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Sustainable Skyscrapers: A Review of Green Features

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ABSTRACT

Increasingly, architects and engineers are interested in pursuing sustainable design. Yet, they lack sources that summarize best practices. As such, this review paper maps out and examines prominent examples of "sustainable" skyscrapers of varying geographic locations, climates, and socio-cultural contexts. It discusses the design themes and green features of "LEED skyscrapers" and elaborates on recent developments in architecture and engineering. The presented 12 case studies do not intend to evaluate LEED rating systems. Instead, they illustrate how LEED has advanced the green design agenda and encouraged the pursuit of innovative design and engineering solutions. The mapped-out green features in this article should be helpful to all professionals interested in green architecture.

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1. Introduction

As cities cope with rapid urban population growth and grapple with urban sprawl, policymakers, planners, and architects have become increasingly interested in the "vertical city" paradigm. The United Nations estimates that by 2050 the urban population will increase by about 2.5 billion people, which translates to 80 million dwellers a year, 1.5 million new a week, or 220 thousand a day [1]. Furthermore, the United Nations estimates that by 2100 the urban population will reach about 9 billion inhabitants, doubling today's urban population of 4.5 billion. Consequently, to accommodate the influx of urban population while reducing urban sprawl, we must engage the vertical dimension of cities [2-4].

Certainly, tall buildings are not the only means to accommodate the increasing urban population. However, cities are embracing the tall building typology for additional reasons, including land prices, demographic change, globalization, urban regeneration, agglomeration, land preservation, infrastructure, transportation, international finance, and air right, among others [5-8]. Indeed, in the last two decades, the world has witnessed an unprecedented surge in constructing tall buildings. In the previous two decades, the world added 12,979 tall buildings (100+ m) to the 7,804 buildings they previously built. Further, cities have erected over 1,361 towers with heights that exceed 200 m, while they built only 284 before. Cities also constructed 150 supertalls (300+ m), while they constructed merely 24 supertalls previously. Further, cities recently completed three megatalls (600+ m); and obviously built none before [9, 10].

Climate change demands a new sustainable design that addresses serious challenges such as massive storms, earthquakes, and flooding. Urban planners have recently developed new sustainable models. For example, the "sponge city" model intends to design buildings and infrastructure that would safely accommodate anticipated massive flooding. The "sponge city" model builds on the Green Infrastructure (GI) model that aims to improve water management systems and enhance the ecological wellbeing of urban habitats. Integrating green elements in buildings and their surrounding will surely help to absorb rainwater. Similarly, incorporating innovative engineering and architectural solutions helps capture and recycle rainwater, further reducing the likelihood of flooding.

This research is significant because, given the mega-scale of skyscrapers, any improvement in their design, engineering, and construction will have mega impacts and significant savings. Therefore, the extracted design elements, principles, and recommendations from the case studies examined in this article are substantial. For example, tall buildings require an extensive amount of structural materials [11]. Therefore, we can significantly reduce costs and carbon emissions by employing appropriate technologies and efficient structural systems. Likewise, tall buildings accommodate many tenants who consume enormous quantities of water. We can save valuable potable water by utilizing efficient water systems and grey and black water recycling systems through the full height of tall buildings. Collectively, this article informs the readers of innovative ideas and promising projects that support sustainable architecture, engineering, and urban planning [12-14].

2. Case Studies

Over the past decade or so, a wealth of creative green solutions have been developed through the design and construction of skyscrapers, providing valuable knowledge that will benefit the development of future towers [15, 16]. An in-depth evaluation would require building performance and operation data that are currently unavailable. In some cases, the data is simply not collected, and in others, the data is collected but not shared for liability reasons. Therefore, instead of focusing on evaluation, this paper elaborates on the sustainable design features employed in some of the world's most notable contemporary skyscrapers [17-19]. The following 12 case studies highlight vital green features of modern skyscrapers. They come mainly from three continents, including North America, China, and the Middle East.

2.1. Bank of America (BoA) Tower

Bank of America is one of the world's major financial institutions. Bank of America Tower (also known as One Bryant Park) was designed by Cook + Fox Architects [5]. The 336 m (1,200 ft) tall, 55-story BoA tower is proclaimed to be among the greenest skyscrapers in the U.S. It is the first commercial high-rise to earn LEED Platinum certification, the highest designation from the U.S. Green Building Council (USGBC).

The building's power comes from an on-site cogeneration plant, which works in concert with an ice storage system to reduce the building's peak energy demands. A clean-burning, 5.0-megawatt cogeneration plant provides approximately 65% of the building's annual electricity and lowers the daytime peak demand by 30% [20]. A thermal storage system consisting of 44 storage tanks further reduces peak loads on the city's over-taxed electrical grid by producing ice at night that melts during the day to supplement the cooling system. Ice storage systems provide approximately 25% of the building's annual cooling requirements [20]. This ice battery system saves operational costs because it is activated during off-peak nighttime hours when the electricity-charging rate is reduced. Further, an absorption chiller uses waste heat from cogeneration to heat and cool the building in winter and summer. Another energy-efficiency feature housed in the BoA Tower is a building-integrated photovoltaic (BIPV) system.

The tower employs multiple water conservation strategies. New York's annual 1.2 m (4 ft) rainwater (NYC is among the rainiest cities in the U.S.) and snow are collected through a greywater system that captures and reuses this water to flush toilets and replenish cooling systems. The greywater system also reuses sink water. These strategies, along with waterless urinals and low-flow fixtures, save approximately 29 million l (7.7 million gals) of potable water annually [20]. Collection tanks placed throughout the building take advantage of gravity to transport the greywater.

