Journal of Sustainability for Energy
https://www.acadlore.com/journals/JSE

Effect of Modern Technologies of Energy Conservation on Forming High–Rise Buildings

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Received: 08-19-2023 **Revised:** 09-14-2023 **Accepted:** 09-21-2023

Citation: L. M. Yahya, "Effect of modern technologies of energy conservation on forming high–rise buildings," *J. Sustain. Energy*, vol. 2, no. 3, pp. 119–131, 2023. https://doi.org/10.56578/jse020302.

Abstract: High-rise edifices are emblematic of contemporary construction, encapsulating advancements in environmental, formal, and structural design approaches. Such structures, often considered to consume substantial amounts of energy, primarily due to air conditioning and lighting, epitomise urban progression in developed regions. Concerns over energy and resource consumption have necessitated the exploration of viable alternatives for mitigating energy usage. In response, architectural endeavours have gravitated towards harnessing modern technologies to curtail energy demands, especially in high-rise constructions. Several architectural trends have subsequently emerged, each leveraging a myriad of techniques with the intent to diminish energy usage. This research, therefore, sought to elucidate the technologies deployed in energy conservation for high-rise buildings and subsequently discern their ramifications on architectural formulation. Adopting a qualitative-descriptive approach, an analytical examination was conducted on fifteen distinct cases of energy-efficient structures, aiming to gauge the influence of such technologies. Data, procured from visual and descriptive evaluations, were systematised using an observation sheet. It has been observed that certain environmentally-focused design methodologies may inadvertently compromise the architectural aesthetics of high-rise structures. Consequently, there emerges a pressing need for architects to harmonise aesthetic aspirations with contemporary energy-saving imperatives, ensuring judicious use of natural resources.

Keywords: High-rise structures; Double-skin facade; Energy conservation; Environmental design approach; Shading techniques

1 Introduction

In recent decades, heightened awareness of sustainability has illuminated the deleterious effects of energy consumption on climate change and the broader environment. The rapid advancement of technology is noted to escalate energy demand, aligning with the evolving requirements of the technological era. Furthermore, concerns regarding the energy crisis and the imminent depletion of conventional energy sources have steered scholarly and design focus towards energy reduction, emphasising the integration of renewable energy sources such as solar and wind energy [1].

Energy reduction is often defined by scholars as the optimal utilisation of available energy, while energy efficiency is characterised by the capacity to yield optimal outcomes with minimal wastage in energy, manpower, resources, and finances [2]. In several developed nations, it has been observed that the construction industry accounts for as much as 65% of total energy consumption [3]. High-rise structures, in particular, have emerged as a prominent architectural trend in both developed and developing nations and are identified as some of the most energy-intensive building types. Thus, the matter of energy reduction in high-rise structures has garnered substantial academic interest [4].

Historically, Chicago is recognised as the pioneering city for high-rise structures. Such a building is typically defined as a tall edifice, distinct in its urban context, significantly influencing the city's skyline [5]. The proliferation of high-rise buildings is attributed to various factors, including technological advancements in construction, burgeoning urban populations, and escalating land costs [6]. A classification of high-rise structures, based on their height, is delineated in Table 1 [7].

Energy conservation in high-rise structures can be realised by judiciously reducing energy consumption within the building and capitalising on site-specific attributes. Furthermore, energy conservation strategies for these edifices are recommended to incorporate renewable energy systems and align with the latest technological innovations, as depicted in Figure 1 [8, 9].

Table 1. Classification of high-rise structures based on height parameters

Type	Maximum Height	Number of Floors
Small high-rise building	< 74 m	13 to 18
High-rise building	< 120 m	19 to 30
Very-high-rise building	< 240 m	31 to 60
Ultra-high-rise building	> 240 m	more than 60

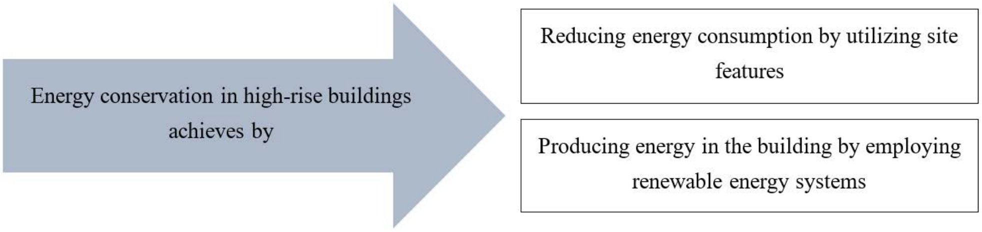


Figure 1. Techniques for energy conservation in high-rise edifices, adapted from Saeed [8] and Mostafavi et al. [9]

Introducing modern technologies for energy conservation in high-rise structures has been observed to influence the architectural form of the building. Architectural form, as defined, pertains to the external, sensory construction of materials and is a consequence of organising a set of elements within a governing framework. These elements are defined by a specific set of relationships and principles that guide their interrelation. A pertinent research inquiry posed in the present study is: "How might the application of contemporary technologies for energy conservation influence the architectural form and formulation system in high-rise structures?" To address this query, it is essential to underscore the research objectives, which, in turn, inform both the literature review and the chosen methodology.

