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Optimizing Energy Efficiency in Existing Public Schools Through Computational Modeling: Case Study of a Basic Education School in Hurghada, Egypt

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Energy Efficiency - Near-zero energy buildings (nZEB) - Hot climate - Public schools - Thermal insulation

Abstract: Globally, buildings are experiencing a significant surge in energy consumption due to climate change and rapid population growth. Within the Egyptian context, the building sector accounts for approximately 66-74% of total electricity consumption (Egyptian Electricity Holding Company, 202٤), necessitating a comprehensive revision of Egypt's building codes to incorporate sustainable design standards that mitigate this excessive consumption. This is particularly critical for educational buildings, which constitute a substantial portion of this consumption share. This study employs an integrated digital modeling methodology to enhance energy efficiency in educational buildings located in hot climatic zones. The research proposes implementing the Nearly Zero-Energy Building (nZEB) concept, which combines energy conservation strategies through optimization of the building envelope's thermal properties with the integration of renewable energy solutions. The methodology was applied to a case study of a public school in Hurghada City, Red Sea Governorate. Multiple scenarios were evaluated, including: Thermal insulation improvements for roofs and walls Enhanced window and opening efficiency Optimization of HVAC systems Integration of photovoltaic solar systems The results **After** implementing the redesign scenario for Al-Bahr Al-Ahmar School in Hurghada demonstrate a potential 45% reduction in energy consumption through building envelope improvements alone, with the possibility of achieving up to 65% energy savings when renewable energy systems are incorporated. This study provides a methodological framework that can be generalized to educational buildings in hot-arid regions, while accounting for site-specific climatic characteristics.

1. Introduction

Amid escalating global environmental challenges posed by climate change and surging energy demand, improving energy efficiency in the building sector has become critically important. Buildings account for **nearly 40% of global energy consumption** and **36% of energy-related CO_2 emissions**, according to the International Energy Agency (IEA, 2022). This issue is particularly pressing in developing countries with hot climates, such as Egypt, where **public**

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schools consume an estimated 8–12% of the total energy used by government, yet many lack basic energy-efficient designs (Ministry of Education, 2021). [1].

This study focuses on analyzing the key energy consumption challenges confronting public schools in Egypt, which include: (1) reliance on traditional architectural designs incompatible with hot climate requirements, (2) inadequate thermal insulation systems, (3) use of inefficient cooling systems, and (4) limited utilization of renewable energy sources. The research aims to develop an integrated methodological framework for transforming these educational facilities into near-zero energy buildings, thereby contributing to environmental and economic sustainability. [*2*]. The significance of this study lies in its attempt to address a notable research gap in the literature concerning near-zero energy building applications in hot climates, particularly within the Egyptian context. Furthermore, the study provides practical solutions for stakeholders in the education and urban development sectors. An additional contribution of this work stems from the scarcity of applied research on this topic in Egypt's specific environment. The study presents a scalable model that could be extended to other types of public buildings, supporting the achievement of national sustainable development goals.

2. The Main Objective of The Research:

This study examines the potential for converting educational buildings—particularly public schools into nearly zero-energy buildings (nZEBs) through a dual-phase strategy:

(a) reducing energy demand by optimizing the building envelope, thermal insulation, and passive lighting and ventilation systems

(b) Meeting the remaining energy needs through solar power integration.

3. Zero-Energy Schools (ZES) :

The refers to educational facilities designed to balance their annual energy consumption with equivalent energy production. These schools rely on an integrated combination of energy-efficient building design, renewable energy sources, and smart energy management systems to achieve this goal. This model represents a pioneering sustainable solution in the education sector, as it reduces carbon footprints while optimizing resource efficiency. Shown in **Fig. 1**. [3]

4. Zero-Energy Schools" (ZES) citrine:

4.1 Improving natural light:

Natural lighting in schools are among the most important components that contribute to enhancing the quality of the educational environment. They play a role in improving concentration, productivity, and visual and psychological well-being. [6]

4.1.1 Application for natural lighting :

4.1.1.1 Robotic Solar Mirrors :

Smart Automated Mirrors (Installed on School Rooftops) That Track the Sun and Redirect Light Indoors Through Specific Openings Artificial intelligence algorithms are employed to optimize the reflection angle based on the time of day and weather conditions. Shown in **Fig. 2**. [7]

Fig.1. (A) Access ro utes to zero-energy buildings source [4]
(B) NYC first net-zero school source [5]