The tower provides a high-quality indoor environment that results from "hospital-grade…air [quality], abundant natural daylight, 2.9 m (9.5 ft) ceilings, an under-floor ventilation system with individually-controlled floor diffusers, and round-the-clock air quality monitoring" [20, p. 23]. The air filtration system removes 95% of airborne particulates, compared to 35% for conventional buildings and 85% at 4 Times Square, while the air monitoring system tracks CO_2, CO, VOCs, and tiny particulates [17]. Interior materials were mostly selected to be low-VOCs, sustainably harvested, manufactured locally, and recycled. Besides, the tower is clad with a high-performance curtain wall that minimizes solar heat gain through the low-E glass and heat-reflecting ceramic frit. It also uses an automated daylight dimming system that reduces the use of artificial lighting.

A high percentage of the building's materials come from recycled or locally sourced materials located within 800 km (500 mi) of New York City (NYC) to reduce transportation costs and greenhouse gas emissions. For example, the building's steel was made from 87% recycled materials, and the concrete was made from cement containing 45% recycled materials [20]. 91% of all construction and demolition waste was recycled or otherwise diverted from going to landfills. To divert materials from landfills further, trade contractors returned most of their empty wood reels and packaging pallets for future reuse [18].

2.2. The Visionaire Tower

The Visionaire Tower is a 35-story building located in Battery Park City, NYC. Completed in 2008, the tower contains 251 condominium units. Notably, it was the first to receive the LEED Platinum from the U.S. Green Building Council (USGBC) in New York City and is considered one of the greenest residential condominiums in the U.S. Pelli Clarke Pelli served as the architect [17].

The tower's skin integrates an insulated low-E curtain wall and terra cotta rain-screens that provide thermal insulation, reduce the need for heating and cooling, and accentuate aesthetics. The curtain wall was prewired for motorized solar shades to reduce solar gain. It, therefore, reduces the energy needed to cool interior spaces. To reduce the energy used when apartments are unoccupied, the tower employs a lower exhaust rate for ventilation and uses sensors and master switches to control lighting and appliances [17].

The building's efficient HVAC system conditions, filters, and supplies fresh air into every apartment, yielding a 35% energy savings over code-compliant HVAC systems. The facility collects approximately 5% of its electric load through building-integrated solar panels, while 35% of its electric load is sourced from Green-e energy-certified providers that employ wind and other renewable energy sources. Natural gas powers the residential cooling systems and contributes to lowering peak electricity demands on New York City's power grid [17].

The building also incorporates high-efficiency air filtration and humidification systems and employs environmentally safe paints, adhesives, sealants, and no or low VOC materials to support healthful indoor environments. The wood used in the flooring was harvested according to Forest Stewardship Council certified standards, and all appliances were Energy Star® approved. The developer ensured "green" construction by using materials that contained a minimum of 20% recycled content and recycling over 85% of the construction waste. Furthermore, half of all materials used to construct the tower were sourced within an 800 km (500 mi) radius [3].

Water conservation is also integral to Visionaire's sustainable scheme. All building fixtures incorporate features that reduce potable water use, and an on-site blackwater treatment system ensures that all toilet water is recycled and treated. Specifically, a 94,635-liter-per-day (25,000-gallon-per-day) wastewater treatment plant in the basement recycles water for the building's dual-flush toilets while providing make-up water for the HVAC system's cooling tower. The building also gathers rainwater and stores 18,927 l (5,000 gals) of recycled water to irrigate the rooftop garden, which provides an essential layer of insulation and helps conserve energy. All the building's potable water is centrally filtered. Additionally, a natural gas-powered microturbine on the roof harnesses its waste energy to heat water [17].

2.3. One World Trade Center

On September 11, 2001, the twin towers of the World Trade Center and several other buildings in Lower Manhattan were damaged or destroyed. Soon after the devastation, the ambitious reconstruction to replace and honor the World Trade Center began. The massive One World Trade Center on the northwest corner of the 6.5-ha (16-ac) site was completed in 2015. The radio antenna that tops the 123 m (400 ft) spire reaches a symbolic height of precisely 541 m (1,776 ft) high to honor the year of America's independence. The 105-floor 1WTC is the tallest in North America [8].

Designed by Skidmore, Owings, and Merrill (SOM), the tower incorporates new architectural and safety standards and state-of-the-art green features. Twelve hydrogen fuel cells, which generate 4.8 megawatts of power, partially power the building. Waste heat output from this fuel cell system is recycled and used for hot water and heating, amounting to 70,000 BTUs of high-grade heat and 500,000 BTUs of low-grade heat. Air conditioning is supplied, in part, by a highly efficient 12,500-ton Central Chiller Plant (CCP) that uses water from the Hudson River to cool the tower, the WTC Transportation Hub, the National September 11 Memorial and Museum, retail space, and some non-commercial areas. The CCP plant circulates about 113,562 l (30,000 gal) of river water every minute—the tower uses the Hudson as a way of both dissipating heat and preheating water. Because water below a certain depth enjoys a constant temperature of about 7-10ºC (45-50ºF), the tower requires less energy to heat and circulate water during the winter. It requires less energy for cooling during the summer [18]. Overall, the tower draws as much as 70% of its power from green energy sources.

The annual 1.2 m (4 ft) of New York City rainwater that falls on the site is collected via a greywater system to cool the building, irrigate the landscape, and provide fire protection. Also, the large square reflecting pools which mark the 'footprints' of the original World Trade Center twin towers feature two 360-degree waterfalls that serve as rain collection systems themselves. Low-flow plumbing fixtures also reduce water consumption by 30%.