The primary focus of this research is to elucidate the repercussions of employing modern technologies for energy conservation on the design and structural features of high-rise edifices. Emphasis is placed on two prominent technologies, as illustrated in Figure 1 and informed by the works of Saeed [8] and Mostafavi et al. [9]. These are: modern techniques aimed at energy consumption reduction, including insulation techniques, double-skin facades, courtyards, shading methods, and intelligent building technologies; and renewable energy system technologies, encompassing the integration of solar photovoltaic panels and wind turbine systems. A refined framework, based on descriptive analysis from selected case studies across the globe, is adopted in this study.

Energy consumption in high-rise structures remains a subject of paramount importance, largely due to mounting urbanisation and the escalating global demand for sustainable building practices. With high-rise edifices becoming ubiquitous in major global cities, their energy consumption has profound implications both for environmental sustainability and economic efficiency. The energy intensity of these structures is notably significant, necessitating vast electrical resources for lighting, heating, cooling, ventilation, and other amenities. According to the International Energy Agency (IEA), structures account for nearly 36% of global energy consumption and almost 40% of CO_2 emissions, both direct and indirect. High-rise structures, owing to their expansive size and population capacity, contribute substantially to this energy consumption, which holds extensive ramifications for sustainable urban planning and economic viability. Hence, endeavours focused on the energy efficiency of high-rise edifices are crucial for sculpting sustainable future urban landscapes.

The energy demands of a typical residential edifice can fluctuate markedly, contingent on various determinants such as location, dimension, design, insulation standards, appliance efficiency, and the HVAC systems in place. In terms of space heating and cooling, it is noted that these are the predominant energy consumers in residential settings. An average U.S. dwelling, for instance, might utilise around 4,000 to 5,000 kWh of electricity or its natural gas equivalent annually, subject to climatic conditions and heating and cooling system types. Furthermore, energy consumption from appliances and lighting has been found to diverge based on the efficiency and number of appliances. Approximately, these utilities account for 20-25% of a household's energy demand, amounting to nearly 2,000 to 2,500 kWh annually. Consequently, an average residential structure might expend between 10,000 to 13,000 kWh of electricity or its equivalent in natural gas yearly. However, such consumption is observed to vary considerably across regions and individual households. Notably, more energy-efficient dwellings, possibly equipped with superior insulation, efficient appliances, and renewable energy installations, might have markedly lower consumption than the aforementioned estimates.

This study is poised to identify contemporary technologies designed to augment energy conservation in high-rise structures, particularly highlighting the implications on the architectural formulation system. To fulfil these aims, 15 international case studies, derived from various geographic locales featuring high-rise structures, have been selected for analysis, with variables distilled from preceding studies detailed in subsequent sections.

2 The Impacts of Energy Conservation Technologies on Architectural Form

A considerable body of literature has been devoted to elucidating the repercussions of integrating modern energy conservation technologies with regard to building form and functionality. In their seminal work, Zhigulina and Ponomarenko [10] posited that the incorporation of advanced technologies into building construction necessitates a strategic emphasis on energy-efficient applications. This involves harnessing diverse technologies capable of converting renewable energy sources into efficient energy required for both the construction and operation phases of buildings. Comparisons have been drawn between LEED and BREEAM systems for evaluating these technological implementations, with particular attention given to the eventual architectural outcomes [10]. A noteworthy observation was made by Sev and Tuğrul [11] who underscored the profound influence of technological advancements on architectural design, more prominently in the realm of tall structures. Two paramount technological criteria, namely Ideological (pertaining to intellectual systems) and Physical (related to structural systems), were identified as pivotal in shaping the formative system of towering edifices [11].

The symbiosis between energy conservation technologies and the design ethos of tall structures was further illuminated in a competition orchestrated by eVolo magazine, as highlighted by Erdoğan and Begeç [12]. Submissions manifested as futuristic architectural prototypes that married innovative technological techniques with digital design software, yielding structures characterized by freedom, dynamism, and a pronounced environmental ethos [12].

Shedding light on sustainable environmental strategies, Elotefy et al. [13] posited the significance of an integrated approach in high-rise design, aiming for optimal energy conservation across stages, ranging from initial design conceptualisation to operational management. The choice of an efficacious strategy, it was argued, is contingent upon the site's climatic conditions. Their contribution lay in the proposal of sustainable strategies with minimal architectural form impact [13].

