	Manitoba Hydro Place, Manitoba, Canada 2009 21 Office Kuwabara Payne McKenna Blumberg Architects	Geothermal energy Double curtain wall Automated environmental controls Daylighting Natural ventilation Solar chimney Atria	

Table 1. Continued.

Continent/ Region	#	Building Name, Location, Year of Completion, Number of Floors, Function, and Architect	Critical Energy Feature	Thumbnail Image
North America	7	Torre Cube, Guadalajara, Mexico 2005 20 Carme Pinós	Solar shading Double curtain wall Daylighting Natural ventilation Central atrium	
South America	8	São Paulo Corporate Towers, São Paulo, Brazil 2016 30 Pelli Clarke Pelli	Solar shading Double curtain wall Automated environmental controls Daylighting Natural ventilation Sky gardens Atrium	
Asia	9	Pearl River Tower, Guangzhou, China 2013 Office SOM/AS+GG	Solar shading Double curtain wall Automated environmental controls Wind turbines Photovoltaic panels Daylighting Natural ventilation	
	10	Shanghai Tower, Shanghai, China 2015 128 Mixed-use Gensler	Geothermal energy Double curtain wall Automated environmental controls Daylighting Natural ventilation Sky gardens Atria	
Oceania	11	1 Bligh Street, Melbourne, Sydney, Australia Office Ingenhoven Architects of Germany and Architectus of Australia	Solar shading Double curtain wall Automated environmental controls Daylighting Natural ventilation Sky gardens Atrium Radiant floors slabs	
Middle East	12	Al Bahar Towers, Abu Dhabi, UAE 2012 26 Office AHR/Arup	Solar shading Double curtain wall Automated environmental controls Photovoltaic Panels Daylighting Natural ventilation Sky gardens	

Asia, Australia, and the Middle East. We have selected 12 recent case study sustainable tall buildings to analyze with the criteria that they were built in the 21st century, contained different types of usages and occupancies, and exemplified cutting-edge technology on different continents in diverse climate zones. (Table 1).

Second, this section offers a detailed account of case studies. Due to limits on article length, the authors had to choose six of the 12 buildings identified in Table 1. They have selected buildings in the continents that are

considered leaders in sustainable design, including Europe, North America, and Asia (China). They will address the remaining six cases in a subsequent publication. The cases discussed in this article exhibit outstanding features in terms of façade design, natural ventilation and daylighting, and renewable energy, which are among the most salient elements for creating energy-efficient buildings demonstrated in the theory section of this paper.

3.1. GSW Headquarters, Berlin, Germany

The 22-story, 85-m (279-ft) high GSW Headquarters building of the year 1999 in Berlin is often referred to as "Germany's first ecological high-rise" – for it integrates numerous sustainable features that facilitate the provision of natural ventilation (stack and cross-ventilation) and daylight to save energy. It employs narrow floor plates, automatically and manually operated windows, sunscreens, blinds, thermal storage, and double skin thermal flue on the west facade. These features have helped to lower the building's energy requirements by 40 to 50% compared to a conventional high-rise building of comparable size.

The layout of existing infrastructure, buildings, and roads on the site dictated an unwanted east-west orientation to the new tower. In response, the architects provided a double-skin system with a thermal flue for the west facade, which contains automatically and manually operated triple-glazed windows on the inner skin. The 0.9-m (3-ft) wide interstitial space encompasses shading devices (a series of vertically pivoting and sliding louvers), which keep out unwanted light rays from the harsh afternoon sun (Wigginton and Harris, 2002). The air cavity of the double skin at the western facade functions as a chimney by inducing vertical airflow through the stack effect and thermal buoyancy.

The eastern facade is also double-skin, and solar blinds are placed in the cavity. When windows on the two facades (i.e., east and west) are open, fresh air flows from the east to the west. The tower's narrow 11-m (36-ft) wide floor plate empowers cross-ventilation. Natural ventilation is activated when the room temperature ranges between 5ºC (41ºF) and 28ºC (82ºF). Otherwise, the mechanical system will start automatically, initiated by