The curtain wall that begins at the 20th floor and continues to the observation deck uses a thermally interrupted unitized wall system that incorporates insulated glazing units (IGUs), powerful enough to withstand the wind pressure at high altitudes, also ensuring stringent security requirements. To maximize daylight and reduce energy usage, ultra-clear glass has been installed. Furthermore, metal spandrels were painted a pewter color and slanted inwardly to increase daylight within the building. To reduce energy consumption further, the building uses automatic dimming devices in every space within 4.5 m (15 ft) of the building's façade to ensure efficient light use. Individual electrical supply meters are incorporated to encourage tenants to reduce their overall energy consumption.

All the building's structural materials (from the facility's gypsum boards to the ceiling tiles) contain a minimum of 75% recycled materials, making the new tower already 75% "old" regarding its physical constituents. Consequently, the design reduced the building's environmental footprint and reduced the demands on the natural resources and the energy needed to produce these materials. Fifty percent of all wood products installed in the tower were certified by the Forest Stewardship Council, which mandates that the wood used in a building must come from responsible sources and not from endangered trees or forests [21-23].

Several measures were taken to ensure indoor air quality. Over 3000 monitoring stations within the building were linked to air handling software to provide fresh air when necessary. If a monitor senses more carbon dioxide than is allowed in the space, a signal is transmitted to the air handling software, informing it of the need to provide more fresh air. In response, the system automatically increases the fresh air mix in the space. Additionally, to support healthy indoor living, no building materials in the tower contain either VOCs or chemicals that leach in a gaseous form [9, 24, 25].

2.4. The Tower at PNC Plaza

The 33-story, 167 m (554 ft) Tower at PNC Plaza is the new corporate headquarters for the PNC Financial Services Group, one of America's oldest financial institutions. Gensler led the tower's architectural design, and Buro Happold led the building's engineering in collaboration with the consulting firm Paladino & Co. The tower was completed in 2015 and received LEED Platinum certification [26].

The design of PNC Tower attempts to take advantage of Pittsburgh's relatively mild climate by providing natural ventilation and daylight, and hence, reducing its dependence on HVAC and artificial lighting systems. To that end, the tower employs multiple strategies, including a relatively small lease span of about 9 m (30 ft) that provides abundant natural light. In contrast, ventilation is facilitated by the double-skin-façade (DSF). The DSF incorporates vents in the outer skin, operable windows in the inner skin, and a building management system (BMS) informed by sensors that control these vents and windows. The DSF's vents and windows remain closed on hot and cold days and are open on "net-zero" days. These strategies allow the building to "breathe" by taking in fresh air from the outside and expelling out hot air. It is estimated that the tower will operate in this natural ventilation mode, without the need for fan power, for more than 40% of working hours [17]. Furthermore, the 1-m (3-ft) cavity between the two glass skins is accessible to maintenance crews and tenants via glass sliding doors [27, 28].

Another integral element of the building's passive system is its solar chimney, which comprises two shafts at the core of the building's trapezoidal floor plate, facilitating hot air exhaust through the stack effect. A 465 m^2 (5,000 ft^2) diamond-shaped glass roof that functions as a solar heat collector is placed atop the solar chimney. It is slanted to the south to maximize solar power harnessing. A "thermal" chamber is placed between the glass roof and the solar chimney to preheat cold air in the winter and remove hot air during the summer. When outside air is undesirable, too hot, humid, or full of pollen, for example, the rooftop HVAC units operate the system in reverse, turning the solar chimney into an air-supply duct where fans push the conditioned air down the chimneys where it is delivered to office spaces [20, 29].

The tower conserves water by employing low-flow fixtures, harnessing rainwater, and treating grey and black water. The tower also uses locally sourced building materials, including FSC-certified red maple wood grown in western Pennsylvania for the interior curtain wall. Wood has been selected over aluminum for the curtain wall due to aluminum's high-embodied energy. Wood also performs better on thermal energy measures while evoking a "warmer" aesthetic feel [10]. All the building's furniture was made from recycled materials.

2.5. Salesforce Tower

The 326 m (1,070 ft) tall, iconic Transbay Tower is the tallest building in San Francisco, CA. Designed by Pelli Clarke Pelli Architects, the 80-story office tower is located adjacent to the San Francisco Transbay Transit Center (SFTTC), a multi-modal transportation hub. The building received LEED Gold certification [10].

The tower employs improved indoor environmental quality with the use of full outside air economizer ventilation systems. It integrates floor-by-floor air intake via high-efficiency air-handlers that augment natural ventilation. It incorporates an under-floor air distribution (UFAD) that reduces dependence on HVAC system and improves occupant comfort and zone controllability. The building also integrates metal sunshades that maximize light and views while reducing solar heat gain. It also employs a high-performance, low-E glass that reduces cooling loads and enhances energy and light transmission performance. It has floor-to-ceiling windows that bring in natural daylight and offer spectacular views [10].

The tower features comprehensive water management and recycling system that captures, filter, and reuse the facility's greywater and stormwater, collectively reducing water use by 54%. Further, a 2.2-ha (5.4-ac) rooftop "City Park" above the Transit Center includes an amphitheater, gardens, a trail for running/walking, open grass areas for picnics, lily ponds, etc. The rooftop park absorbs the carbon dioxide from buses and offers a habitat for birds and other animals. This living "green" roof provides thermal mass and passive cooling [27-29].

2.6. Devon Energy Center

The Devon Energy Center is the new headquarters of the independent oil and natural gas producer Devon Energy Corporation, located in the heart of Oklahoma City. The 50-story building was completed in 2012. Designed by New Haven-based architect Pickard Chilton, the Devon Energy building is among the largest LEED-NC Gold-certified buildings in the world [17].

The curtain wall consists of continuous high-performance clear glass with a low-E coating that maximizes daylight and reduces heat gain. A vertical glass blade characterizes the façades with a ceramic frit attached to five-foot modules to a stainless-steel-and-aluminum cladding system. Additionally, the all-glass curtain wall provides breathtaking views of the expansive prairie landscape surrounding the city. Maximizing natural light is also enabled by accommodating 12 full-corner offices that bring natural light deep into the building. The interior spaces integrate a raised-floor office environment, demountable walls, and flexible lighting [20].