While previous studies broached the topic of energy usage efficiency in the context of tall building designs, a lacuna remains concerning the foundational principles governing the adoption of contemporary energy conservation technologies and their ramifications on architectural form. There exists a potential risk of compromising aesthetic integrity in the singular pursuit of energy efficiency. This nexus between form and function, where architectural beauty coexists harmoniously with energy conservation, merits further exploration.

The present inquiry, therefore, seeks to establish a theoretical framework delineating the confluence of advanced energy conservation technologies with architectural form. This framework is predicated on insights gleaned from extant literature, aiming to gauge the nature and magnitude of the relationship between energy conservation mechanisms and architectural aesthetics, which could manifest as either synergistic or antagonistic interactions.

3 Energy Conservation in Building Design

Energy conservation in the architectural realm emerges as a pivotal mechanism for curtailing energy consumption. Architectural strategies have been developed to minimise energy utilised for lighting, ventilation, and air conditioning, whilst concurrently ensuring optimal comfort for inhabitants. The building envelope, recognised as the barrier demarcating the internal and external ambiances of an edifice, is identified as a determinant of energy consumption patterns [14]. It has been noted that design intricacies of this envelope directly influence heating and cooling demands, subsequently abating reliance on mechanised air conditioning systems.

Heat-insulating materials are deployed to attenuate heat transfer between a building's interior and exterior. The efficacy of the building envelope is observed to be augmented through the employment of diverse insulating variants. For instance, the envelopment of structures with the ICF model, heralded as one of the most robust insulating types, presents formidable resistance to penetration, thereby moderating the edifice's temperature by regulating ingress and egress of air [15]. In parallel, reflective constituents, including reflective glass and multi-layered window systems, have been utilised to temper the thermal repercussions of solar radiation, devoid of compromising visibility. An intriguing development is the introduction of gel substances capable of preserving up to 75% of natural light transmittance as an insulator for glass, complemented by innovations like Nano paints [16].

Among the pantheon of technologies dedicated to energy conservation, double-skin façades are lauded for their efficacy. Characterised by the addition of a secondary glazed layer to an edifice's façade, these structures facilitate an optimal influx of natural daylight, devoid of concurrent heat transfer, thus bolstering the energy performance within the structure [17–19]. Ventilation mechanisms underpinning double-skin façades are contingent upon the air circulation within the façade's cavity, stemming from temperature differentials between the building's exterior, the cavity, and its interior [19]. This system is reported to diminish thermal loads within interior spaces, offering a dual advantage: it acts both as a bulwark against excessive heat and as a modulator of heat gain and loss, paving the way for enhanced lighting efficiency. Additionally, solar energy harnessed on the double façade, particularly via a dehumidification system, can be channelled to mechanical tiers through direct gain, thereby servicing heating demands. Architecturally, double-skin façades manifest in diverse configurations, spanning Box façades, Box-frame façades, Air passage interfaces, Multi-storey façades, to Ventilated façades [13].

Efforts to eliminate or mitigate portions of façades subjected to intense solar radiation have been explored, revealing the potential to create spaces conducive for daylight penetration, augmenting spatial misinformation, and minimising solar gains [20]. It has been observed that such spaces can either interface or undergo spatial shifts, resulting in openings exposed to the external environment. These openings are postulated as crucial connectors between the interior and the surrounding milieu. The induction of external apertures, in conjunction with a central courtyard, has been documented to fortify natural ventilation, predominantly leveraging the chimney effect. Notably, windows, regarded as primary conduits for heat and light penetration into edifices, necessitate meticulous considerations. Various shading methodologies, calibrated in response to the sun's diurnal trajectory, its positional shifts, and radiation interception objectives, have been delineated in the literature. Among these, solar breakers emerge as prominent, targeting the curtailment of undesired solar radiation either on the building's external shell or its internal ambiances [21]. Efforts to modulate natural lighting have led to the development of distinct solar breaker designs, encompassing horizontal, vertical, and dual orientations. An integration of solar cells with solar breakers, which are reportedly rotatable and self-regulating, has been devised to accommodate the sun's dynamic inclination and facilitate optimal energy production [21]. Furthermore, automatic curtains, responsive to solar activities (termed self-moving façades), have been recognised as potent instruments in refining internal building conditions and optimising energy expenditure by dynamically altering the thermal and optical properties of building envelopes in tandem with climatic shifts [15]. Their deployment is asserted to attenuate energy consumption by mediating solar energy dynamics, encompassing both gains and losses, thereby diminishing solar radiation impacts on structures and bolstering natural lighting efficacy [22].