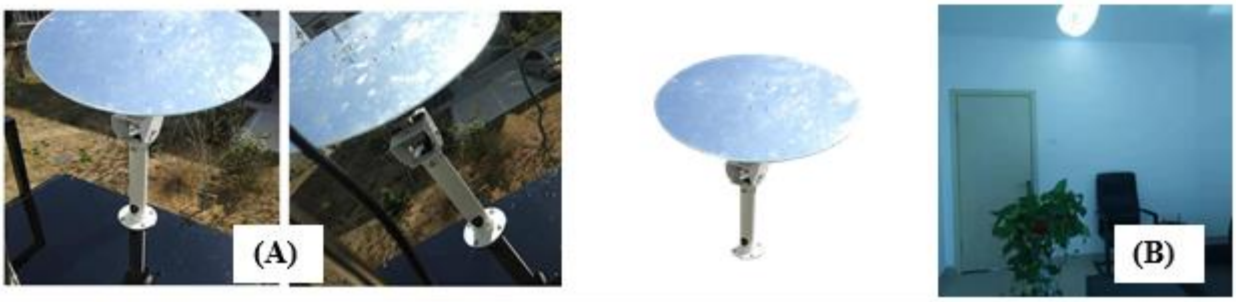

Fig.2. (A) Robotic Solar Mirrors source [8]

4.1.1.2 Bio façades with Microalgae :

Microalgae (such as *Spirulina* or *Chlorella*) are cultivated within double-glazed glass panels featuring an integrated aqueous nutrient flow system. The microalgae absorb CO_2 and release oxygen via photosynthesis while simultaneously filtering natural light. Shown in **Fig. 3**. [9]

Benefits in Educational Settings:

1. **Air Purification:** Reduce indoor carbon dioxide levels by up to 80% within classrooms.
2. **Thermal and Phototropic Insulation:** The algae absorb excess heat and diffuse light evenly, minimizing glare.

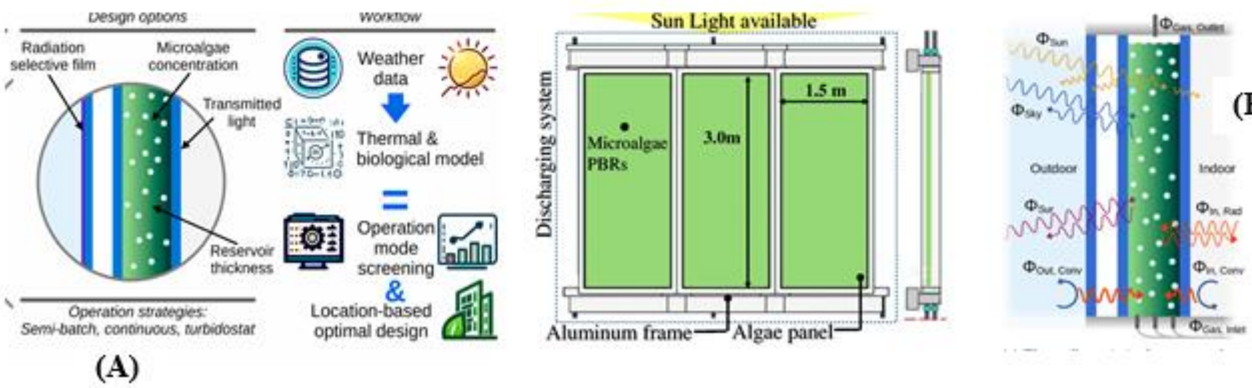

Fig.3. (A) and (B) Bio façades with Microalgae source [10]

4.1.1.3 Liquid Light Windows :

These windows incorporate nanofluidic systems (e.g., smart liquid crystals) that dynamically modulate optical properties in response to electrical or photonic stimuli. A key feature is their ability to **convert** ultraviolet (UV) radiation into visible light, effectively doubling ambient natural illumination *without* associated heat gain. Shown in **Fig. 4**. [11]