District cooling has modulated energy use with on-site cogeneration, and the project site affords easy access to public transit. The tower also incorporates a water conservation system that contains highly efficient plumbing fixtures and recycles used water, reducing consumption by up to 40%. Furthermore, materials from the pre-existing parking lot and garage were reused in the new site, diverting 68,000 tons of waste and concrete from landfills [17, 30].

2.7. Manitoba Hydro Place (MHP)

Manitoba Hydro is a major government-owned energy utility (electric and natural gas) in Manitoba, Canada. The complex consists of two 18-story twin office towers that sit on a stepped, three-story podium. Completed in 2009, it is the first in Canada to achieve LEED Platinum Certification from the Canada Green Building Council (CaGBC), the highest certification available under the LEED program. The challenge was to design an energy-efficient building in a place that experiences extreme climates—temperatures fluctuating from -35ºC to +34ºC (-31ºF to +95ºF) over the year. To that end, the building employs the following features [16].

MHP has implemented an extensive closed-loop geothermal system where 280 boreholes, each 15 cm (6 in) in diameter, penetrate the site to a depth of 125 m (400 ft). The system circulates water through a heat exchanger and distributes it through the thermal mass of the concrete structure. In the winter, heat in the ground warms glycol (de-icing fluid), which transfers the heat to water. Then, water is circulated through pipes embedded in the exposed building's concrete slabs that radiate heat into the workspaces. In the summer, the system works in reverse by transferring heat from the building into the ground. About 228,600 m (750,000 ft) of pipes run through the concrete slabs, which possess a high thermal mass and provide radiant temperature control. The geothermal strategy employed by the building provides a sustainable "net zero" energy exchange system where heat energy extracted from the ground in the winter returns to the earth in the summer. The building is 100% cooled and 50% heated by this geothermal system [8, 31-33].

The towers also feature a natural ventilation system provided by a solar chimney, winter gardens, and operable windows. Fresh air is drawn into the three 6-story winter gardens, containing water elements that humidify/dehumidify the fresh air. In the winter, when water is warmer than air, moisture evaporates and humidifies the building. In the summer, when water is colder than the air, water absorbs additional moisture and dehumidifies the building. Fresh air from the winter gardens is transferred into the workspaces via a raised floor system, and stale air rises (from heat generated by occupants and other sources). The solar chimney draws used air out of the building during the summer and intermediate seasons (spring and fall). In the winter, fans push warm exhaust air to the bottom of the solar chimney to warm the parkade and preheat the incoming cold air. Atop the chimney, 632 pipes filled with 17 tons of sand store the sun's heat during the day to ensure that cool night air does not interrupt the stack effect. Finally, automated and operable windows help to create natural ventilation. In the intermediate seasons (spring and fall), the mechanical ventilation system is shut, given that the building relies on natural ventilation made possible by the open windows. Natural ventilation minimizes the need for the automated system, reducing power consumption and greenhouse gas emissions [17].

The tower's spaces enjoy abundant natural light by employing narrow floor plates—no office is more than 9 m (30 ft) from a window—and the high floor-to-ceiling glazing allows light to penetrate deep into the service core. The tower also benefits from the high thermal protection facilitated by a low-iron DSF with a 1 m (3ft) wide cavity, which provides a thermal buffer and an automated louver shading system that controls glare and heat gain. To prevent overheating within the cavity, the building management system (BMS) [guided by sensors placed on the DSF] opens vents on the outer skin to exhaust hot air as it accumulates. T5 fluorescent lights with sensors and a dimming system coordinate between natural and artificial light, facilitating optimal lighting of the interior spaces at minimal costs.

The building also employs intensive, deep-soil green roofs that sit atop the podiums, providing the multiple benefits of reduced stormwater runoff and urban heat-island effect, boosting thermal insulation, and enhancing aesthetics. The green roofs use native prairie plants to minimize water usage and maintenance. They also use reflective coatings to reduce heat gain and the urban heat island effect in the summer [20]. Furthermore, the building enjoys a relatively low profile (only 21 stories), resulting in minimum shading on neighboring buildings and public spaces. The towers are also arranged to streamline the prevailing wind, minimizing their impact on the surrounding environment. Finally, standards in "green" construction have been observed, with 80% of the building's materials coming from previously existing structures on the site.

2.8. The Bow

EnCana Energy Company needed a significant building to consolidate its scattered staff and help revitalize Calgary's downtown, Alberta, Canada. The tower was named after the Bow River and forms the first phase of a master plan covering two city blocks on the east side of Centre Street, a central axis through downtown Calgary. The 58-story Bow office building rises to 238 m (779 ft) and is the tallest office tower in Calgary. The skyscraper is the headquarters for energy giants EnCana (TSX:ECA) and Cenovus (TSX:CVE), among other companies. The 238 m (781 ft) tower was designed by Foster and Partners and completed in 2012. The Bow has achieved LEED Gold certification [34].

The bow-shaped building provides the most excellent perimeter accommodation, creating protected outside public space within the arc, facing south. It also provides an aerodynamic form (with the convex façade positioned against the prevailing wind), mitigating the impact of Calgary's strong current, decreasing the required structural support for the already efficient diagrid structure. The aerodynamic form, orientation, and diagrid system collectively reduced the steel necessary by 30%. The diagrid is a large-scale system wherein each triangulated section unifies six stories, resulting in segments, which enhance the tower's visual impact while avoiding a monolithic appearance [34].