A noteworthy approach to shading is the incorporation of vegetation, both in terms of external green spaces and the infusion of plants within architectural designs, referred to as green construction [23]. Such biophilic interventions have been posited to not only offer shading to interior spaces and external walls but also mitigate reflective aberrations. The cooling effect attributed to water evaporation processes on building façades has been studied extensively [24]. Such processes are suggested to curtail the consumption of cooling energy and act as barriers against wind in high-rise structures [25]. An innovative manifestation of the green building concept is through the utilisation of green façades or walls, often termed 'living walls'. These comprise the cultivation of either climbing or sequential vegetation, covering entire façades or dedicated support structures designed for the purpose [26]. Green roofing, another facet of this approach, introduces vegetation atop buildings. Beyond providing a verdant expanse, these roofs have been indicated to diminish thermal loads on structures, functioning as insulators and preventing excessive heat transfer [27]. Reports suggest that the employment of green building techniques can lead to a reduction in energy consumption by 24% to 50% [28].

The incorporation of green technologies has been identified as a pivotal mechanism for optimising energy resource utilisation, thereby enhancing the building's habitability for its occupants. Within this spectrum, smart materials—characterised by their ability to adapt to external stimuli—are discerned into three primary categories: those capable of property alterations, those proficient in energy conversion, and those designed for reflection [29]. Buildings, when interfaced with intricate computer networks that govern subsystems like heating, cooling, ventilation, lighting, and fire protection, have been noted to operate with heightened automation. The array of smart technologies also encompasses myriad energy measurement apparatus, including smart meters, energy storage devices, sensors for lighting detection, and systems for automated light management [30].

Furthermore, weather sensors, tasked with monitoring parameters such as temperature, wind velocity, and solar illumination levels, are integral components of what is colloquially termed 'smart buildings'. Such edifices are postulated to harness advanced control systems to achieve optimal performance levels, whilst maintaining minimal energy consumption [31]. Specifically, these technologies and materials are credited for introducing environmental controls within buildings, offering automated surveillance and regulation of air conditioning properties and electrical supply, ultimately curtailing energy wastage.

Transitioning to renewable energy systems is frequently emphasised as paramount in fostering a sustainable and eco-conscious energy framework. In high-rise structures, unique architectural features, such as extensive surface area and elevated height, are perceived as valuable assets for energy generation. Wind energy, harnessed and converted into electrical or mechanical power, or directly channelled for building ventilation, is one such modality. Simultaneously, solar energy, either transmuted into power or directly assimilated for building heating and illumination, presents considerable promise. When solar and wind energies are conjointly utilised, energy savings of up to 35% have been documented [32]. Solar photovoltaic panels, replacing conventional construction materials on exteriors like roofs, façades, and skylights, have garnered significant attention, particularly in the context of high-rise edifices, as formidable energy generation tools [33]. Furthermore, advancements in photovoltaic panel design allow for flexibility, facilitating installation on contoured surfaces.

Wind turbines, pivotal in the generation of clean energy, have evolved substantially. Their integration into towering structures has been pursued with vigour. Such convergence of renewable energy technologies within tall edifices seeks to diminish their reliance on conventional energy sources. It is posited that the synergy between external and internal environments profoundly influences energy efficiency, fostering a conducive internal ambiance, especially in functionally intensive structures [34].

Table 2 summarises the predominant techniques employed to bolster energy conservation in high-rise buildings. Broadly, these can be categorised as:

•**Solar Energy**: Sunlight is harnessed predominantly through Photovoltaic (PV) cells, which directly transmute solar radiation into electricity. In contrast, solar thermal systems leverage sun-induced fluid heating to drive generators. Common manifestations include solar panels on edifices or expansive solar farms.

•**Wind Energy**: Energy is derived from air movement via wind turbines. The kinetic energy of wind is captured as it propels turbine blades, thus generating electricity. Dedicated wind farms, erected in regions with consistent wind patterns, ensure maximised power generation.

•**Hydropower**: Flowing water's potential energy is channelled for electricity production. Constructions like dams facilitate reservoir creation, and the regulated water flow through turbines culminates in power generation.

•**Biomass Energy**: Organic materials, spanning wood to agricultural by-products, serve as energy sources. Direct combustion yields heat, whereas biogas or biofuel conversion can facilitate electricity generation.

•**Geothermal Energy**: The Earth's core heat is the focal energy source. Drilled wells tap into geothermal reservoirs, and the ensuing hot water or steam is employed to drive turbines.

•**Ocean Energy**: This umbrella term encapsulates tidal energy, wave energy, and ocean thermal energy, each harnessing distinct oceanic dynamics for power.

•**Hydrogen Fuel Cells**: While not directly renewable, when hydrogen production sources are renewable (e.g., water electrolysis), fuel cells offer a sustainable energy conversion mechanism, with applications in both stationary and transportation sectors.