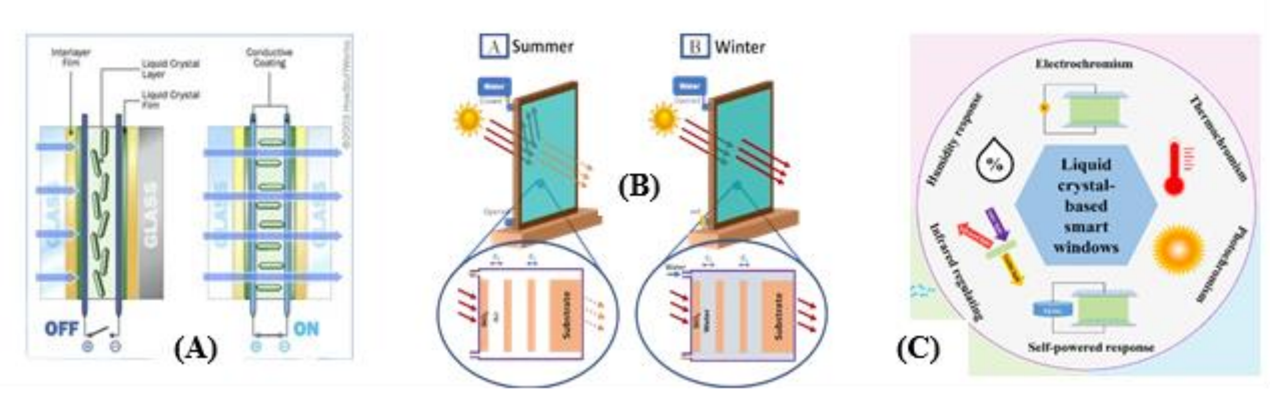

Fig.4. (A), (B) and (C) Liquid Light Windows source [12]

4.1.1.4 Artificial Photosynthesis Walls:

Wall surfaces coated with photocatalytic nanomaterials (e.g., nano-titanium dioxide/TiO_2) that:

(a) Absorb CO_2 and release oxygen via light-activated redox reactions. Shown in **Fig. 5**. [13]

(b) Homogenously scatter sunlight, eliminating glare while maintaining luminous efficacy.

Functioning as synthetic plants, these systems operate without irrigation or organic substrates.

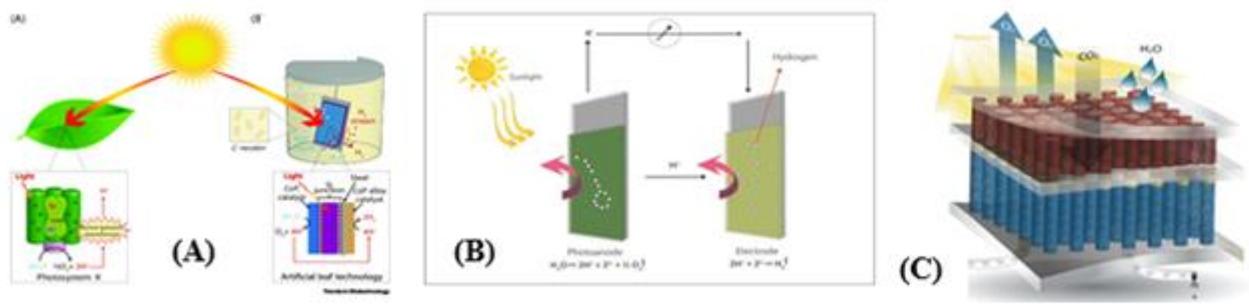

Fig.5. (A), (B) and (C) Artificial Photosynthesis Walls source [14]

4.1.2 Light-Reflective Paint Technologies for Educational Facilities :

4.1.2.1 (Luminous Paints) :

They absorb light during the day and emit it faintly at night. Made from non-toxic materials such as strontium aluminate, their benefits in schools include:

- **Uniform Light Distribution:** Reducing the need for artificial lighting. Shown in **Fig. 6**. [15]
- **Student Health:** Minimizing glare and visual fatigue.

4.2 Improving natural Ventilation:

4.2.1 Wind Catcher Tower Design:

Represent an optimal ventilation solution for educational buildings, combining energy efficiency with measurable improvements in learning environments. The tower structure is elevated above the building's roofline, incorporating an enlarged intake aperture designed to capture and channel airflow downward through a vertical ventilation shaft. Shown in **Fig. 7**. [17]