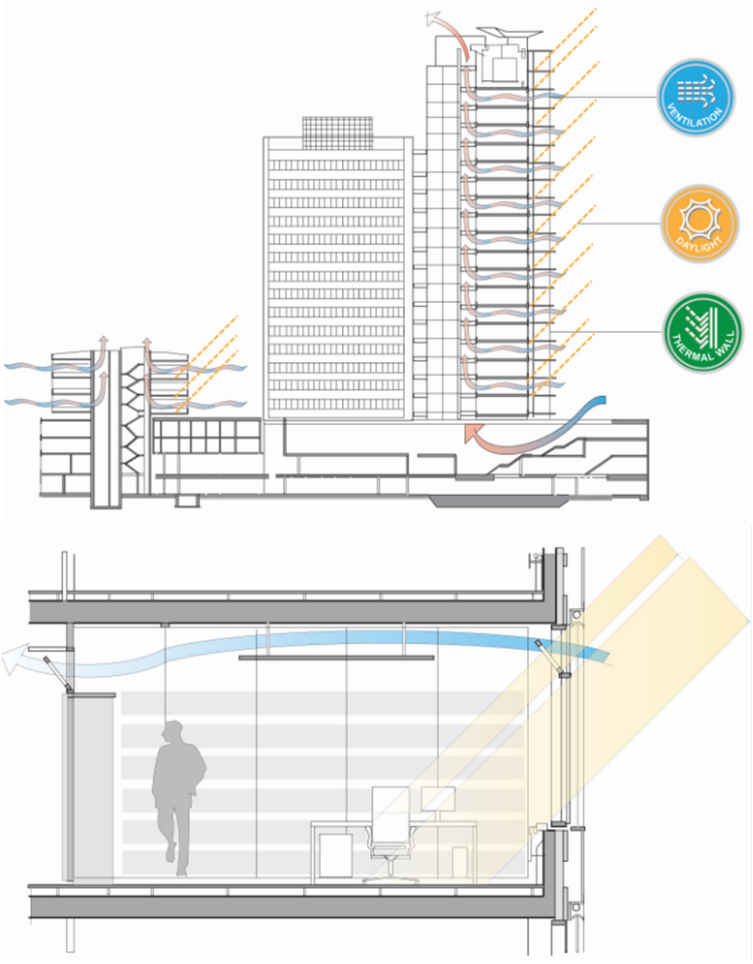


Figure 1. GSW Headquarters, Berlin, Germany. Illustration of the double-skinned façade and the natural ventilation system. (Illustration by P. Armstrong)

BMS, which receives information about weather conditions through sensors placed on the facades (Figure 1). Sauerbruch Hutton Architects designed the tower.

3.2. Post Office Tower, Bonn, Germany

The 41-story, 163-m (535-ft) tall Post Office Tower (also known as the Deutsche Post Tower) of 2002 in Bonn, Germany, is characterized by engaging technically and ecologically sophisticated design to promote high-quality working environments. The skyscraper uses double-skin façades, sky gardens, natural ventilation, water from the neighboring Rhine River, and sky gardens to reduce energy use.

Two structurally connected concrete cores between the two ellipses provide structural stability. The central space separating the two buildings along the sky gardens functions like "lungs" that improve natural ventilation. Through its east-west orientation, the sky garden can be well cross-ventilated. The facility employs a double-skin façade with reflective solar protection that reduces heat gain and provides ventilation to the interior throughout the seasons without a central mechanical system. The façade uses gas-filled, thermally insulated glass walls that stretch from floor to ceiling, allowing daylight to flood in (Figure 2). To reduce energy consumption, daylight sensors automatically adjust office artificial light levels (Al-Kodmany, 2018).

Energy saving is also attained by using groundwater to heat and cool the tower. Groundwater is extracted from wells connected to heat exchangers that pass water through 210 km (130 mi) pipes running through the concrete ceilings. Along these pipes, the concrete slabs' thermal mass helps to control temperature. Even on hot summer days when the outside temperature reaches 39ºC (102ºF), the south-facing office remains below the 26ºC (79ºF) mark. The only primary energy used in this system is the electricity to drive the pumps. To further reduce energy consumption, daylight sensors automatically adjust office light levels. German-American architect Helmut Jahn designed the tower (Al-Kodmany, 2018).

3.3. New York Times Tower, NYC, USA

It is a 52-story, 319-m (1,046-ft) tall building, completed in 2007 in NYC. Cruciform in the floor plan, the steel-framed tower uses a screen of thin horizontal ceramic rods mounted on the exterior of the glass curtainwall on the east, west, and south facades. The rods, 1.5 m (5 ft) long and 4 cm (1.5 in) in diameter, are placed on a steel framework, 0.46 m (1.5 ft) in front of the low-E glass curtainwall. The ceramic rods, totaling 186,000 pieces, create the second skin of the curtain wall, diffuse sunlight, help to block direct sunlight, and absorb Sun's heat, reducing cooling loads. They reduce the solar gain through the curtainwall by 50%, from 42.4 kBtu/26.4 to kBtu/hr (Al-Kodmany, 2018) (Figure 3).

The tower's design optimizes the daylight that penetrates the building. Daylight sensors adjust electric light levels to maintain a consistent overall light level for workers. Quantum lighting controls allow spaces to use only 0.38 watts per square foot—an energy savings of 72 percent. Ceramic rods, mechanized shades, and more than 18,000 individually dimmable fluorescent fixtures that supplement natural light collectively provide an overall energy

