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Comparative Analysis of Net Zero-Energy Office Buildings Across Hot Climates in Developing and Developed Countries

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Abstract

Buildings contribute 20% to 40% of global energy consumption, with heating, ventilation, and air conditioning (HVAC) systems accounting for nearly half of this usage. In Egypt, the building sector constitutes a significant portion of electrical energy consumption, especially in office buildings that adopt international design practices without considering local climatic conditions. In response to the growing urgency for sustainable development, the concept of net-zero energy buildings (NZEBs) has emerged as a viable solution to enhance energy efficiency and reduce carbon footprints. In this context, this research employs both descriptive and comparative analytical methodologies to provide a comprehensive overview of the NZEB concept, accreditation standards, and strategies for achieving energy neutrality. It compares the strategies implemented in four zero-energy administrative buildings located in both developed and developing countries with hot climates, aiming to identify best practices suitable for implementation in Egypt. The findings indicate that net-zero energy buildings can be realized through the usage of solar photovoltaic energy and highlight Egypt`s considerable potential for adopting NZEB principles. The study emphasizes the effectiveness of both passive and active design strategies, including optimal building orientation, natural ventilation, and high-performance insulation. Furthermore, the integration of government policies, programs, and financial incentives would accelerate the adoption of NZEBs in Egypt.

Keywords: *Net zero energy building, Renewable energy, Active strategies, Passive strategies.*

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1. Introduction

The built urban environments represent more than 70% of total greenhouse gas GHG emissions, making urban development an urgent priority to address. Over 50% of the world's population currently lives in cities, with this percentage expected to rise to 60.4% by 2030 (Nations, 2023). It is essential to tackle this aspect to mitigate existing environmental challenges and move towards a carbon-free world by 2050 (Samir Idrissi Kaitouni, 2024).

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Zero energy buildings (ZEB) aim to achieve zero annual energy consumption by reducing building demand through energy efficiency techniques and integrating renewable energy production. They are increasingly being discussed in national policies and global forums to promote a more sustainable built environment (Zakaria, 2021) (Salwa El Gindi, 2024).

This study examines the feasibility of key NZEB design issues for hot climates using field experiences from four projects. While developed countries have made significant progress in ZEB implementation, developing countries face unique challenges such as economic constraints, lack of technical expertise, and inadequate infrastructure. In the US, NZEB policies are implemented based on building owner rights, with federal buildings aiming for Net Zero Energy by 2030 (Energy.gov, 2024). Additionally, the goal of all new commercial buildings is to achieve net zero energy use by 2030 (Commission, California Energy, 2019). India's Energy Conservation Building Code (ECBC) launched in 2007, focuses on energy efficiency in the building sector, particularly in new commercial buildings, aiming to reduce energy demands through increased efficiency and renewable resources (Singh, 2023).

This review analyzes the progress and challenges of zero-energy office building in both developed and developing countries by comparing case studies, regulatory frameworks, and technological advancements. It highlights diverse approaches and lessons learned from each context.

1.1. Research Problem

Globalization has significantly impacted Egyptian office buildings, resulting in excessive energy consumption largely due to inefficient cooling systems. To address this issue, it is imperative to adopt design strategies that are tailored to Egypt's hot climate. These strategies are essential for enhancing energy efficiency and promoting sustainable construction practices.

1.2. Research Question

How can sustainable design strategies appropriate for hot climates be effectively implemented in office buildings in Egypt to achieve energy efficiency and conform to net-zero energy building (NZEB) standards?

1.3. Research Objectives

The research aims to develop and articulate specific implementation techniques to achieve net-zero energy buildings NZEB in office structures within Egypt`s design considerations.

1.4. Net Zero Energy Building Definition

The International Living Future Institute (ILFI) defines NZEB as "*NZEB—one hundred percent of the building's energy needs on a net annual basis must be supplied by on-site renewable energy. No combustion is allowed.*" ((ILFI), 2016)

It is important to review the existing ZEB definitions for leading countries that are targeting ZEB and have action plans to reach their goal. The National Renewable Energy Laboratory (NREL) defines the Zero Energy Building (ZEB) in the United States as "*An energy efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy*" (Haleh Moghaddasi, 2021).

1.5. Zero Energy Building certifications

Many Zero Energy Buildings (ZEBs) do not actually achieve zero energy, necessitating the development of rating systems such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREAM) (Ismail, 2020). Among the most prominent certifications are those from the International Living Future Institute's (ILFI), which stipulate the buildings must annually utilize renewable energy sources, avoid combustion, and comply with maximum shading allowances for adjacent properties, while ensuring access to fresh air, sunlight, and natural waterways (Zero Energy & Passive House Certifications, 2019). Furthermore, in 2018, the LEED Zero certification was introduced, which recognizes buildings or spaces that achieve a net-zero energy balance over a 12-month period (Zero, LEED Program Guide, 2019).

2. The roadmap for achieving NZEB in hot climates.

This study explores renewable energy sources for zero-energy building (ZEB) design, focusing on passive and active systems in warm environments, as well as identifying suitable types for zero-energy projects as shown in figure 1.

2.1. Passive strategies

Passive strategies include all the strategies that do not require energy for operation. By effectively implementing these techniques, they can provide buildings with low energy consumption. Typically, low-energy buildings will comprise a high level of insulation, energy efficient windows, high level of airtightness and natural/mechanical ventilation with efficient heat recovery to reduce heating/cooling needs (Shambalid Ahady, 2019).

2.2. Active strategies

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Active approaches in a net zero energy building (NZEB) combine passive strategies with renewable energy systems (APEC, 2018). By using high efficiency HVAC, equipment, and control strategies reduce energy consumption and heat gains, reducing the need for additional cooling. IoT technologies are applied throughout the building, enhancing energy management. Demand-controlled ventilation, lighting controls, and equipment controls are linked to air quality, daylight, occupancy, and power usage. Strategies for recovering and reusing heat are also included (Jeongyoon Oh, 2017).