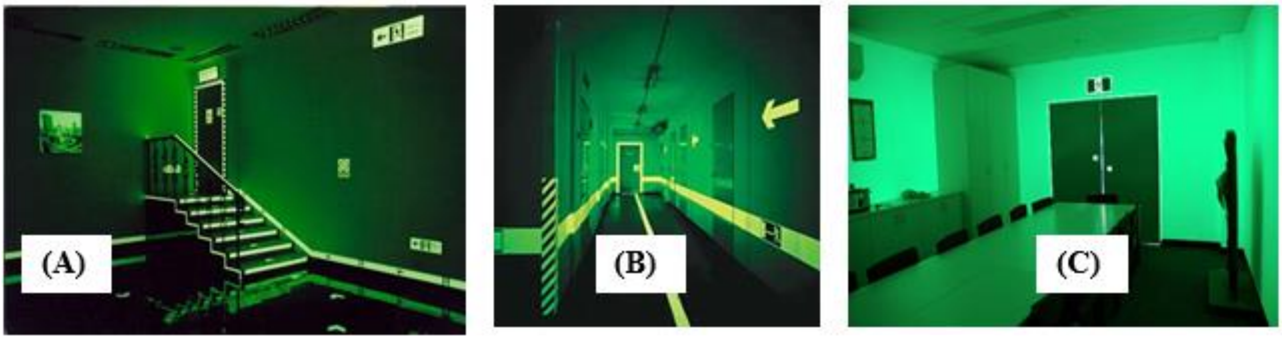

Fig.6. (A), (B) and (C) Luminous Paints source [16]

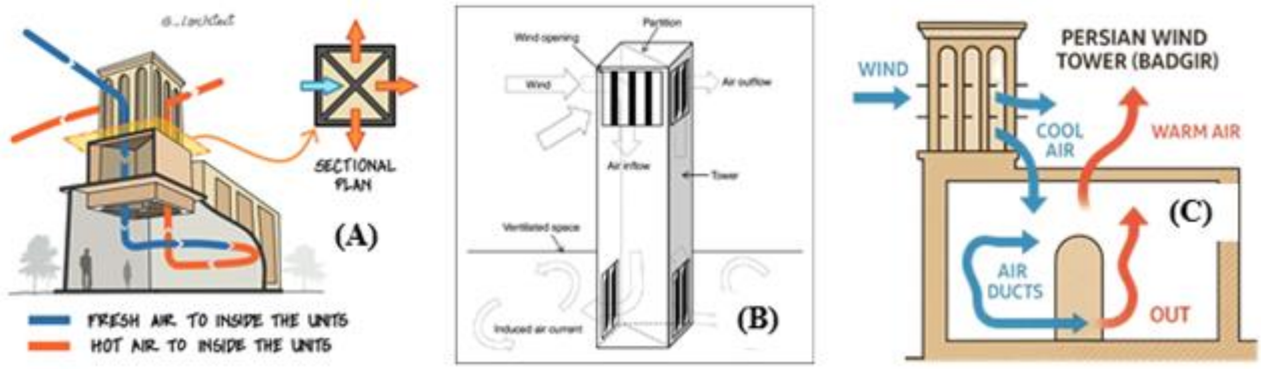

Fig.7. (A), (B) and (C) Wind Catcher Tower source [16]

4.2.2 Cross-Ventilation Works:

- **Opposing Openings:**

Cross-ventilation relies on having windows or other openings on two opposite walls of a room Shown in **Fig. 8**. [19]

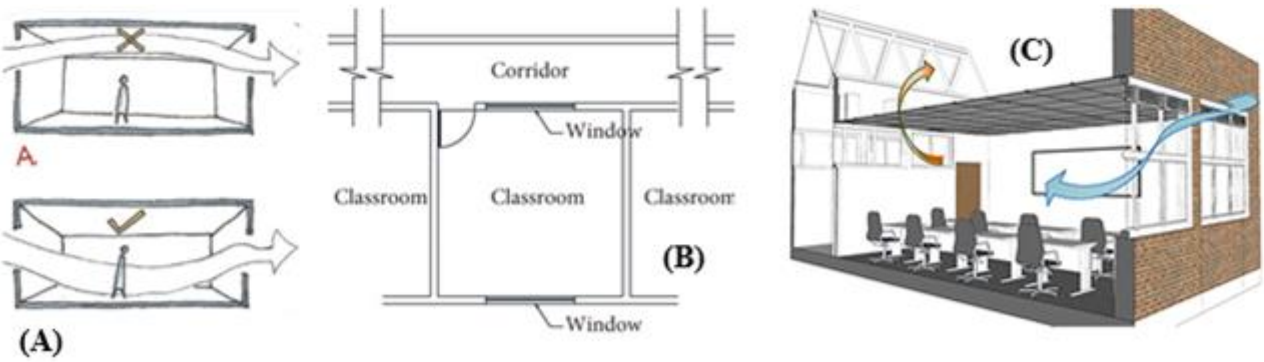

Fig.8. (A), (B) and (C) Cross-Ventilation Works source [20]