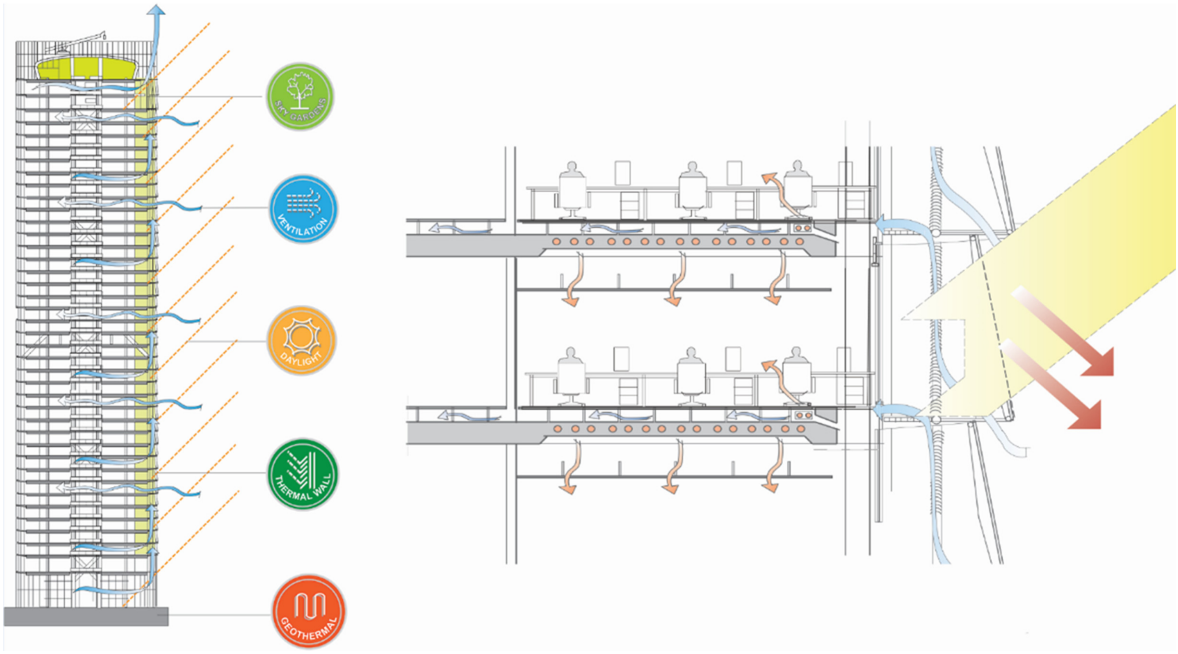


Figure 2. The Deutsche Post Office in Bonn, Germany. It employs a segmented natural ventilation strategy that helps to control varying diurnal and seasonal ventilation requirements. (Illustration by P. Armstrong)

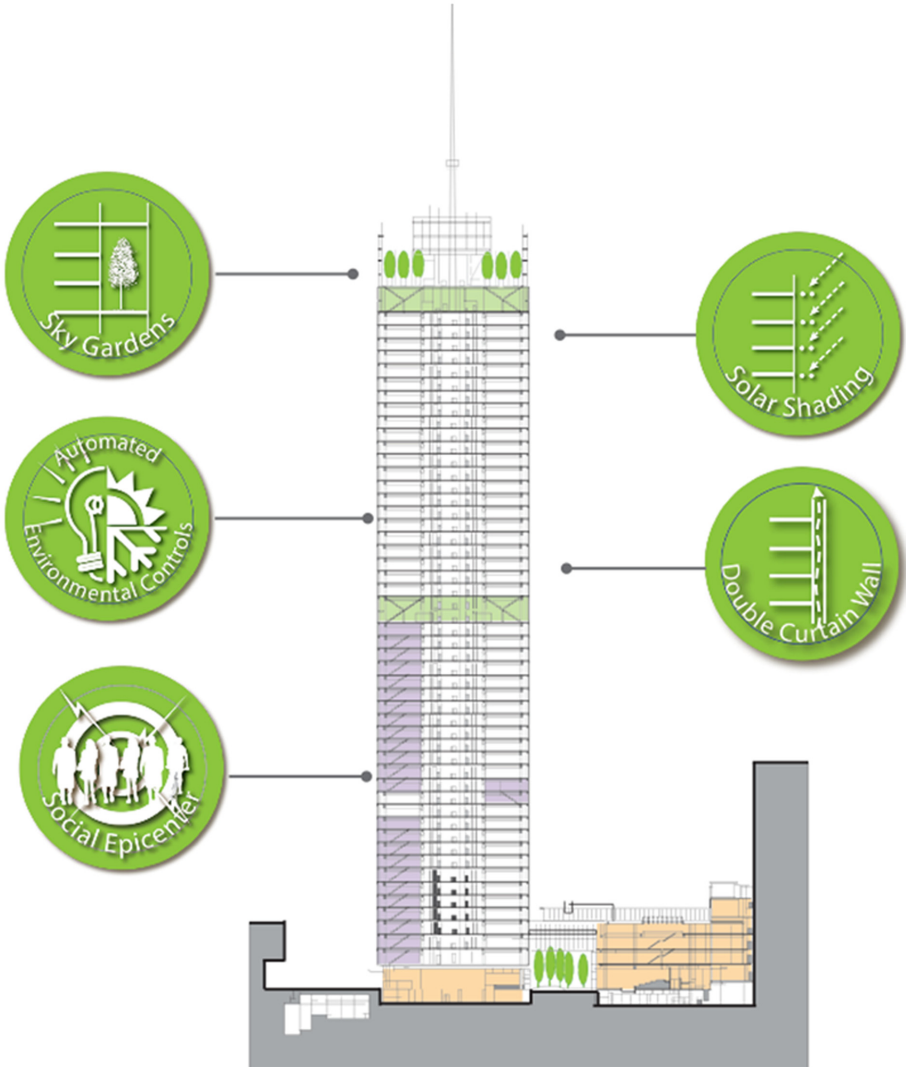


Figure 3. New York Times Headquarters, NYC. When compared to other office buildings of a similar size, it uses significantly less electricity annually, uses less than half as much heating energy, and reduces its peak electric demand. (Illustration by P. Armstrong)