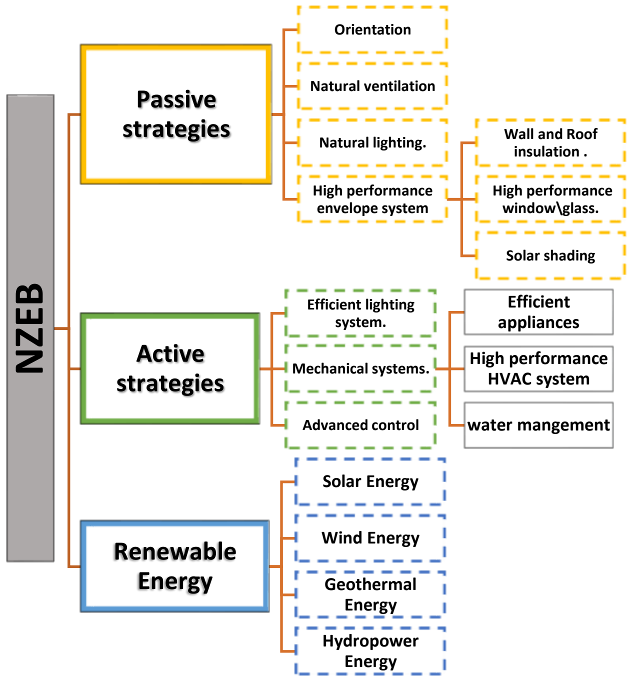


Figure 1: The roadmap for achieving NZEB in hot climates.
Source: (Balkar Singh S. K., March 2021), Edited by: The researcher.

2.3. Renewable energy

Renewable energy systems are key features of net zero energy buildings (NZEBs). These sources can be connected to the grid through either on-grid or off-grid systems. On-grid systems allow for both purchasing and selling energy, with a 17% return on investment. Off-grid systems, on the other hand, require electricity storage to manage peak loads and are not connected to the main grid (Zakaria, 2021). There are various types of renewable energy systems as shown in figure 2.

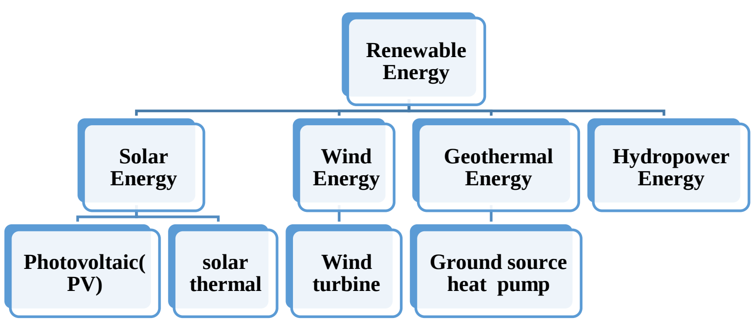


Figure 2: Net zero energy building techniques from renewable energy
Source: (Zakaria, 2021), Edited by: The researcher.

3. Case studies of Net Zero Energy Office Buildings NZEOBs

Figure 3 presents the criteria utilized for selecting case studies, along with the analytical framework employed in this research.

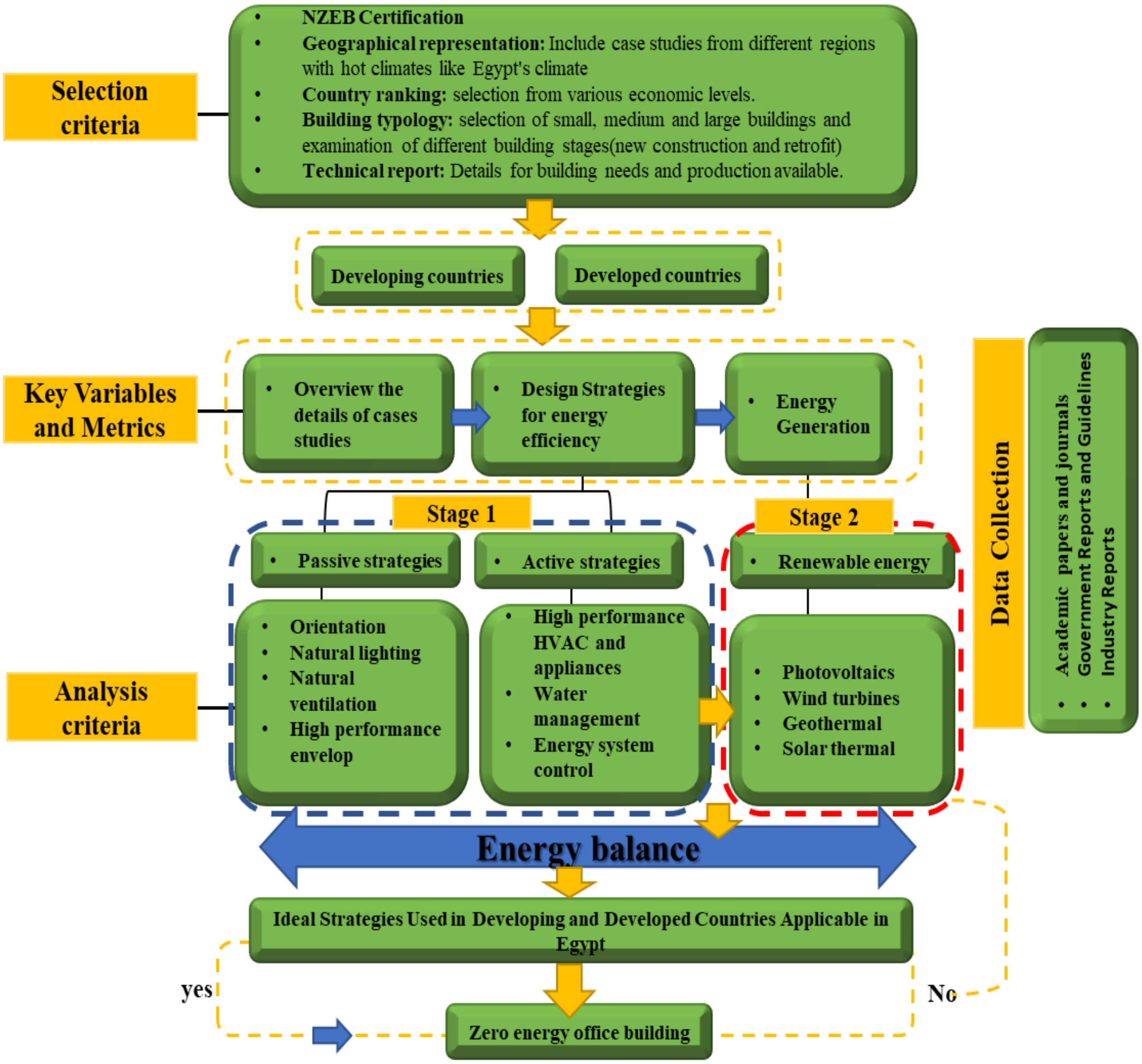


Figure 3: analytical framework of zero energy office buildings cases studies. Source: The Researcher