4.3 Improving Thermal insulation:

4.3.1 Phase Change Materials (PCMs) :

Phase change materials (PCMs) are substances capable of absorbing or releasing significant amounts of thermal energy during melting and freezing processes (solid-liquid phase transition). This characteristic renders them highly effective for thermal energy storage and temperature regulation in diverse applications. Shown in **Fig. 9**. [*21*]

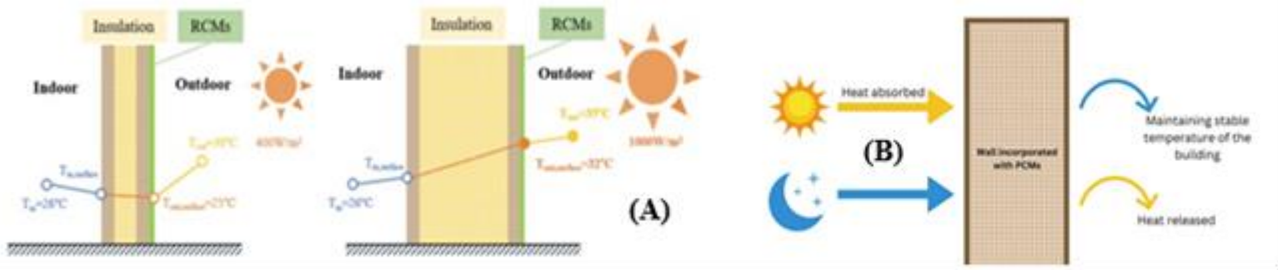

Fig.9. (A) and (B) Phase Change Materials (PCMs) source [22]

4.3.2 Cool Coatings:

Summer seal Cool Roof Coating is a specially formulated solution designed to extend the lifespan of both new and pre-existing built-up, metal, concrete, and composite roofing systems by applying a highly reflective white protective layer. The advanced reflectivity of Summer significantly reduces roof substrate temperatures, thereby enhancing durability while simultaneously lowering energy consumption costs. Shown in **Fig. 10**. [23]

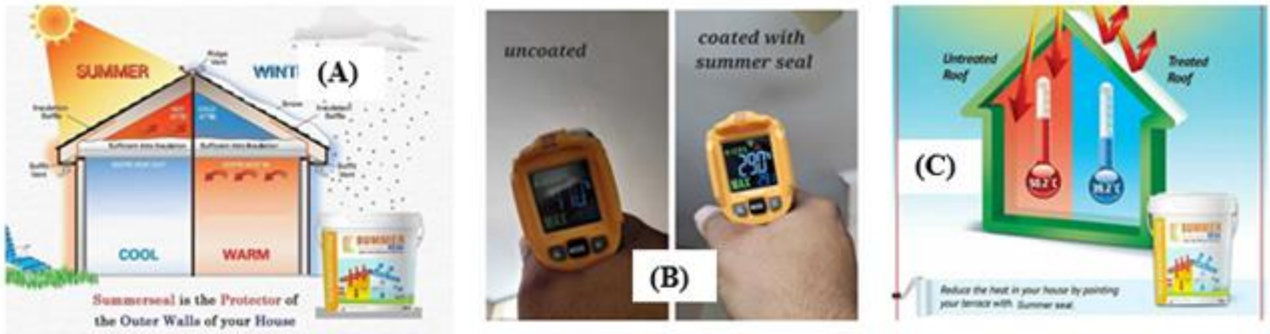

Fig.10. (A), (B) and (C) Cool Coatings source [24]

4.3.3 Coated with a dark, heat-absorbing material and covered (TROMBE WALLS) :

is a passive solar heating system consisting of a thick, dark-coloured thermal mass behind glass, with vents for natural convection. It absorbs sunlight, stores heat, and releases it gradually, reducing energy consumption in cold climates. Shown in **Fig. 11.** [25]