savings of 30%.

Other green features include an on-site natural gas 1.4-Megawatt cogeneration plant that supplies up to 40% of the electrical need of the building. The cogeneration plant provides significant savings and ensures that the building keeps running in the event of a blackout. The tower employs a destination-oriented elevator system. Floors occupied by The New York Times Company utilize a UFAD system, which have advantages over overhead systems, including improved thermal comfort, enhanced indoor air quality, and reduced energy use. Italian architect Renzo Piano designed the tower.

3.4. Manitoba Hydro Place, Manitoba, Canada

Manitoba Hydro of 2009 in Winnipeg, Manitoba, Canada, is the major government-owned energy utility (electric and natural gas) in the Province of Manitoba. The company wanted to make Manitoba Hydro Place a prominent model for the future of healthy, ecological, and energy-efficient office buildings in extreme weather climates -- temperature changes from –35ºC (–31ºF) to +34ºC (+93ºF). The + signs are unnecessary and can be removed. Over the year. The complex comprises a three-story podium that anchors two 18-story twin office towers.

To achieve energy efficiency while maintaining a healthy environment, the design of this building complex relies on 1) Heating and cooling provided primarily by the geothermal system; and 2) ventilation provided by a combination of the solar chimney, winter gardens, and overall building design and orientation. This contrasts with conventional HVAC systems, where a substantial portion of the ventilation air is often recirculated through the building, resulting in a stale environment (Figure 4).

The building complex has implemented an extensive closed-loop geothermal system where 280 boreholes, each 15 cm (6 in) in diameter, penetrate the site 125 m