3.1. Analysis of case studies in Developing Countries

3.1.1 Indira Paryavaran Bhawan (IPB), New Delhi, India

IPB is the Ministry of Environment and Forest (MoEF)'s office building, see figure 4, designed in accordance with the Net Zero Energy Building concept. It is located at Aliganj on JorBagh Road in South Delhi (G.Palani Selvan, 2022). Table 1 will provide some basic information about the building.

Figure 4: Indira Paryavaran Bhawan. Source: (G.Palani Selvan, 2022)

Table 1: Overview of Indira Paryavaran Bhawan Building

Office Building Overview			
Location	New Delhi, India	**Building typology**	Office Building

Architects	CPWD Architecture	**Working hrs.**	10:00 am to 5:00 pm
Date completed	2014	**No. of floors**	7 floors and 3 basement floors
Area	9565 sq m	**Climate zone**	humid subtropical climate
Building state	New building	**Awards**	LEED Platinum GRIHA 5 Star

A. Passive Design Strategies

1- Orientation and form: The north-south-oriented building. It has a rectangular plan shape as shown in figure 5.
2- Natural lighting: The 15m room depth and center courtyard provide ample daylight for offices as shown in figure 6 with a light shelf ensuring consistent light distribution for a pleasant working environment and 75% Total Daylit Area Reduction of artificial lighting (Rati Khandelwal, 2020).

3- Natural Ventilation: Porous elements like Jaalis[1] promote air flow and cross ventilation in common open areas as shown in figure 7, reducing mechanical ventilation needs. Vegetation cools air, creating a pleasant microclimate (Hassan, Nov 7, 2021).

B. Building Envelope

4- Walls: AAC Block Masonry Wall and Fly-ash-Based Plaster with U-value as low as 0.34 and rock wool is used for insulation.
5- Roof insulation: High reflectance terrace tiles are used for cool roofs due to their high strength and durability and are also coated with PV cells.
6- Openings: The use of uPVC window frames and double glazing with a VLT of 0.6 and a U-value of 1.8 and a 20% window wall ratio reduces heat gain and high-efficiency glass requirements (Rati Khandelwal, 2020).
7- Solar shading: The window, recessed deeper into the wall, creates an "overhang" setting large overhang roof and double-glazing as shown in figure 8.
8- Materials: used recyclable materials like Fly Ash Bricks, Terrazzo Flooring and Calcium Silicate Tiles (Balkar Singh S. S., 2020).

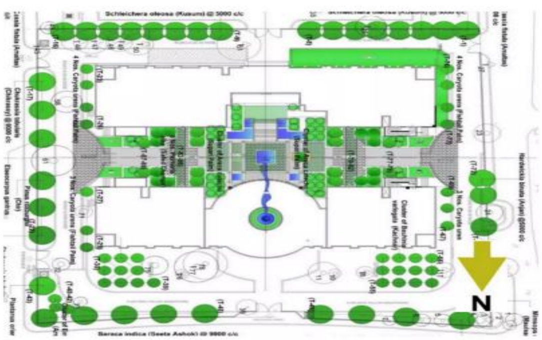


Figure 5: The north-south-oriented building

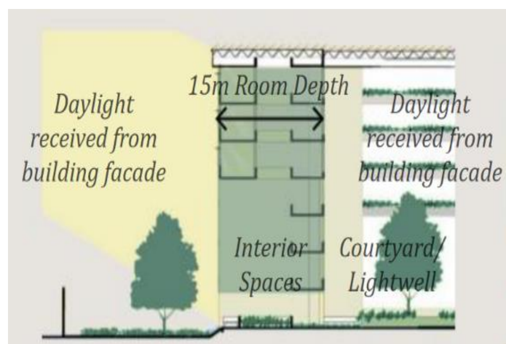


Figure 6: The depth and center courtyard for daylighting

Source: (Hassan, Nov 7, 2021).

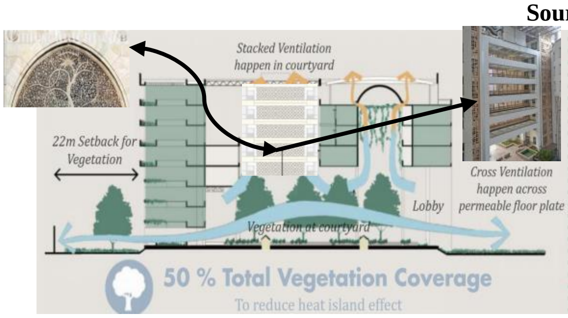


Figure 7: natural ventilation methods. Edited by reseacher.

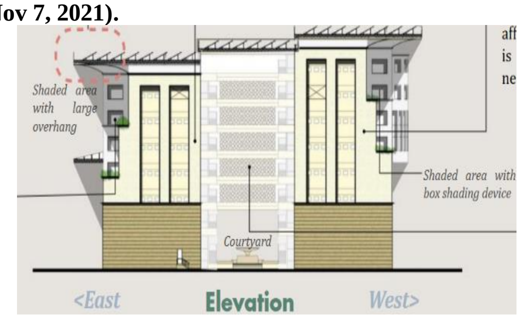


Figure 8: large overhang roof in West and East elevation.

Source: (Hassan, Nov 7, 2021).

[1] *Jaalis are intricate perforated screens or latticed structures found in Indian and Islamic architecture, typically made from stone, wood, or metal.*

C. Active Design Strategies

9- HVAC system: Chilled beam systems require less supply air from the building air handling system (AHU).

10- Water management: Rainwater is harvested, filtered, stored, and treated to reduce freshwater use in everyday applications like HVAC Absorption Chillers, gardens, and cleaning toilets as shown in figure 9.