The concave structure contains three sky gardens that run the full height of the atria and act as climatic buffer zones that insulate the inner office space. In the winter, the sky gardens provide thermal insulation and gather sunlight to heat the space, while in the summer, they cool the space and allow adjacent offices to open their windows. The social functions of the sky gardens have been augmented by their vertical access as they feature fresh air, light, plants, mature trees, seating, meeting spaces, cafes, and catering facilities [17].

2.9. Shanghai Tower

The Shanghai Tower is the third tower in the trio of supertall buildings, including Jin Mao Tower and the Shanghai World Financial Center, located in the heart of Shanghai's new Lujiazui Finance and Trade Zone. Rising to a height of 632 m (2,073 ft), it is the tallest building in China. The 121-story tower offers a mix of functions, including offices, hotels, shops, restaurants, and the world's highest open-air observation deck at 562 m (1,844 ft). The tower has achieved LEED Platinum certification [18].

The Shanghai Tower represents a new paradigm of rethinking the sustainable vertical city. It is a "city within a city," a collection of multiple neighborhoods. It is divided into nine areas, stacked vertically, making it a self-contained city. Each area in the tower contains a sky garden intended to evoke the landscaped courtyards of Shanghai's historic homes. In traditional lane houses found in Beijing's hutongs and Shanghai's shikumen, families live in close-knit dwellings organized around a communal open space. In Shanghai Tower, the neighborhoods are vertical, each comprising 12 to 15 floors and featuring a 24-hour accessible sky garden to foster social interaction and a sense of community.

Furthermore, the sky gardens ease traffic jams near elevators and provide spectacular views of the city [34, 35]. They also offer energy savings and ventilation advantages by acting as buffer zones between the inside and the outside by warming up cool winter air and dissipating accumulated summer heat from the building's interior. Stale indoor air is blown across each garden before being exhausted from the building.

The tower's form resists the typhoon-level winds common to Shanghai by embracing multiple strategies, including asymmetry, tapering, rounded corners, and a reduced floor plate as the tower rises. Testing scenarios and simulations were carried out to simulate typhoon-like conditions, suggesting a 120-degree twist as the optimal rotation for minimizing wind loads. The resulting form reduced the lateral loads of the tower by 24 percent, saving $58 million in building materials [36, 37].

Renewable energy technologies have been employed to provide on-site energy. Wind turbines, located directly beneath the parapet, generate power for the upper floors, while a 2,130 kW natural gas-fired cogeneration system provides electricity and heat energy to the lower floors. Rainwater is collected via the building's spiraling parapet and has been used for the tower's heating and air conditioning systems. Water treatment plants have been incorporated into the tower's shaft, podium, and basement to reduce the energy required for pumps. The building also recycles greywater and stormwater for irrigation and toilet flushing. These strategies result in a 38% overall reduction in water consumption.

The HVAC systems, strategically placed in the mechanical floors, provide heating, ventilation, and cooling to the building's various vertical zones. They also precondition, filter, and measure air quality before entering the building. Mechanical floors also house electrical transformers, water systems, and other equipment. Locally sourced materials with high-recycled content have been used throughout. The sustainable measures employed by Shanghai Tower are expected to reduce the building's carbon footprint by 34,000 metric tons per year compared to a typical structure of the same size [18].

2.10. Greenland Group Suzhou Center

At 358 m (1,175 ft), Greenland Group Suzhou Center (also known as Wujiang Greenland Tower) visually anchors the Wujiang waterfront of Suzhou City, China. The tower is part of a larger multi-block development, and Suzhou Center aims to function as the catalyst. The 78-floor tower accommodates a mixed-use program of hotels, serviced apartments, offices, and retail space. The building was completed in 2021 and aimed to achieve LEED-CS Silver status [6].

The striking feature of the tower is a 30-story tall slim, and slender opening—containing the atrium for the hotel and residential apartments—that spectacularly marks the tower's presence on the city skyline. In addition to aesthetics, the atrium plays multiple functions, including maximizing daylight penetration, facilitating mixed-mode ventilation in the lobbies and public spaces, and providing additional structural strength. The atrium divides the interior space of the upper floors into two wings and then reunites them toward the top. Via the vertical stack effect, the atrium helps warm interior spaces and reduces the need for mechanical systems to provide heat. This mixed-mode ventilation system was optimized by employing Computational Fluid Dynamics (CFD) models that rely on robust meteorology data. The system monitors the entire ventilation process, optimizing the atrium's functioning as the building's "lungs." Furthermore, since the greatest concentration of pollutants can be found at lower elevations, fresh air is supplied through large openings at the tower's top. Due to its high-quality air and natural ventilation, the building was dubbed "the Breathing Tower" [18].

Structurally, the 30-floor atrium provides an opportunity to strengthen the tower through a split-core arrangement. "By placing half of the building's core…on each side of the lobby and interconnecting them with structural steel braces, the combined core becomes more effective than a typical center core system" [18, p. 291]. Also, the "hollow" core reduces the weight that is usually placed on the building's foundation. Furthermore, the convex primary façade, coupled with the elliptical plans, mitigate the wind's impact on the tower, minimizing vortex shedding, resulting in fewer structural supports. Highly engineered composite core and structural outrigger systems will be employed to strengthen the building at minimum costs. The tower reveals its structural logic aesthetically by exposing the X bracing at slender and narrow openings along the 30th floor [20].

Water management, conservation, and reuse strategies include efficient building fixtures, rainwater harvesting, condensate recovery, and efficient use of processed water. According to SOM, the building's design firm, multiple green features are predicted to help the tower achieve a 60% savings in energy consumption compared to the conventional American high-rise [38].