Table 2. Energy conservation strategies in high-rise edifices

<table>
<tr><td rowspan="27">Technologies of Energy Conservation in High-Rise Buildings</td><td rowspan="24">Modern technologies of reducing energy consumption</td><td rowspan="3">Insulation technique</td><td colspan="3">Use of double walls</td></tr>
<tr><td colspan="3">High performance reflective glass</td></tr>
<tr><td colspan="3">Use of conventional or Nano insulating materials</td></tr>
<tr><td rowspan="5">Double skin facades technique</td><td colspan="3">Box facades</td></tr>
<tr><td colspan="3">Box frame facades</td></tr>
<tr><td colspan="3">Air passage interfaces</td></tr>
<tr><td colspan="3">Multi-storey facades</td></tr>
<tr><td colspan="3">Ventilated facades</td></tr>
<tr><td rowspan="4">Court technique</td><td colspan="2" rowspan="2">Interspaces</td><td>opposite spaces</td></tr>
<tr><td>non-adjacent spaces</td></tr>
<tr><td colspan="3">Continuous central courtyard</td></tr>
<tr><td colspan="3">Non-continuous central courtyard</td></tr>
<tr><td rowspan="10">Shading technique</td><td rowspan="6">Full</td><td rowspan="3">Green building technologies</td><td>green facades or walls</td></tr>
<tr><td>Cultivation of roofs at different levels</td></tr>
<tr><td>Use them together</td></tr>
<tr><td rowspan="3">Automated interfaces</td><td>Folding items in different shapes</td></tr>
<tr><td>foldable items</td></tr>
<tr><td>vertical, horizontal, moving elements</td></tr>
<tr><td rowspan="4">Partial</td><td rowspan="2">solar refractors</td><td>Horizontal or vertical curtain walls</td></tr>
<tr><td>Integrated breakers with solar panels</td></tr>
<tr><td colspan="2">balconies</td></tr>
<tr><td colspan="2">Rotated or tilted of the masses</td></tr>
<tr><td rowspan="2">Smart building technology</td><td colspan="3">Building automation and the use of sensors</td></tr>
<tr><td colspan="3">smart materials</td></tr>
<tr><td rowspan="3">Technologies of renewable energy systems</td><td colspan="4">Solar photovoltaic panels</td></tr>
<tr><td rowspan="2">Wind turbine system</td><td colspan="3">Horizontal</td></tr>
<tr><td colspan="3">Vertical</td></tr>
</table>

4 Architectural Formulation of Building Structures

The architectural formulation serves as an external manifestation of materials, delineating a process wherein visual vocabulary and design principles are transformed into structured blocks and spaces through a specific system [35]. This process of organisation encompasses elements within a guiding framework of relationships, defining their interrelation. Successful formulation is discerned through relationships that foster an urban unit embodying both structural and visible qualities, such as the juxtaposition of light and shadow, and the interplay between solids and voids [36]. This collective assembly of parts and their interconnectedness, both internally and externally, bestows the unique character to a structure. It is this meticulous formulation that births novel characteristics and relationships [37].

The design configuration of buildings is influenced by myriad elements. Technical components, for instance, engender innovative architectural formations, rejuvenating and modernising architectural concepts [36]. Furthermore, it is posited that the aesthetic of the architectural form reaches fruition when it aligns with the intrinsic forces that mould it [36]. The relationship between modern design technologies and the proliferation of knowledge remains reciprocal and synergistic [37]. Formative tools such as shape, colour, texture, and luminosity are not independent entities but collaboratively function [36].

It has been observed that the integration of energy-conservation technology and architectural form holds a pivotal, interwoven relationship. The design and establishment of structures, alongside the assimilation of energy-efficient technologies, significantly contribute to the minimisation of energy wastage and environmental repercussions, paving the way for more sustainable architectural environments. The architectural form can be influenced by and tailored to cater to environmental requirements and energy utilisation technologies as elucidated below:

•**Building Envelope Design**: It has been demonstrated that a building's architectural configuration directly correlates with its energy performance. Factors such as building orientation, window size and positioning, insulative materials, and shading devices, which all stem from architectural decisions, profoundly affect a building's energy efficiency. For instance, passive solar architectural designs that optimally utilise natural sunlight can drastically reduce energy needs.

•**Energy-Efficient Materials**: High thermal insulation properties or materials with reduced embodied energy are often chosen by architects, impacting a building's energy consumption and overall sustainability.

•**Ventilation and Airflow**: Architectural designs promoting natural ventilation and passive cooling have been developed. Features facilitating natural airflow have been shown to reduce the dependency on energy-intensive systems.

•**Daylighting**: Architectural designs that maximise natural daylight permeation reduce energy requirements for artificial lighting.

•**Integration of Renewable Energy**: Innovative designs incorporating features like solar panels, wind turbines, or green roofs seamlessly integrate renewable energy sources, enhancing a building's energy profile.