11- Energy-Efficient Lighting: used LED lighting and T5 uses for areas needing higher luminance, like basement carparks.

12- Energy system control: The energy system is managed through an integrated building management system (BIMS) (G.Palani Selvan, 2022), while the lighting system is controlled by sensors,
preventing human errors and waste as shown in figure 10.

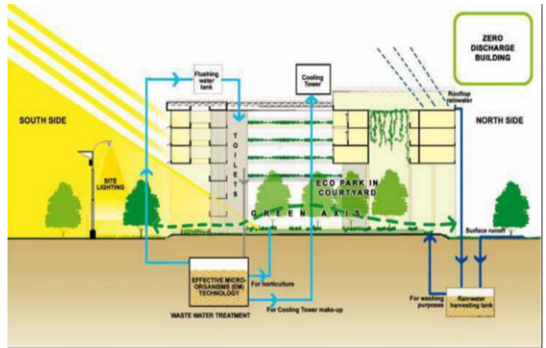
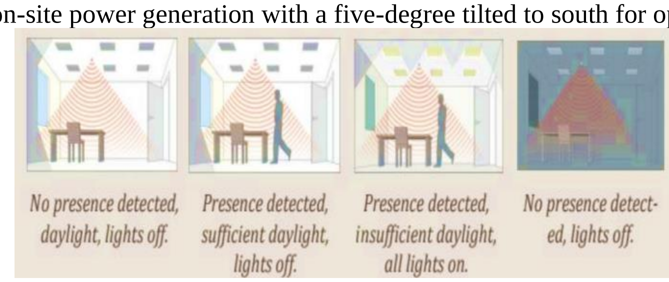


Figure 9: Daily uses of rainwater harvesting.
Source: ((DPAP), 2022)

D. Applied Renewable Energy

13 - ***Solar energy*** (photovoltaic systems): the building has installed 2,844 photovoltaic panels on its roof, ensuring 100% on-site power generation with a five-degree tilted to south for optimal energy output as shown in figure 11.



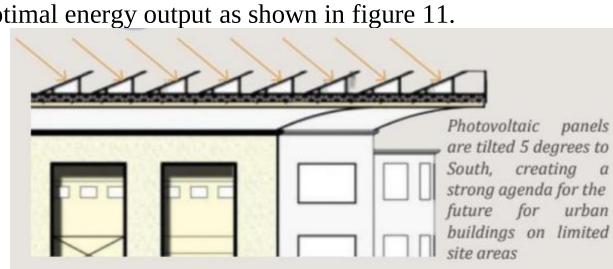


Figure 10: lux level sensor. **Figure 11: Photovoltaic panels are tilted 5 degrees to South.**
Source: ((DPAP), 2022)

Annual energy consumption (EUI) equals 14.21 Lakh kWh, and energy generation equals 14.3 Lakh kWh. Therefore, total energy consumption equals total energy production.

14- ***Geothermal energy:*** The building has 180 vertical bores with 32mm outer diameter U-loops connected to a central air conditioning plant room, each with 0.9 TR heat rejection capacity, achieving 160 TR without a cooling tower (Rati Khandelwal, 2020).

E. Policy support

The Indian government's commitment to sustainability led to the successful completion of a $33.7 million project by the New Delhi Municipal Council and EESL, highlighting the importance of institutional support in green building initiatives.

3.1.2 PUSAT TENAGA Malaysia PTM ZEO Building

The Green Energy Building, formerly known as the Pusat Tenaga Malaysia ZEO building, is the first Zero Energy Office in Malaysia, see figure 12, (Dhruv Repuriya, 2021). Table 2 will show some basic information about the building.

Figure 12: the Pusat Tenaga Malaysia (PTM) ZEO.
Source: (Sdn, last accessed 16\8\2024)

Table 2: Overview on Pusat Tenaga Malaysia building

Office Building Overview			
Location	Bangi, Malaysia	**Building typology**	Office Building
Architects	Dato Ruslan Khalid Architects	**Working hrs.**	8:00 am to 6:00 pm
Date completed	2007	**No. of floors**	4 floors and 1 basement floor
Area	4,100 sq m	**Climate zone**	tropical rainforest climate
Building state	New building	**Awards**	ASEAN Energy Award "Zero Energy Building"

A. Passive Design Strategies

1- Orientation and form: The north-south-oriented building, it has a rectangular plan shape with a ratio of 3:1 as shown in Figure 13 (mgtc, 2019).

2- Natural lighting: The 11m-deep building receives daylight from the south and north façades, with atriums featuring large semi-transparent PV modules harvesting daylight. Daylight reflects from light shelves and ceilings, and roof lights distribute diffused natural lighting (Dhruv Repuriya, 2021).

3- Natural Ventilation: The building has a high coefficient of performance (COP), and low-energy HVAC systems are installed throughout the building.

B. Building Envelope

4-Walls: AAC Blocks with mineral wool with U-value as low as 0.34

5-Roof insulation: 150mm thick Styrofoam with U-value 0.39 (Dhruv Repuriya, 2021).

6-Openings: Double Glazing with reflective mirror with VLT-50 and a 35% window-wall ratio.

7-Solar shading: Exterior Overhangs and internal reflector as shown in figure 14 (mgtc, 2019).

8-Materials: used local Materials like AAC Blocks, and Smart Materials like Phase change materials (BocaPCM-TES).

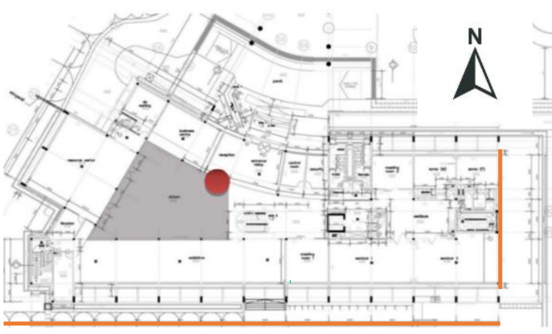


Figure 13: The north-south-oriented building. **Figure 14: Exterior Overhangs and internal reflector.**

Source: (mgtc, 2019)

C. Active Design Strategies

9- HVAC system: The building uses a unique cooling system with PEX pipes embedded in concrete floor slabs, storing energy at night, and utilizing a phase change thermal storage system with only one of AHU.