2.11. Parkview Green FangCaoDi

Parkview Green FangCaoDi complex is located in the heart of Beijing's Central Business District (CBD). It is an iconic landmark and a potent symbol of creative design thinking that promotes attractive forms, efficient utilities, functionality, and enjoyable experiences. The project was designed by Integrated Design Projects, engineered by ARUP, developed by Hong Kong Parkview Group, and is owned by Beijing Chyau Fwu Properties Ltd. Parkview Green FangCaoDi has achieved LEED Platinum certification. The project was opened to the public in 2012 [39, 18].

The complex (dubbed "the urban pyramid") simulates a city-within-a-city or a "vertical neighborhood." It occupies two city blocks covering 200 m by 200 m (656 ft by 656 ft) and is sheltered by a mega pyramidal envelope. A spinal bridge connects the two opposite ends of the blocks diagonally, allowing outside pedestrians to make a walkable shortcut through the complex. Parkview Green complex comprises four towers (two 9-story & two 18-story towers) that include luxury retail spaces, Grade-A commercial office space, a luxury boutique hotel, restaurants, a state-of-the-art cinema, and an underground parking garage. The complex's components include towers, atria, sky-gardens, terraces, and bridges, which cluster around a central interior space (courtyard or public plaza) and are sheltered by way of a microclimatic envelope.

Technologically, the mega pyramid's microclimatic envelope comprises a Texlon ETFE membrane system of glass and structural steel façades. The envelope protects tenants and visitors from adverse weather conditions while providing an outdoor environment with abundant natural light and thermal comfort. ETFE provides numerous advantages. It does not degrade under ultraviolet light or atmospheric pollution. It also facilitates the transmission of light and is very low weight compared to that of glass (about 1%), creating light and elegant structures. The smooth and non-stick outer surface of Texlon ETFE is self-cleaned externally by rain, while the inner surface of cushions may be cleaned with water every few years. Texlon ETFE is 100% recyclable. The ETFE roof is set at a constant distance of 3 m (10 ft) from the inner buildings to maintain air movement [6, 17].

The pyramidal form stimulates the natural stack effect or "natural chimney" effect that allows hot air to rise and exit through the roof. As the air escapes, cooler and fresher air is drawn up from the bottom of the building, creating air movement and natural ventilation. Furthermore, the complex is "sunken" down 10 m (30 ft) below street level and recessed about 15 m (50 ft) to provide another buffer space that contains a sunken garden. In the summer, this garden is the coolest space in the building and supplies the complex with intake air through operable openings in the basement. Interestingly, a large waterfall with fountains is located in the garden, which helps cool air in the summer while simultaneously increasing oxygen levels [40].

The complex also incorporates water-conservation systems, including electronic taps, water-saving sanitary ware, and low-flow shower facilities. Wastewater from sinks, showers, and washing faucets are also treated for flushing and irrigating the native, drought-resistant plants present in the surrounding landscape. The complex also gathers rainwater from the roof and paved areas, filtered and recycled to irrigate the landscaped areas. Native plants and trees were chosen for their low water intake and low maintenance. Collectively, the sustainable strategies employed at the Parkview Green FangCaoDi add up to a savings of 48% in water use.

The structure includes recycled content from building demolitions, and 25% of the total building materials were made from recycled materials. Quickly growing softwoods were used instead of hardwoods. The design of the interior spaces embraces an adaptive reuse scheme to accommodate future changes and rising needs, enabling tenants to save 10-15% on renovation costs. The project also pursued a "green" construction standard where 81% of its construction waste was recycled, minimizing the complex's carbon footprint [4, 20].

2.12. Al Bahar Towers

Al-Bahar Towers, the new headquarters for the Abu Dhabi Investment Council, occupies a prominent site on the North Shore of Abu Dhabi Island in the United Arab Emirates (UAE). Completed in 2012, the project comprises two 25-story, 150 m (490 ft) tall office towers. They are among the first buildings in the Gulf to receive the U.S. Green Building Council LEED Silver rating [20].

The architectural design of Al Bahar Towers relies on local climate and culture, perhaps the intuitive and longstanding sources of inspiration for any design. The towers have modernized the traditional mashrabiyya, a shading device formed by perforated wooden-lattice screens in geometric patterns that are commonly found in vernacular Islamic architecture. The traditional mashrabiyya fulfills multiple functions by providing privacy, reducing solar gain, and protecting inhabitants from glare. Furthermore, it adds visual complexity and interest to the building's exterior. However, unlike the static and two-dimensional traditional mashrabiyya, Al-Bahar's mashrabiyya is dynamic and three-dimensional, consisting of a series of transparent units [made of PTFE (polytetrafluoroethylene)] that open and close in response to external solar conditions. Sensors on the façades communicate solar conditions to the building's management system (BMS), which controls the opening and closing of the units—creating an intelligent façade [17, 18, 20].

The outer skin is set two meters from the inner skin, consisting of a glass curtain wall. The mashrabiyya system—forming the outer skin—features 2000 translucent umbrella-like units (1000 on each tower), which have been strategically placed along the exterior to block the direct light of the sun. In response to direct sunlight, the mashrabiyya can unfold to cover the façade, and when the sun is obscured, they can close to allow for light penetration. Parametric and algorithmic modeling has been used to optimize the mashrabiyya's location on the façade, precluding the use of dark tinted glass, which would permanently restrict incoming light. The system provides a 50% reduction in solar gain, decreasing energy consumption and CO_2 emissions. Geometrically, the mashrabiyya system follows a hexagonal pattern that simulates traditional Arabic-Islamic design. As the mashrabiyya system opens and closes, the towers constantly change their appearance stimulating intriguing aesthetics. The south-facing roof of each building incorporates photovoltaic cells to generate enough power to operate the mashrabiyya system adequately. The system was designed by Aedas from London Studio in collaboration with the engineering firm Arup.