•**Building Shape and Compactness**: Compact designs, which minimise surface area, have been identified as reducing heat loss.

•**Smart Building Systems**: Integration of smart building systems into architectural designs optimises energy usage, adjusting energy-consuming components based on occupancy and environmental factors.

•**Energy-Efficient Landscaping**: It is found that landscaping, including shading structures, affects a building's energy profile by providing natural barriers against elements.

•**Passive Design Principles**: Passive design elements, such as thermal mass storage, have been effectively used to moderate indoor temperatures.

•**Aesthetic Considerations**: While energy-efficient methodologies remain paramount, it is equally crucial to ensure architectural forms resonate with cultural and occupant preferences.

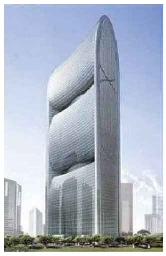
In summation, the intricate weave of architectural formation and energy-efficient technologies not only charts the course for sustainable building designs but also forges a harmonious relationship between built structures and their encompassing environments.

5 Methodology

A qualitative approach to analysis was employed for this research. Fifteen global high-rise buildings, representing varied height categories as previously described, were chosen for case studies. These structures were categorised based on their energy-saving measures, as depicted in Table 3. Case analyses were conducted using observation sheets (15 in total), which were selected based on purposeful sampling criteria. The criteria encompassed the availability of information, the incorporation of contemporary energy conservation technologies, and the aesthetic value of the buildings (refer to Table 4). Through these observations, contemporary technologies implemented within these structures were identified. These findings will be detailed in the results section to discern the most prevalently utilised technologies that positively influence architectural form. Nevertheless, a more comprehensive description of each case necessitated additional information. Consequently, a thorough examination of articles, books, and multimedia resources was undertaken.

Table 3. Chosen case studies for the research

No.	Information	Description	Image
Case 1	National Commerce Bank, Jeddah, 1984, 27 floors, 120 m height	• Early high-rise incorporating natural ventilation with three strategically placed courtyards ensuring wind circulation. • Features outdoor gardens across three levels, apparent as facade voids. • Central courtyard facilitates upward movement of accumulated heat through the roof opening. • Voided facade optimises daylight while minimising direct sunlight, consequently reducing temperatures. • Automated building control system in place. • Greenery enriches the flats (rooftops of three openings). • Tinted (grey) glass implemented to mitigate glare.	
Case 2	Commerzbank Tower, Frankfurt, Germany, 53 floors, 259 m height	• Achieves a 40% reduction in energy consumption. • Harnesses natural lighting via a central atrium. • Dual interface equipped with an air passage. • Procures natural ventilation from yards and openings. • Structure divided into three sections with floors segmented into four 12-floor units featuring private garden floors. • Advanced computer and wind chiller systems installed.	
Case 3	Deutsche Post Office Tower, Germany, 2002, 42 floors, 163 m height	• Designed to save up to 79% of heating and cooling energy. • Incorporates Sky Gardens between building halves. • Natural ventilation is achieved through central illuminators and openings. • Features a dual interface with an air passage. • Central atrium divided into sky gardens is situated between the building's halves.	
Case 4	Swiss Re Tower, London, 2004, 41 floors, 179 m height	• Engineered to save up to 50% of energy compared to similar structures. • Maximises daylighting and natural ventilation. • Building features a ventilated double glazed facade and computer-operated curtains. • Equipped with a weather sensor system and a central courtyard. • Integration of gardens is observed.	
Case 5	Bahrain World Trade Center, Bahrain, 2008, 50 floors, 240 m height	• Distinctively the first commercial structure to integrate wind turbines for energy generation, with a streamlined shape directing wind flow. • Achieves energy savings of up to 15%. • Integration of photovoltaic panels noted. • Double insulating glazing is utilised. • Building is equipped with weather sensors and automated control systems.	