10- Water management: The building uses solar thermal systems to heat water and Collected rainwater indirectly supports the efficiency of hot water systems.

11- Energy-Efficient Lighting: used LED task light and T5 fluorescent tubes (2 units) with DALI electronic ballast.

12- Energy system control: Control of HVAC equipment, occupancy, CO2, and monitoring of all systems through an integrated building management system.

D. Applied Renewable Energy

13- Solar energy: (Solar BIPV systems).

The building consists of three components: a 47.28 kWp polycrystalline BIPV system on the main roof, a 6.08 kWp amorphous silicon BIPV system in the second roof, an 11.64 kWp monocrystalline glass system in the atrium, and a 27 kWp monocrystalline BIPV system in the car park roof. The result was a saving of almost 500,000 kWh per year with energy generation was about 103 MWh/year on average (Riham Hagag, 2019).

E. Policy support

The Pusat Tenaga Malaysia (PTM) was funded by the Malaysian government, GreenTech Malaysia, the United Nations Development Programme (UNDP), and the EC-ASEAN Energy Facility, promoting energy efficiency and renewable energy initiatives in the region.

3.2. Analysis of case studies in Developed Countries

3.2.1 Makers Quarter Block D building

Block D, part of the Makers Quarter Development in San Diego's East Village, is a dynamic office hub designed to foster collaboration and innovation among entrepreneurs and artists as shown in Figure 15 (Edward Dean, 2022). Table 3 will provide some basic information on the building.

Figure 15: Elevation of Makers Quarter Block D. Source: 16 (Edward Dean, 2022).

Table 3: Overview of Makers Quarter Block D building

Office Building Overview			
Location	San Diego, United States	**Building typology**	Office Building
Architects	BNIM Architects	**Working hrs.**	8:30 am to 5:00 pm
Date completed	2018	**No. of floors**	6 floors
Area	4954 sq m	**Climate zone**	Mediterranean climate
Building state	New building	**Awards**	LEED Platinum - Net Zero Energy certification

A. Passive Design Strategies

1- Orientation and form: The east-west oriented building, with its main facade facing west as shown in figure 16, is a rectangular plan shape with a 3:1 ratio, matching its surroundings.

2- Natural lighting: The design and orientation of the building allow for taking advantage of natural lighting and communicating with the streetscape through windows, which contributed to increasing productivity.

3- Natural Ventilation: The building relies on natural ventilation from three sides, with the western facade utilizing wind movement. The western facade features garage doors as shown in figure 17 and a terrace along the northern and western facades.

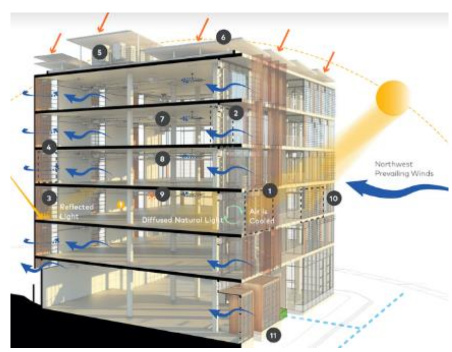


Figure 16: The north-south oriented building. Figure 17: Movement of western winds on the building

Source: (BNIM, 2019)

B. Building Envelope

4- Walls: The wall insulation has an R-value of 13 for the opaque part, with the west wall featuring a glass curtain wall and roll-up garage doors, the east wall being bare concrete, and the north wall featuring metal panels with 6" mineral wool insulation, achieving R=23.

5- Roof insulation: Use the entire roof area of the building covered with photovoltaic panels. R-value averages R=25.

6- Openings: The double-glazing glass used is highly efficient, with a U value of 0.29, SHGC (typical) of 0.38, SHGC (East side) = 0.29 (Edward Dean, 2022).

7- Solar shading: The facade features a 2m setback for ground floor roof shading, with automatic screen control systems for the southern and western facades as shown in Figure 18. These systems adapt to daylight and year and can be controlled by users to provide suitable shading.
8- Materials: 75% percentage by weight of construction waste diverted from landfill, Renewable, non-toxic, and local materials were used.

C. Active Design Strategies

9- HVAC system: The building uses natural ventilation, except for areas requiring air conditioning and heating as shown in Figure 19. The VRF system allows easy control of these aspects based on occupancy rates and demand control. DOAS external air supply units convert thermal energy.
10- Water management: The project manages stormwater, installing a low-flow system in restrooms, and selecting a mechanical system based on water usage performance and LEED standards to reduce indoor potable water (BNIM, 2019).
11- Energy-Efficient Lighting: The LED electric lighting system's daylight controls adjust the electric light levels in response to the available daylight.
12- Energy system control: Maker collaborates with LOCBIT for energy efficiency, cost reduction, fault detection, IoT, data, and API solutions. Three floors are individually controlled, with a year-round shading system.

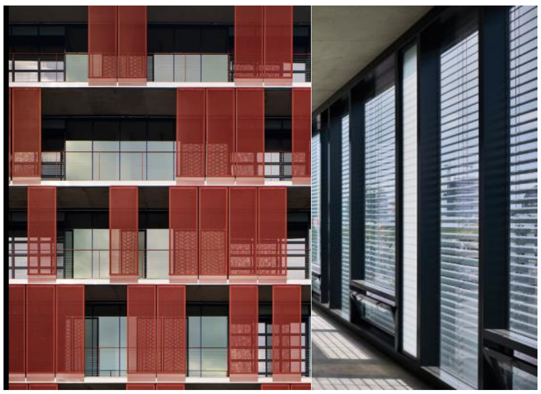


Figure 18: exterior shade mechanism

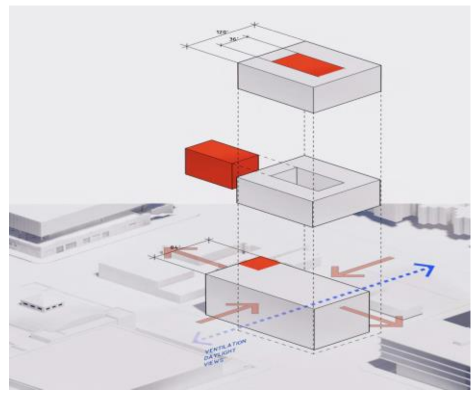


Figure 19: Red areas require air conditioning.