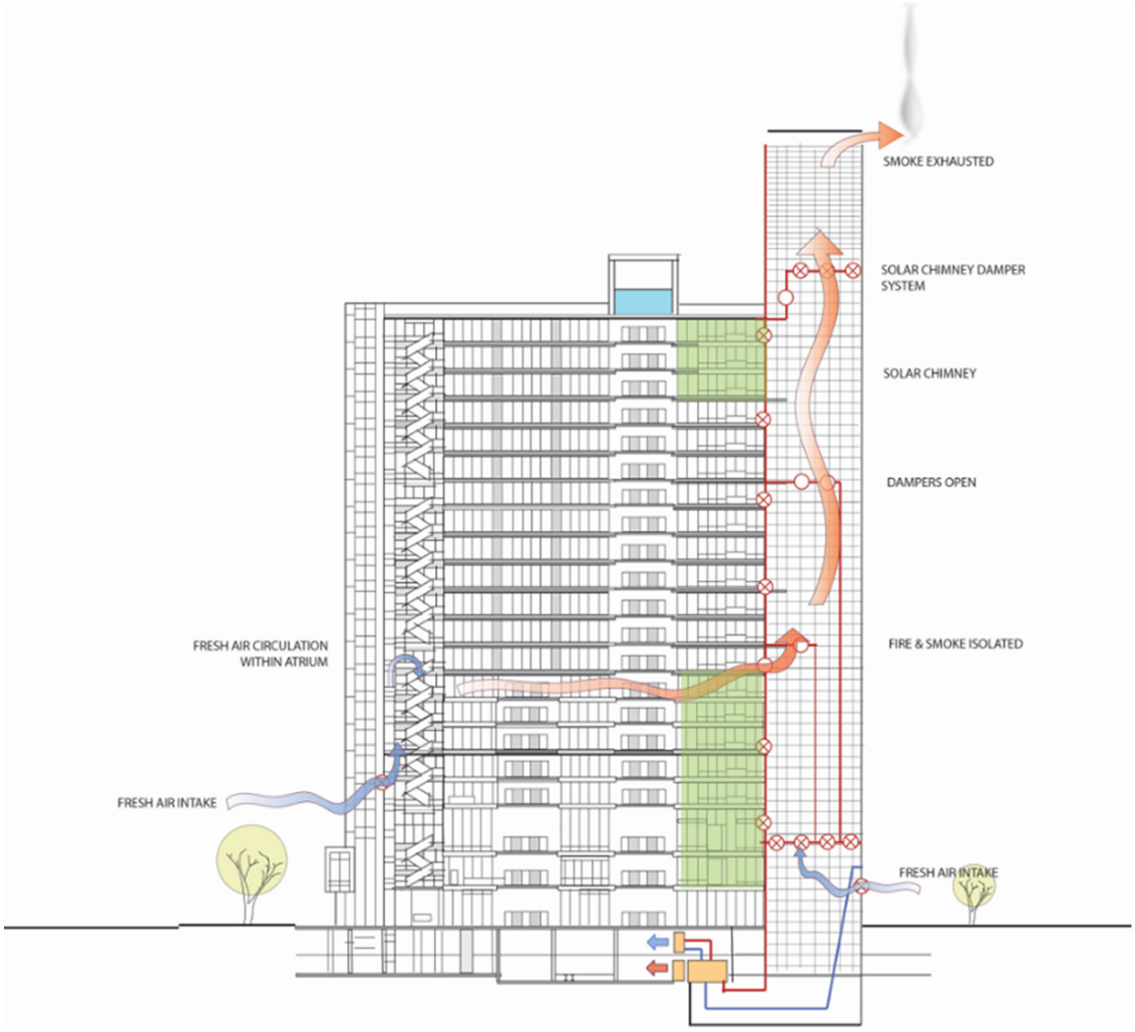


Figure 4. Manitoba Hydro Place, Manitoba, Canada. Among the salient green features of the building is the 115 m (377 ft) -tall solar chimney – located at the north elevation and main entrance on Portage Avenue – that provides passive ventilation. (Illustration by P. Armstrong)

(410 ft) underground. The system circulates water through the heat exchanger and distributes it through the thermal mass of the concrete structure. In winter, heat in the ground warms glycol, which transfers heat to water circulated through pipes embedded in the exposed building's concrete slabs -- heat radiates from these slabs into the workspace. In summer, the system works in a reversed manner by transferring heat from the building into the ground. The building is 100% cooled and 50% heated by the geothermal system. Further, the building employs deep soil-intensive green roofs atop podiums, boosting thermal insulation. It also uses reflective coating to reduce heat gain in summer (Kuwabara et al., 2009).

The towers' spaces enjoy abundant natural light by employing high floor-to-ceiling glazing that allows light to penetrate deep inside, reaching the service core, and narrow floor plates where no office is more than 9m from a window. The towers also feature high thermal protection facilitated by a low-iron double-skin façade with a 1-m (3-ft) wide cavity that provides a thermal buffer and an automated louver shade system that controls glare and heat gain. To prevent overheating in the cavity, the BMS opens vents on the outer skin to exhaust hot air when it accumulates. T5 fluorescent lights with sensors and a dimming system coordinate between natural and artificial light, facilitating the optimal provision of light to interior spaces (Kuwabara et al., 2009). In May 2012, Manitoba Hydro Place became the only office building in Canada to obtain the LEED Platinum designation, highlighting it as one of the most energy-efficient office skyscrapers in North America. Canadian architect Bruce Kuwabara, founding partner of the firm KPMB Architects, designed the tower (Parker et al., 2013).

3.5. Torre Cube, Guadalajara, Mexico

The 17-story tall Torre Cube is a landmark tower of 2005 in Guadalajara, Mexico. The tower's design takes advantage of the mild and sunny climate to bring natural

ventilation and light to the building. This is a unique example of a high-rise building that depends entirely on natural ventilation and daylight year-round, reducing energy consumption and eliminating the spaces needed to house mechanical HVAC equipment. The building's double-skin façade and central atrium enable 100% natural ventilation. Also, *brise soleil* screens (wooden-latticework screens) forming the outer skin, reduce solar gain, collectively obviating the need for air-conditioning (Figure 5). Sky gardens and a central atrium that spans the entire building height and opens at the top support natural ventilation. Further, the fan-shaped office spaces help funnel air into the central atrium and enhance cross-circulation. The Catalan architect Carme Pinós designed the tower.

3.6. Pearl River Tower, Guangzhou, China

The 71-story Pearl River Tower, built in 2013 in Guangzhou, China, is a highly energy-efficient pioneering tower. It was designed to harvest wind energy and minimize wind pressure, which reduced the needed structural materials and embodied carbon to build it. The building features a sculpted form that relieves stress as it accumulates on its windward face by directing and funneling wind into four large openings measuring 6 m × 6.8 m (20 ft × 22 ft) at its mechanical floors that contain wind turbines. The funneling form accelerates incoming wind (up to 1.5 to 2.5 times) and pushes turbines to generate up to 15 times more power. The wind pulled in is re-routed throughout the tower's ventilation system, with the air filtered through the building's floor