3. Discussion

3.1. Vital Green Features

The reviewed case studies offer a wealth of green features. These are inspirational and form a solid foundation for architects interested in sustainable skyscrapers. Table **1** summarizes the prime green features of each case study. It gives the reader a quick overview and comparison among the different buildings. We notice that there are some overlaps. Therefore, Table **2** offers a shorter summary of shared green features by grouping them based on critical topics.

Table 1: Summary of vital green features that were used in the examined case studies.

#	Building	Green Features
1	***Bank of America Tower*** ***NYC*** ***55-story*** ***2009***	• on-site cogeneration plant, ice storage system • building-integrated photovoltaic (BIPV) system • the air filtration system removes 95% of airborne particulates • air monitoring system tracks CO_2, CO, VOCs, and small particulates • curtain wall with low-E glass and heat-reflecting ceramic frit automated dimming system • water management and recycling system (greywater); harvest rainwater; waterless urinals and low-flow fixtures • a high percentage of the building's materials and furniture come from recycled or locally sourced materials located within 800 km (500 mi) of NYC • building's steel was made from 87% recycled materials, and the concrete was made from cement containing 45% recycled materials • interior materials are low-VOCs, sustainably harvested, manufactured locally, and recycled wherever possible • 91% of all construction and demolition waste was recycled or otherwise diverted from going to landfill
2	***The Visionaire Tower*** ***NYC*** ***35 stories*** ***2008***	• insulated low-E curtain wall and terra cotta rain-screens that provide thermal insulation reduce the need for heating and cooling and accentuate aesthetics • the curtain wall was prewired for motorized solar shades to reduce solar gain • a single master switch at the entrance of each unit allows residents to turn off lights in all rooms simultaneously as they leave the residence • building-integrated solar panels • 35% of its electric load is sourced from Green-e energy certified provider that employs wind and other renewable energy sources • natural gas powers the residential cooling systems and contributes to the lowering of peak electricity demands on New York City's power grid • on-site blackwater treatment system; low-flow fixture, harvesting rainwater • building's potable water is centrally filtered • uses environmentally safe paints, adhesives, and sealants, and no or low VOCs materials to provide healthful indoor environments • wood was harvested in conformity with Forest Stewardship Council certified standards • half of all materials used to construct the tower were sourced within an 800 km (500 mi) radius
3	***One World Trade Center*** ***NYC*** ***105 stories*** ***2014***	• twelve hydrogen fuel cells, which generate 4.8 megawatts of power, partially power the tower • waste heat output from the fuel cell system is recycled and used for hot water and heating • Central Chiller Plant • the building draws as much as 70% of its power from green energy sources • a water management system that collects rainwater and recycles greywater, which is used to cool the building, irrigate the landscape, and provide fire protection • low-flow plumbing fixtures • curtain wall with insulated glazing units and ultra-clear glass • automatic dimming devices • over 3000 monitoring stations within the building were linked to air handling software to provide fresh air when necessary • building's structural materials contain a minimum of 75% recycled materials • used Green Concrete • fifty percent of all wood products installed in the tower were certified by the Forest Stewardship Council • the building does not contain VOCs or chemicals that leach in a gaseous form
4	***The Tower at PNC Plaza*** ***Pittsburgh, PA*** ***33 stories*** ***2015***	• DSF incorporates vents in the outer skin, operable windows in the inner skin with the 1-m (3-ft) cavity. They work in a concert of building management system (BMS) informed by sensors to facilitate natural ventilation • solar chimney, which enables the exhaust of hot air through the stack effect • water conservation and management systems that treat grey and black water, harness rainwater, and utilize low-flow fixtures • uses locally sourced building materials, including FSC-certified red maple wood grown in western Pennsylvania • building's furniture was made from recycled materials • small lease span

Table 1 (contd….)

#	Building	Green Features
5	***Salesforce Tower*** ***San Francisco, CA*** ***80 stories*** ***2018***	• full outside air economizer ventilation systems with floor-by-floor air intake via high-efficiency air-handlers • Underfloor Air Distribution (UFAD) reduces dependence on HVAC systems and improves occupant comfort and zone controllability • floor-to-ceiling glazing • water management and recycling system that reduces water use by 54% • rooftop "City Park"
6	***Devon Energy Center*** ***Oklahoma, OK*** ***50 stories*** ***2012***	• floor-to-ceiling glazing with high-performance clear glass and low-E coating • raised-floor office environment • energy use has been modulated by district cooling with on-site cogeneration • water conservation system that contains highly efficient plumbing fixtures and recycles used water, reducing consumption by up to 40% • materials from the pre-existing parking lot and garage were reused in the new site, diverting 68,000 tons of waste and concrete from landfills
7	***Manitoba Hydro Place (MHP)*** ***Province of Manitoba, Canada*** ***21 stories*** ***2009***	• heating and cooling are provided primarily by a geothermal system • a natural ventilation system is provided by a solar chimney, automated and operable windows, and three 6-story winter gardens, containing water features that humidify/dehumidify the fresh air • narrow floor plates • floor-to-ceiling glazing • DSF with a 1 m (3ft) wide cavity • T5 fluorescent lights with sensors and a dimming system • intensive, deep-soil green roofs • low-profile (only 21 stories) • 80% of the building's materials come from previously existing structures on the site
8	***The Bow*** ***Alberta, Canada*** ***58 stories*** ***2012***	• efficient diagrid structural system • aerodynamic form • sky gardens that run the full height of the atria and act as climatic buffer zones that insulate the inner office space
9	***Shanghai Tower*** ***Shanghai, China*** ***121 stories*** ***2015***	• the tower is divided into nine vertical neighborhoods with 12-to-15-story-tall sky gardens, which act as buffer zones between the inside and the outside and form DSF • the tower's form aims to resist the typhoon-level winds by embracing multiple strategies, including asymmetry, tapering, rounded corners, and a reduced floor plate as the tower rises • advanced lighting controls • efficient Central Plant • wind turbines • natural gas-fired cogeneration system • rainwater collector • greywater recycling system • mixed-use tower
10	***Greenland Group Suzhou Center*** ***Suzhou, China*** ***78 stories*** ***2021***	• a 30-floor atrium that facilitates the vertical stack effect • water management and conservation system that uses efficient building fixtures, rainwater harvesting, condensate recovery • aerodynamic form • mixed-use tower
11	***Parkview Green FangCaoDi*** ***Beijing, China*** ***18 stories*** ***2012***	• pyramidic "microclimatic" envelop that improves the thermal performance of the building, which work in tandem with natural stack ventilation • DSF with a significant gap that improves the building's thermal performance • water-conservation features; greywater system • mixed-use complex • 25% of the total building materials were made from recycled materials • employing Texlon ETFE, 100% recyclable material • 81% of its construction waste was recycled, minimizing the complex's carbon footprint
12	***Al-Bahar Towers*** ***Abu Dhabi, UAE*** ***25 stories*** ***2012***	• outer skin revives the traditional mashrabiyya. It comprises a series of transparent umbrella-like units [made of PTFE (polytetrafluoroethylene)] open and close in response to external solar conditions. Sensors on the façades communicate solar conditions to the building's management system (BMS), which controls the opening and closing of the units