Source (Pintos, Paula, 2024)**.**

D. Applied Renewable Energy

13- Solar energy (photovoltaic systems): the building's photovoltaic panels, oriented east at 20 degrees with a Capacity 174 kW, save over 48% on energy costs, making it net-zero and 41.6% less energy-efficient than an ASHRAE90.1 building and generation141,000 kWh per year (Edward Dean, 2022).

E. Policy support

The Makers Quarter Block D in San Diego was funded by government incentives and private investment. Utilizing the City's Sustainable Building Expedite Program and San Diego County's Green Building Incentive Program.

3.2.2 DPR Construction Phoenix building

DPR Construction built the Phoenix Regional Office, as shown in Figure 20, to integrate its values and culture, providing a sustainable and cost-effective work environment. The project transformed an abandoned, distressed building into a modern, sustainable facility, breaking down perception barriers to Net-Zero Energy (INSTITUTE N. L., 2022). Table 4 will show some basic information about the building.

Figure 20: DPR Construction Phoenix.
Source: (INSTITUTE N. L., 2022)

Table 4: DPR Construction Phoenix overview.

Office Building Overview			
Location	Phoenix, USA.	**Building typology**	Office Building
Architects	Smith Group JJR.	**Working hrs.**	8 hours per day
Date completed	1972 (Major Renovation) 2011	**No. of floors**	One floor
Area	4954 sq m	**Climate zone**	Hot desert climate
Building state	Existing Building Renovation	**Awards**	(NZEB) certification from the (ILF Institute) - LEED Platinum

A. *Passive Design Strategies*

1- Orientation and form: The east-west oriented building. it has a square plan shape.
2- Natural lighting: A daylighting analysis revealed the use of 82 solar tubes as shown in Figure 21, combined with natural light from new windows, significantly reduced artificial light use by over 80% (DPRhq).
3- Natural Ventilation: The design team utilized computational fluid dynamics (CFD) modeling to develop a thermal chimney/shower tower system to enhance airflow and cooling and incorporate a garage-style roll-up door in training rooms, cafe kitchens, and exercise spaces to bring outdoors inside (Jays Robin, 2014).

B. *Building Envelope*

4- Wall: Existing block with new insulation with an R-value of 19 (INSTITUTE N. L., 2022).
5- Roof insulation: Existing wood deck with new insulation and foam roof Overall R-value 43.
6- Openings: The building has 87 operable automated windows as shown in Figure 22, with a glazing percentage of 43% north, 0% south, 38% east, and 0% west, with a U value of 0.1 (INSTITUTE N. L., 2022).
7- Solar shading: large windows on the north and south protected by green steel screens.
8- Materials: The building's components were recycled, with 78% of waste diverted from landfills. Wood from FSC sources was used, and FSC bamboo screens made up 3.35% of the project's material value (DPRhq).

C. *Active Design Strategies*

9- HVAC system: The building's existing rooftop air-conditioning units were upgraded in 2012 and 2013 to operate 13 rotary ceiling fans at low speeds in colder months.
10- Water management: The project utilizes waterless urinals, purification systems, and solar water heaters, and implements diffuse-tolerant landscaping and drip irrigation.
11- Energy-Efficient Lighting: used LED lighting with daylight sensor (usgbc, 2023).
12- Energy system control: The facility implemented a 'vampire' switch, reducing non-essential loads by 90% and plug loads by 38%, using an integrated building management system and real-time occupant monitoring (Jays Robin, 2014).

D. *Applied Renewable Energy*

13- Solar energy (photovoltaic systems): The system, installed over parking canopies, comes in two configurations: staggered array and flat tilted array, with a capacity of 79 kW -DC and ten-degree tilted panels as shown in figure 23. The annual energy consumption (EUI) is 129,589KBTU/ft2, with energy generation being 142,844 kWh. Total energy consumption is -13,220 kWh, which is less than total energy production (Jays Robin, 2014).

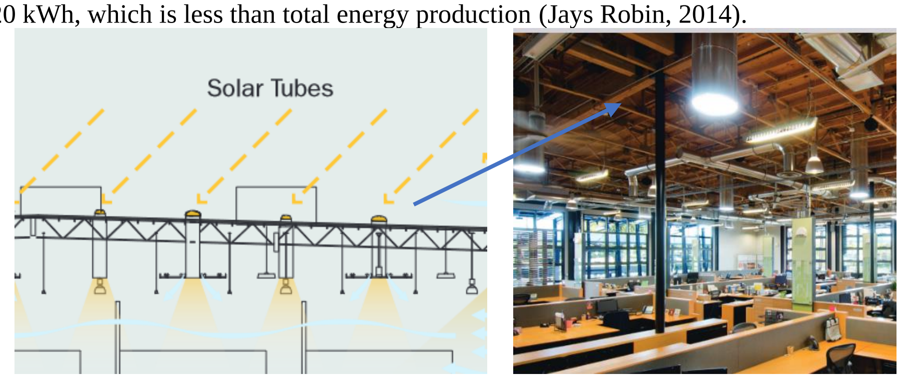


Figure 21: Availability of natural lighting through solar tubes and new windows
Source: (Jays Robin, 2014). Edited by the researcher.

A. Policy support

Phoenix can achieve net-zero energy building through government subsidies, project incentives, and self-funding, utilizing City of Phoenix Green Building Program, local initiatives, and federal programs.

Figure 22: 87 operable automated windows

Figure 23: Photovoltaic panels are tilted 10 degrees.

Source: (Jays Robin, 2014).

4. Results and Discussion

Case studies of zero-energy office buildings situated in diverse climatic zones - including tropical and subtropical climates, desert climates, and Mediterranean climates, like those found in many regions of Egypt - reveal a high percentage of these buildings achieving LEED Platinum certification. This discussion seeks to determine the strengths and weaknesses of the strategies employed in net-zero energy office buildings, with the goal of establishing specific standards for implementation in Egypt. Table 5 illustrates the relative strengths and weaknesses of these strategies, with further clarification provided in the accompanying discussion.

Table 5: The strengths and weaknesses of the utilized zero-energy buildings` strategies achieved in the selected case studies.