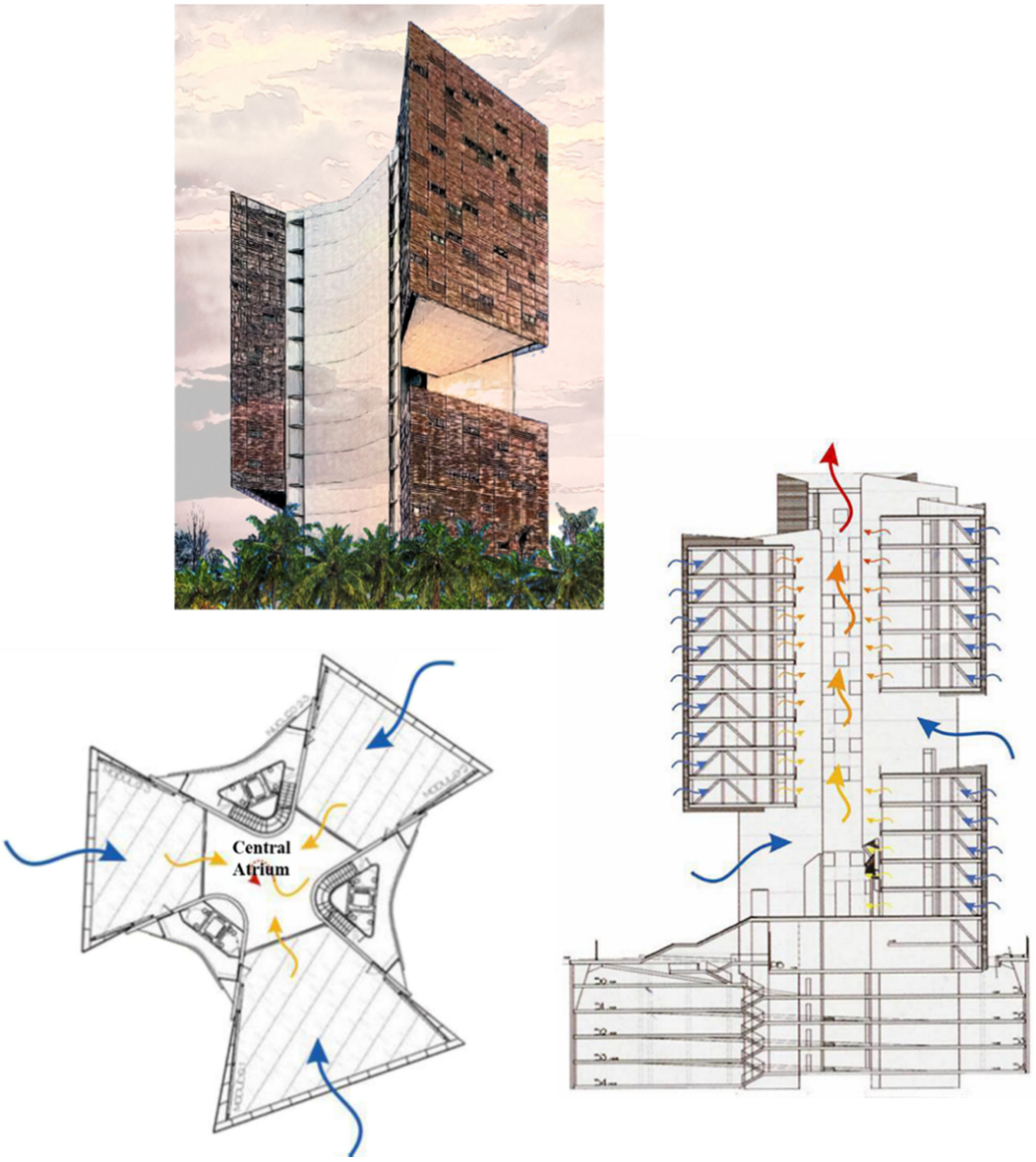


Figure 5. The 17-story Torre Cube in Guadalajara is naturally ventilated without any mechanical plant for heating, cooling, or ventilation. (Sketch by K. Al-Kodmany)

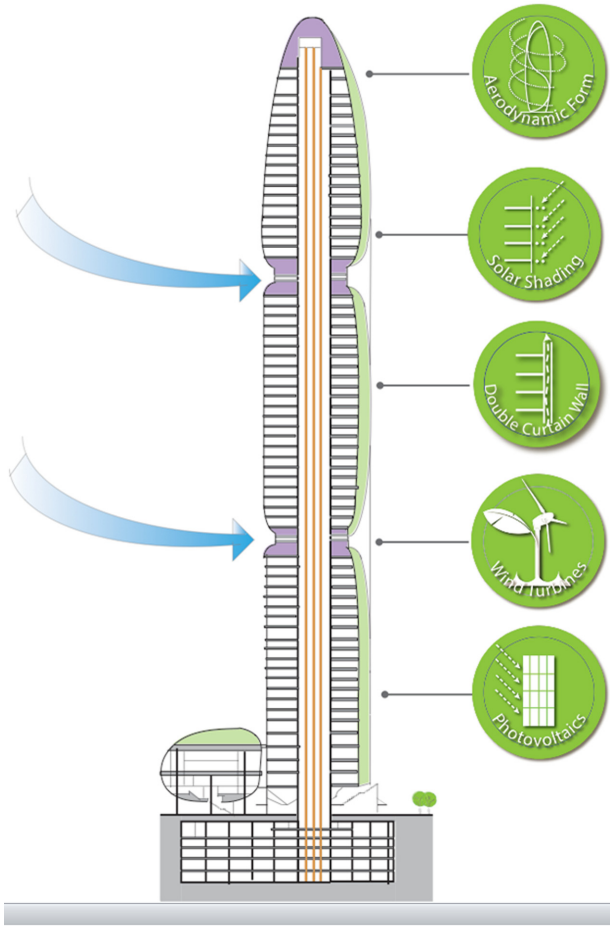


Figure 6. Pearl River Tower, Guangzhou, China. It is a first-of-its-kind tower that uses the shape of tall buildings to not only reduce wind pressure, which allows less steel and concrete to be used and less carbon to be put into the building, but also to harvest wind power. (Illustration by P. Armstrong)