No.	Information	Description	Image
Case 6	Manara Tower, 2010, 66 floors	• Achieves a notable 65% reduction in energy consumption. • Wind turbines positioned in the building's upper third. • Facade on the northwest side features integrated solar energy units, numbering 400 photovoltaic units. • Incorporates vertical gardens and a ventilated double facade. • East and west facades are adorned with solar breakers incorporating photovoltaic cells. • Maximises natural lighting, regulated by automated curtains.	
Case 7	Strata SE1, London, 2010, 43 floors, 148 m height	• Features three wind turbines at its apex, marking it as one of the pioneering buildings employing wind turbines. Generates 50 megawatt-hours annually, satisfying 8% of the building's energy requirements. • Facade designed for high thermal performance, achieving air permeability up to 50%.	
Case 8	Al Bahr Towers, Abu Dhabi, 2012, 29 floors, 145 m height	• Three sides of the building are enveloped with 2000 solar canopies which adjust automatically based on solar exposure, halving radiation influx and conserving air conditioning energy. • Equipped with double glazed airway facades, natural lighting mechanisms, sensors, and photovoltaic panels covering the facades.	
Case 9	Bosco Verticale, Italy, 2014, 26 floors, 110 m height	• Employs vertical greening with trees serving functional roles. • Achieves reduction in industrial facade materials through the integration of renewable energy systems and plants.	
Case 10	Pearl River Tower, China, 2016, 71 floors, 310 m height	• Features a double facade with air passages and self-operated luminous curtains. • Employs solar energy dehumidification systems and integrated photovoltaic panels on the southern facade and rooftop. • Incorporates solar breakers amalgamated with photovoltaic panels and vertical wind turbines on mechanical levels.	
Case 11	Cleantech Tower, United States, 2008	• Represents a high-performance, zero-energy multi-use development. • Building design focuses on harnessing natural energy resources with corner wind turbines. • Vaulted dual roof design encourages wind flow, while photovoltaic cells provide shading and solar energy benefits. • Sun breakers are programmed to adjust according to the sun's inclination.	

No.	Information	Description	Image
Case 12	Pertamina Energy Tower, Indonesia, 2015, 99 floors, 530 m height	• Rooftop design captures wind to operate vertical wind turbines, leading to energy savings of up to 25%. • Facade enveloped with photovoltaic panels. • Curved facade optimised for year-round solar energy harvesting. • Building incorporates shading panels to mitigate unwanted thermal gain and brightness.	
Case 13	The Gate, Egypt, 13 floors	• Comprises eight semi-connected towers. • Integrates nine large trees to redirect wind for natural ventilation. • Photovoltaic cells extensively cover building surfaces. • Rooftop incorporates wind turbines and green walls for energy and insulation respectively. • Building design includes double walls for enhanced insulation and integrated smart systems.	
Case 14	Al-Sheraa Building, United Arab Emirates, 15 floors	• Designed as a zero-energy structure. • Photovoltaic panels span over 20,000 m^2 of the rooftop, generating 4,000 kW. • Incorporates more than 1,000 m^2 of integrated photovoltaic panels, yielding a total of 6500 MW. • Employs intelligent systems and features an open celestial courtyard at its centre.	
Case 15	Acros Building, Japan, 14 floors	• Terraced gardens throughout the building.	

(Source: the researcher)

6 Results and Discussions

Building examples were analysed based on inferences from the theoretical framework, as indicated in Table 4. This table delineates the energy conservation technologies employed within each case, accompanied by a descriptive analysis.

The impact of each technique on the architectural formation of buildings, as well as the degree of this effect, is highlighted in Table 5. This table elucidates the relationship between modern energy conservation technologies and the consequential effects of each method. Furthermore, the intensity of usage corresponding to the location of effect is indicated.

It was observed that approximately 60% of the analysed cases employed high-performance or reflective glazing, making it the predominant insulation technique. Concurrently, double facade technology with an integrated air corridor was found in about 40% of the buildings, optimising natural ventilation and serving dual purposes of thermal and sound insulation. Specifically, 60% of high-rise and Very high-rise structures adopted this method. Vacuum techniques (or opposite spaces) were incorporated in 27% of the buildings, whilst 33% utilised atriums or ‘heavenly courtyards’. In 73% of the structures, shading techniques employing rooftop vegetation were evident at various levels. Meanwhile, dynamic facades for shading were evident in 46% of cases, with 27% integrating adaptable elements in diverse configurations.

About 60% of the selected case studies strategically positioned structures to optimise sunlight, thereby facilitating energy generation and enhancing wind utilisation. Smart building technologies, which involve building automation and sensors controlling energy consumption, were observed in 67% of the structures. Photovoltaic panels, converting solar energy to electricity, were evident in 53% of the buildings, whereas 40% employed wind turbines for energy generation. Interestingly, 56% of high-rise buildings capitalised on wind power through both horizontal and vertical turbines, leveraging consistent wind velocities at varying altitudes.