Zero energy buildings in hot climates	Energy efficiency												Energy generation		Policy support		
	Passive design elements								Active strategies				Renewable energy		Government Subsidy	Project Incentive	Self-fund
	1	2	3	4	5	6	7	8	9	10	11	12	13	14			
Indira Paryavaran Bhawan	●	●	●	●	◉	●	◉	●	●	●	●	●	●	●	●	○	○
Pusat Tenaga Malaysia	●	●	○	●	●	●	●	●	●	●	●	●	●	○	●	●	○
Makers Quarter Block D	●	●	●	●	◉	●	●	●	●	◉	●	●	●	○	●	○	●
DPR Construction Phoenix	●	●	●	◉	●	●	●	◉	◉	●	●	●	●	○	●	○	●
Achieved: ● Strong ◉ Medium ○ Weak																	

4.1. Passive strategies of NZEB

The analysis of passive strategies in case studies of buildings aims to achieve net zero energy by evaluating design elements and techniques that reduce energy consumption without active mechanical systems.

4.1.1. In Developing Countries

The achieved strengths in Indira Paryavaran Bhawan building revealed in the effective use of north-south orientation minimizes solar heat gain. Courtyard design enhances daylighting. Jaali features reduce mechanical cooling needs. High-performance envelope materials (AAC blocks, fly-ash plaster, reflective roof tiles) minimize heat gain. And Double-glazed windows improve insulation. While the weaknesses evolved in which the ventilation depends on specific design elements, limiting adaptability to seasonal variations. Double-glazing adds upfront costs and complexity in retrofitting.

On the other hand, the achieved strengths in Pusat Tenaga Malaysia building revealed in the orientation and atriums enhance natural lighting and ventilation. Daylight reflectors maximize light penetration. In addition to Low U-value AAC blocks and reflective glazing reduce thermal transmittance. Local and smart materials enhance sustainability. While the weaknesses appeared in the total reliance on artificial ventilation increases the cost of energy consumption and thus increases the solar panels and the payback period. High reliance on internal reflective systems adds complexity and maintenance and High insulation levels increase initial costs; material sourcing might be region-specific.

4.1.2. In Developed Countries

The achieved strengths in Makers Quarter Block D building revealed in the natural ventilation through three sides reduces cooling loads. Responsive shading system adapts to daylight changes, and High R-value walls and adaptive shading systems effectively manage heat gain. Curtain wall system maximizes daylight. While the weaknesses appeared in the west-facing facades could still experience heat gain, increasing cooling demand, and large glazed surfaces may compromise insulation if improperly managed.

On the other hand, the achieved strengths in DPR Construction Phoenix building revealed in the Solar tubes that provide daylighting with minimal artificial light. Thermal chimney system enhances ventilation, and Foam roof and highly insulated walls achieve exceptional thermal resistance. Automated windows improve ventilation. While the weaknesses appeared in the high dependency on computational models may limit performance if unexpected airflow patterns occur, Curtain walls increase construction costs, and Over-reliance on operable windows could limit efficiency in highly variable climates.

4.2. Active strategies of NZEB

4.2.1. In Developing Countries

In Indira Paryavaran Bhawan building, the strengths achieved in the Chilled beam HVAC and integrated lighting controls improve energy efficiency. Rainwater harvesting reduces potable water demand. While the complex BIMS that requires specialized operation and maintenance can be considered as weaknesses. On the hand, in Pusat Tenaga Malaysia building, the strengths appeared in the thermal storage which reduces peak loads; energy-efficient equipment cuts consumption. Solar thermal systems reduce heating costs. While the dependence on phase change materials (PCM) that requires precise control for optimal efficiency can be considered as a weakness point.

4.2.2. In Developed Countries

In Makers Quarter Block D building, the strengths achieved in the VRF systems adapt to varying occupancy, and IoT-based energy management improves optimization. Water-saving systems enhance sustainability. The weakness point appeared in the high dependency on technology and system controls may increase operational complexity. While in DPR Construction Phoenix building, the strengths are the upgraded HVAC units and rotary ceiling fans minimize cooling loads and the Low-flow water systems optimize usage. The weak point that appeared in the usage of existing rooftop units may limit efficiency gains compared to fully modernized systems.

4.3. Renewable Energy Systems of NZEB

4.3.1. In Developing Countries

In Indira Paryavaran Bhawan, the strength point is using Solar PV system that generates 100% of required energy, ensuring net-zero balance. Geothermal system enhances efficiency. The weak point is that the high initial investment for geothermal bores may deter widespread adoption. While in Pusat Tenaga Malaysia building, the strengths are the Multiple BIPV systems across building sections diversify generation sources and improve overall capacity. The weak point is the Complexity in managing multiple PV systems can increase maintenance demands.

4.3.2. In Developed Countries

In Makers Quarter Block D building, the strengths revealed in East-facing PV panels at 20-degree tilt optimize solar generation. Large capacity achieves substantial energy savings. The weak point appears to be in the westward exposure that may reduce efficiency without proper seasonal shading strategies. While the strengths in DPR Construction Phoenix building are the Staggered PV arrays on parking canopies achieve net-positive energy and modular configuration that allows flexibility. The weak point appears in the panel tilt and parking lot installation that may reduce land-use efficiency compared to rooftop-only solutions.

5. Conclusion

The successful implementation of net zero energy office buildings in hot climates, whether in developing or developed countries, requires a combination of passive and active strategies tailored to local conditions. Passive strategies, such as optimal building orientation, natural lighting, ventilation techniques, and efficient insulation, are essential for reducing energy demand. Developing countries often utilize cost-effective solutions such as courtyards and local materials, while developed countries employ advanced technologies like light tubes and automated shading systems. Active strategies, including efficient HVAC systems, geothermal and solar thermal energy for water heating, and advanced building management systems, further contribute to minimizing energy use. Additionally, effective water management, energy-efficient appliances, and lighting controls are crucial.

The analysis of NZEB buildings in hot climates indicates stringent energy standard requirements in their respective countries, with an average energy efficiency index of approximately 55 kWh/m²/year in the case study buildings. This is comparable to the energy efficiency index of 56.8 kWh/m² or less, as stipulated by the "Zero Energy Ready" standards developed by the New Buildings Institute in the United States—a valuable benchmark for evaluating the performance of net-zero energy buildings.