and ceiling spaces. To maximize the wind effect, the tower is positioned so that the broadest side of the building faces the prevailing wind directly (Figure 6).

The entire 212,165 m^2 (2,283,725 ft^2) building is also fitted with an advanced, double-glazed facade that provides abundant natural light. The outer skin has high permeability for solar heat, while the inner skin prevents it. The trapped heat rises, creating natural ventilation to the building façade. Toward the top, rising heat meets heat exchangers, where it is absorbed and stored for reuse in both energy generation and heating processes. Inner skins on the eastern and western facades are made of triple-glazed glass that helps insulate the building's interior. The tower's shallow floor plate facilitates natural light's penetration into most interior spaces. On the south façade, large-scale solar panels are installed toward the roof and on lower areas of the wind openings to generate energy (SEÇLUK et al., 2017).

The skyscraper's metal window blinds that automatically track the sun and open and close to regulate solar heat gain are also equipped with photovoltaic cells so that when they are closed, they harvest Sun's energy. Because the building is in a sub-tropical region (characterized by hot and humid conditions), it faced the challenge of cooling it. In this regard, a passive dehumidification system was used to remove moisture, heat sinks, radiant slabs, and underfloor displacement ventilation to cool the building efficiently. Other notable features include a cooling beam structure and a greywater collection system. SOM designed the tower (Baker et al., 2014).

4. Discussion

The case studies have illustrated how energy efficiency and sustainable design principles can be put into practical projects. Designers may consider viable options, including proper massing and orientation, double skin facades, operable windows, vents, thermal flues, solar chimneys (to facilitate natural ventilation), solar shades, blinds (to reduce heat gain and glare), and low-E glass (to improve thermal performance). Atria and sky gardens are good choices to create thermal buffers, invite daylighting, and facilitate natural ventilation. Ensuring adequate lighting and employing lighting control systems and LEDs are standard practices because they offer significant energy savings.

Daylighting and natural ventilation stand as the most critical elements. Almost all the examined case studies have employed means to empower them. Indeed, in addition to energy saving, they have vivid health benefits. The most well-known benefit of sun exposure is the production of vitamin D in the skin in reaction to UVB rays. Additionally, studies indicate that UV exposure may lower blood pressure, suppress hunger, and reduce the risk of obesity, type 2 diabetes, and certain autoimmune disorders. Sunlight exposure helps control our sleep-wake cycles. According to research, an hour of morning sunlight improves a person's sleep quality that night. Natural ventilation manages the inside climate and alters the building's air through vents in the building's exterior and/or roof. The outcome is reduced CO_2 levels for a healthier indoor atmosphere and a cooler interior during the summer (Beedle et al., 2007).

Torre Cube in Guadalajara, Mexico, offers a great example that relies totally on natural ventilation, taking advantage of the mild weather of Guadalajara. By removing three floors of office modules on each side, the open space between the three cores is flooded with natural light from the side. These enormous voids function as "windows" that let fresh air into the interior space. Sliding panels of latticework create a screen on the exterior of the building, offering solar shading. The Manitoba Hydro Place in Manitoba, Canada, takes fresh air into the south atria and conditions it as it rises; air moves through the building via raised floors and up the solar chimney. During winter, the parkade is heated by

exhaust air piped from the solar chimney. The New York Times Tower in New York City utilizes a screen of thin horizontal ceramic rods set on the exterior of the glass curtain wall to distribute and prevent direct sunlight, and absorb the Sun's heat, reducing cooling loads.

Regarding renewable energy, now is the time to incorporate a renewable energy solution into every project we undertake since the cost of renewable energy technologies has dropped drastically while the implications of climate change have increased dramatically. Also, many governments are offering financial incentives for renewable energy applications. Architects and engineers may choose among geothermal systems, photovoltaic technology, wind turbines, and harnessing rainwater systems based on local climate, geography, and geology. Pearl River Tower, Guangzhou in China, offers an excellent example that responds to local climate while using renewable energy. Its rectangular floor plate is slightly offset from Guangzhou's orthogonal gild to make the most of prevailing breezes and to harness the sun's energy through the judicious placement of photovoltaic technologies. The north and south elevations are convex and concave, respectively, while the east and west elevations are straight. The building's south side has been drastically shaped to funnel air through four openings, two on each mechanical floor, where it is then accelerated to power a vertical axis wind turbine (VAWT) measuring two meters wide by five meters tall (6.6 ft × 16.4 ft). The shape of the structure dramatically improves turbine efficiency. At night, the quantity of energy produced by the wind is exhibited by colored and brightening LED lights mounted at the wind tunnel's entrance.