Table 2: Green features based on key topics.

Topic	Green Features
Energy sources	• wind turbines • solar panels/ building-integrated photovoltaic (BIPV) system • on-site cogeneration plant • natural gas-fired cogeneration system • Central Energy Plants • Green-e energy certified provider
Water management and recycling systems	• rainwater harvesting systems • recycling greywater and blackwater systems • low-flow fixtures • waterless urinals
Heating and Cooling	• geothermal systems • ice storage system • the low-E coating that improves the thermal performance of glass • reduce demand on cooling by employing shading systems and heat-reflecting ceramic frit
Air quality	• Natural systems: • automated and operable windows • DSF with significant cavity and vents in the outer skin and operable windows in the inner skin • solar chimney • gardens with water features • tall atria with vents that facilitate the vertical stacking effect • Engineering systems: • complete outside air economizer ventilation systems with floor-by-floor air intake via high-efficiency air-handlers • under-floor air distribution (UFAD) • monitoring stations/sensors that track CO_2, CO, VOCs, and small particulates • sensors are linked to air handling software to provide fresh air when necessary • air filtration systems
Lighting	• Natural lighting: • narrow floor plates or shallow lease span • floor-to-ceiling glazing • Artificial lighting: • automated dimming systems • T5 fluorescent lights
Form	• an aerodynamic form that improves the tower resistance to wind, particularly at higher altitudes where the wind is most potent (e.g., asymmetry, tapering, rounded corners, and a reduced floor plate as the tower rises) • articulate form and reduced height to minimize casted shadow
Materials and systems	• environmentally safe paints, adhesives, and sealants, and no or low VOCs materials • locally sourced materials • recycled and recyclable materials • wood products that are certified by the Forest Stewardship Council • green concrete • efficient structural systems such as the diagrid
Furniture	• made from recycled materials • locally sourced
Construction and demolition process	• recycle and use materials of previously existing structures on the site • recycle and use waste generated materials by the construction process
Landscaping	• vertical landscaping such as green walls, sky gardens, and green roofs
Function	• a mixed-use scheme that integrates multiple uses such as retails, residential, office, hotel, amenities, and recreations
Accessibility	• locate close to mass transit nodes

3.2. COVID-19 and Sustainable Skyscraper Design

Most of the examined buildings were conceived and constructed before COVID-19. However, the recent pandemic has stressed the sustainability mission of making our buildings healthier. For example, COVID-19 has reminded us of the importance of natural ventilation that helps reduce the spread of the virus. In the post-pandemic era, it will be easier to make the case to invest in intelligent systems that ensure a high-quality air supply. Likewise, it is likely to be easier to make a case for water filtering systems to fight situations where a virus can contaminate the water supply.

The pandemic also has reminded us of the importance of green and communal spaces within and around tall buildings, on and beyond the ground level, such as sky gardens, sky parks, green roofs, Phyto walls (modular wall system comprising containers of hydroponic plants), public parks, indoor gardens, plants, and open spaces to offer occupants accessibility to nature within tall buildings and combat adverse effects of high density. Architects and tenants will value outdoor elements such as terraces, courtyards, gardens, and balconies to ease access to natural ventilation, daylight, and fresh air.

Further, because of the pandemic, many people will likely favor natural elements such as green landscaping and community gardens to improve air quality and reduce carbon emissions resulting from transporting food. Similarly, the pandemic has taught us the importance of bringing natural light and sun rays into our buildings and public spaces to kill germs and improve our bodies' immune systems. Extra hygiene could be further emphasized in dense places (such as high-rise buildings) in every aspect and scale, such as elevators, stairways, hallways, corridors, door handles, and the like. For reinforcing indoor hygiene, many other innovations will take place. Spaces for exercise and meditation are likely to be emphasized in future offices. Therefore, we predict that a "value" shift is underway. As public health becomes a priority, the sustainability mission will become a priority [40, 41].

4. Conclusion

This article maps out vital green features of "sustainable" skyscrapers. The identified elements are extracted from outstanding projects that received international recognition, including LEED certification. Architects and engineers will likely find the narrative of each case study and the summary tables helpful to review ideas and innovative work. While not all identified features apply to every project, architects and engineers can choose what fits a particular project. The discussed and listed ideas may spark further innovative work. Finally, COVID will likely underscore the sustainability mission, making this research truly valuable.

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