Renewable energy, primarily solar photovoltaics, is central to all case studies, with installations on building roofs and parking canopies providing necessary energy. The findings highlight that both developing and developed countries can achieve net zero energy by leveraging appropriate strategies and resources. Cross-regional collaboration and knowledge exchange are essential to promoting sustainable practices in diverse hot climates worldwide.

6. Recommendations

The study provides essential recommendations for the application of sustainable design strategies in office buildings in Egypt, drawing on insights from the previously analyzed case studies: Indira Paryavaran Bhawan, Pusat Tenaga Malaysia, Makers Quarter Block D, and DPR Construction Phoenix.

1- Architects should focus on climate-responsive design and use architectural techniques and elements that are compatible with the environment, such as optimize orientation, form, Use courtyards and atriums for daylight penetration.
2- Use advanced insulation materials and reflective coatings and use low U-value materials and reflective roof tiles.
3- The concept of glass facades, which is a major factor in increasing heat load and consequently energy consumption, should be replaced with appropriate wall-to-window ratios for each side of the building.
4- Implement double-glazing and solar shading.
5- Use energy-efficient systems like chilled beams or phase-change thermal storage and improve HVAC systems and implement advanced controls.
6- Integrate building management systems for real-time monitoring and automated controls and install sensor-based energy management and promote smart air-conditioning systems.
7- Architects and Engineers in Egypt must be aware of zero-energy office buildings in architectural practice.
8- Establish programs like India's and Malaysia's initiatives, offering incentives for LEED or GPRS-certified projects. Egypt can leverage its Green Building Council to promote and manage such incentives.
9- Economic feasibility varies in the developed countries may have higher initial costs due to advanced technology, offset by long-term savings, while developing countries may prioritize low-cost, passive solutions like natural ventilation. For Egypt, solar PV systems are highly feasible due to its high solar potential, and passive designs can mitigate infrastructure challenges. Introducing local incentives and building codes for energy-efficient buildings would support adoption.

Finally, the study outlines comprehensive design guidelines for achieving Net Zero Energy Buildings (NZEBs) in Egypt, as summarized in Table 6. These guidelines are derived from an in-depth analysis of international case studies and incorporate both passive and active design strategies tailored to Egypt's climatic conditions. The recommendations include specific measures such as optimizing building orientation, enhancing natural ventilation, implementing high-performance insulation, and utilizing advanced renewable energy systems like solar photovoltaics. Additionally, the guidelines emphasize the importance of integrating government policies, financial incentives, and sustainable construction practices to ensure the successful implementation of NZEB principles in Egypt. The detailed guidelines are intended to serve as a practical framework for architects and stakeholders to promote energy-efficient and environmentally sustainable office buildings in Egypt.

Table 6: Guidelines for achieving ZEBs between developing and developed countries. Source: The Researcher

Building Energy needs	**Passive strategies**	**Building orientation**	Northern orientations are optimal for zero energy buildings in hot regions, both developed and developing.
		Building shape	A compact shape: rectangular shapes in the ratio 1:3 can be greater than 1:6 or square building or simple shapes to maximize energy efficiency.
		Natural ventilation	**In developing countries:** the buildings used courtyards with openings facing them and jaalis. **In developed countries:** the buildings used cooling towers, thermal chimney, Garage doors. The highest percentage method was the use of opposite openings with Greenery, in addition to Optimal building orientation
		Natural lighting	**In developing countries,** ZEB used open courtyards shaded by trees, Sky light, Central Atriums should be shaded, light shelves. **In developed countries,** ZEB used light tube**.** All ZEBs use windows to a large extent on the north facade. Control of the southern facade with shading devices
		External wall	**In developing countries: ZEBs** use local blocks, double wall with insulation layer like TRIC, AAC block and Fly Ash Bricks and the u value ranges from 0.34 to 0.4. **In developed countries: ZEBs** use glass and insulated concrete forms (ICF) and the u value ranges from 0.05 to 0.27 and the use of light colors.
		Roof insulation	**In developing countries:** used Cool roof, step roof with high reflectance, green roof with polystyrene and flat surface with Styrofoam and mineral wool**.** **In developed countries:** used wood deck with foam roof, curved roof with bituminous, other. In addition of using PV to cover roof and the light colors.
		Opening	**In developing countries:** used Double glass with uPVC frame, double reflective glass, semitransparent PV. **In developed countries:** used automated windows, double glazed with thermally frames with Argon fill cavity and Low-E. with an average u value 1.1, VLT more than 50% and WWR on south range from 0.2 to 0.3 or 80% with shading devices and larger windows are on the north side.
		Shadings	For low and medium-rise zero-energy buildings, overhangs are commonly used along with louvers and blinds on the façades. **In developed countries**, automatically moving louvers have been implemented using smart systems and sensors.
		materials	Designing NZE office buildings requires incorporate innovative materials and methods, like ICF construction. In addition to using local and recyclable materials like FSC certified wood with low-emission materials.
	Active strategies	**HVAC**	**In developing countries,** the ZEBs used Chilled beam-based Cooling system and often used VRV system. **In developed countries**, the ZEBs used VRF, VRV and High efficiency ceiling fans. The NZEB cases commonly use a dedicated outdoor air system (DOAS) to treat
		Efficient appliances	Many office buildings reduce plug load energy use by using lower power demands and smart controls, using certified energy-saving equipment like ENERGY STAR
		Energy controls	The NZEB cases show common system using integrated building management for HVAC control, user management, motion sensors, and equipment management, occupancy sensors for lighting and lighting control systems
		Water management	Solar thermal collectors and geothermal systems efficiently provide hot water, while low-flow faucets and low-flow showers minimize water consumption. Rainwater or recycled water can also be used for air conditioning units.
		Lighting	The LED units in main rooms and T5 in service room is highly recommended in lighting design, in addition to installation daylight and occupancy sensor.
Energy production	**Renewable Energy**		Photovoltaics system- small wind turbines- Geothermal
			Low-rise ZE office buildings use PV on roofs, parking, or both. However, mid-, and high-rise buildings are adding integrated photovoltaic panels as an alternative to glass used in skylights and facades. photovoltaic panels were oriented southward with a tilt angle ranging from 5 to 22 degrees.

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