Table 4. Technologies employed in selected buildings

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**	**Case 10**	**Case 11**	**Case 12**	**Case 13**	**Case 14**	**Case 15**
Use of double walls													■		
High performance or reflective glazing	■					■	■	■		■	■	■		■	
Conventional or nanodielectric materials															
Box facades															
Air passage interfaces		■	■	■		■		■		■					
Multi-storey facades															
Ventilated facades															
Opposite spaces			■	■		■	■			■					
Non-adjacent spaces	■	■													
Not continuous central courtyard															
Continuous Central Courtyard (Celestial)	■	■	■	■										■	
Green facades or green walls													■		
Rooftop cultivation	■	■	■	■		■		■	■			■	■	■	■
Folding elements (self-moving)						■		■				■			
Foldable items															
Vertical or horizontal elements					■	■									■
Curtain walls															
Combined breakers with photovoltaic panels					■				■	■					
Balconies					■										■
Rotated or tilted mass			■	■	■			■		■	■	■	■	■	
Building automation	■	■			■		■	■		■	■		■	■	
Smart materials															
Photovoltaic panels					■	■		■		■	■	■	■	■	
Horizontal wind turbines					■	■	■								
Vertical wind turbines										■	■		■		

(Source: the researcher)

Distinct technologies were identified as particularly prevalent in high-rise buildings for energy conservation. These include insulation through high-performance and reflective glazing, double facade technology with an air corridor, rooftop vegetation for shading, and building orientation to maximise natural resources. In addition, smart building technologies—especially building automation—were pronounced. Energy generation technologies predominantly employed photovoltaic solar panels and wind turbines, capitalising on the altitude advantages of high-rise structures.

Certain techniques significantly influenced the facade's aesthetic characteristics, such as colour, texture, and transparency. These encompass insulation with high-performance glazing, double-skin facade technology, green wall implementation, and shade breakers. Techniques like photovoltaic solar panels rendered high-rise buildings consistently luminous and transparent. Conversely, techniques like void spaces, dynamic facades, and wind turbines concurrently influenced both the form and facade. These were observed to be critical distinguishing factors for high-rise buildings employing such methodologies.

7 Conclusion

The incorporation of contemporary energy conservation technology in architectural designs epitomises a global shift towards the development of superior-quality structures, with a trajectory poised to meet imminent integrative needs. From the analysis conducted, the following conclusions were drawn:

Table 5. Levels of technological effect on architectural form

Technologies		The Effect	The Effect Level
Insulation techniques		Only when used as facade materials do they have an impact. High-performance and reflective glazing alter the building's color and texture, imparting a glossy finish	Affects the facades
Double skin facades technique		The building features a glossy facade with either transparent or tinted glazing	Affects the facades
Court technique		Parts of the building mass can be omitted, with variations including mutual, opposing, spiral, or graduated removal	Affects the facades and the form
Green building technologies	Green facades or green walls	Change in the color and texture of the building	Affects the facades
	Cultivation of roofs at different levels	The building's design gradually incorporates terraced surfaces for cultivation, or features extended balconies designed specifically for planting	Affects the form
Automated facades		It can be incorporated within the double facades, consequently influencing the building's transparency	Affects the facades
		Altematively, when applied extemally, it becomes a fundamental component, shaping the building's form	Affects the facades and the form
Solar refractors		Incorporating elements of diverse shapes and configurations, these become integral to the building's architectural form	Affects the facades
Balconies		Evident variations in size and form within the building's mass	affects the form
Rotated or tilted mass		Alterations, deviations, or fissures in the architectural design	Affects the facades and the form
Smart building technology		Influencing the building's transparency and hue	Affects the facades
Photovoltaic panels		Impacting the building's colour, transparency, and texture, giving it a reflective and lustrous finish	Affects the facades
Wind turbines		Sculpting the building's edges with curvature. Aligning the building according to wind direction. Strategically hollowing out complete or partial floors or corners to accommodate vertical or horizontal wind turbines	Affects the facades and the form

(Source: the researcher)

(1) Technological advancements have profoundly influenced architectural paradigms, facilitating environments conducive to human habitation through the integration of modern technologies by design experts.

(2) High-rise building energy optimisation necessitates the concurrent application of multiple technologies, underscoring the importance of holistic strategies that both diminish energy consumption and harness energy-generating techniques.

(3) The energy conservation methods employed manifest diverse impacts on high-rise architectural forms. While certain methodologies exclusively alter a building's facade, others reshape the entire structure, with some influencing both form and facade synergistically.

(4) Components intrinsic to specific energy conservation technologies have emerged as dominant architectural elements, thereby endowing buildings with a signature aesthetic appeal.

(5) Incorporation of photovoltaic solar panels bestows structures with a luminous and sleek exterior.

(6) Architectural configurations, particularly those of high-rise edifices, are increasingly being moulded by the seamless fusion of renewable energy-focused technologies and foundational design principles.

(7) The future of architecture, especially in high-rise constructions, is foreseen to be characterised by the integration of energy conservation and generation technologies.

The study underscored the imperative for a symbiotic relationship between energy conservation technologies tailored for high-rise designs and the architectural aesthetics of such structures. Nevertheless, it is advocated that a comprehensive exploration and analysis of prospective technologies—intended for energy reduction and conservation—be undertaken. It is pivotal that during the design phase, architects embed these technologies judiciously within architectural forms, thereby mitigating any adverse impacts on the building's aesthetics.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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