Building performance simulation (also known as energy modeling) can be used by architects to anticipate the building's energy needs from both conventional and renewable sources and to facilitate the selection of energy-efficient technologies and schemes (such as HVAC equipment, internal loads reduction strategies, and schedules). However, an important factor that governs selecting the right features hinges on understanding the system integration concept, illustrated in the subsequent section.

4.1. Building Systems Integration

To achieve energy efficiency, precise coordination and integration of all building systems are necessary. All design team members, including architects, engineers, planners, contractors, and others, must work together to complete this process, which starts in the early stages of planning. Physical, visual, and performance integration are the three categories of integration (Beedle et al., 2007; Elbakheit et al.; Backman, 2003).

Physical Integration: The sharing of space between systems and components is known as physical integration. In many structures, the floor-ceiling section is separated into several zones for structural, ductwork, and lighting. This region, called the "power membrane," aims to be energy- and space-efficient.

Performance integration: It is concerned with "shared functions" while saving energy. For example, a load-bearing wall serves as a structure and an envelope, combining two functions into a single unit while improving thermal performance. Another example is the ventilated double-skin curtain wall of the Deutsche Post Tower in Bonn, Germany, which combines the duties of two components without joining the parts together.

Visual integration: The development of visual harmony between numerous structural components, energy performance, and their compliance with the intended visual impacts of design is known as visual integration. This could comprise openly displayed and formally expressive building elements that work together to shape the building's appearance. An illustration is the exterior of Abu Dhabi's Al Bahar Towers, which features dynamic solar "parasol" sunscreens that save energy for cooling the building while giving a modernized vernacular visual appearance.

4.2. Greenwashing

"Greenwashing" or "bogus sustainability" is becoming mainstream criticism of sustainable tall buildings. Industries have "hijacked" "green" agendas to profit from the new trend. Surely, integrating "smart" technology and "green" machines into tall buildings could lead to energy saving; however, it could not always be the case. For example, Torre Cube in Guadalajara, Mexico, takes advantage of the mild and sunny climate and harnesses natural ventilation and daylighting, obviating the need for HVAC, lowering energy use and removing the areas required to house mechanical HVAC equipment. Further, we need to question if technology is imported from distant places. For example, the U.S. imports low-E glass from China, entailing additional costs and environmental damage.

4.3. Tenants' Behavior

Buildings' tenants should be educated to abandon wasteful behavior and embrace habits that save energy. People should reduce their consumption of power whenever possible. For example, walking up a few stories rather than using the elevator should be encouraged. Taking advantage of natural lighting and ventilation, when possible, should be encouraged. Turning heating and cooling systems should not be abused. Using sensors costs money, and it is implausible to use them in every space. If buildings are energy-efficient hardware, people's behavior is the software.

Mouzon (2010) illuminates that sustainable behaviors are more effective than relying on costly technologies. He explains that adding solar panels and high-tech glass and preparing for LEED certification are a few examples of how technology is heavily weighted in today's sustainable and green design world. It is all about ADDING things.

The main lesson we may learn from Mouzon's research is how well one can do with less by sharing resources and becoming less consumptive of finite resources and more efficient in everything we do. Interestingly, the "doing well with less" echoes the "less is more" motto embraced and promoted by Modernist architects, such as Ludwig Mies van der Rohe who pioneered tall buildings with the minimalist International Style. Overall, adopting a "sustainable" behavior and lifestyle is essential in delivering greener, cleaner, and healthier buildings.

4.4. Local Expertise

Finally, developing countries that lack "smart" and "green" technologies should weigh the benefits and costs. The effectiveness of technology-based systems hinges on continued monitoring and maintenance and if expertise is lacking in a particular place, their sustainability is questionable. As such, building owners and users must pay attention to the broader sustainability issues and their applications to a specific location.

5. Conclusion

Today, architects and engineers continue to design high-performance tall buildings. In this essay, the authors looked at numerous concerns about the efficiency of energy use in high-rise buildings. Moreover, the authors reevaluated the distinctions between active and passive forms of energy as well as the processes that are utilized to generate energy. Examples of a wide range of projects have been utilized throughout this article to show both the fundamentals and practical applications of energy efficiency. Numerous studies are still being conducted on this critical subject because energy consumption is necessary for the survival of the growing global population. Energy scarcity, global warming, and air pollution will continue to be the maladies of the 21st century until properly integrated sustainable developments and practices are implemented with adequate energy consciousness. Cities are essential to the human race's continued existence, and recent decades have seen an increase in the construction of high-rise buildings worldwide for human residence and economic activities. The energy supply is the lifeline for human survival. It takes the involvement and commitment of engineers, architects, allied professionals, policymakers, and other stakeholders to ensure this through vision and action.

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