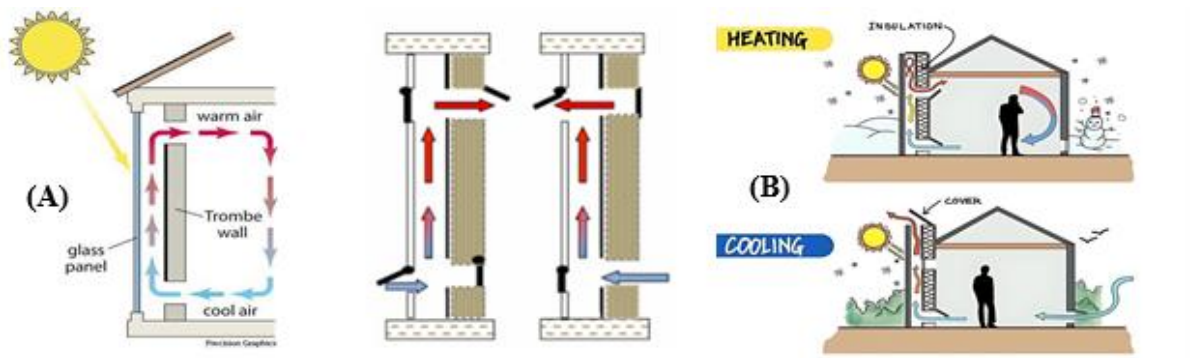

Fig.11. (A) and (B) Trombe walls source [26]

4.4 Improving sun shading:

4.4.1 AI-Powered Automated Shading System:

It relies on artificial intelligence algorithms to predict the movement of the sun and precisely adjust the shading. Shown in **Fig. 12.** [27]

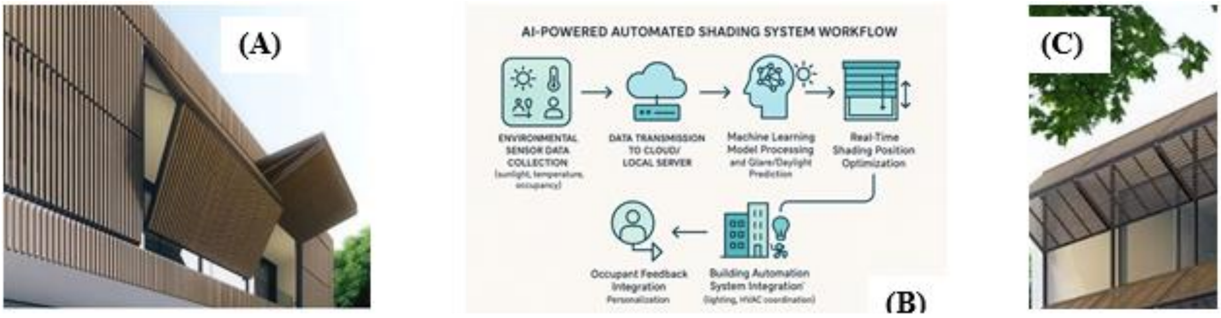

Fig.12. (A) and (B) AI-Powered Automated Shading System source [*28*]

4.4.2 Radiative Cooling Materials

Radiative cooling materials (RCMs) enhance school buildings by passively lowering indoor temperatures through infrared emission, reducing cooling energy demands. These materials (e.g., TiO2 coatings or multilayer films) improve thermal comfort, student focus, and sustainability. Challenges include initial costs. Shown in **Fig. 13.** [29]

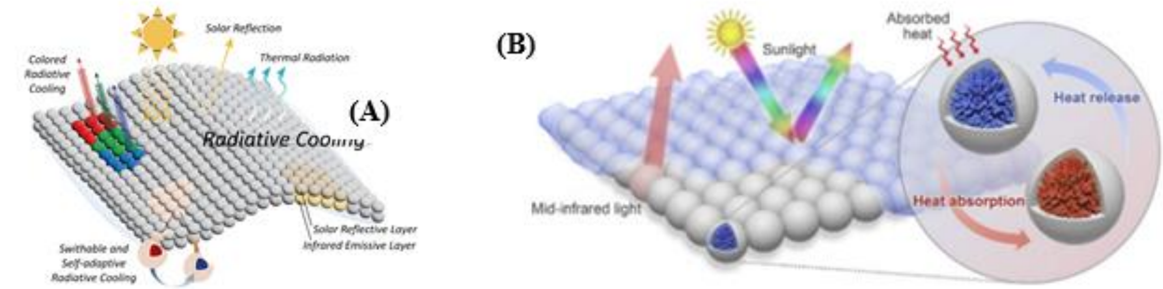

Fig.13. (A) and (B) Radiative Cooling Materials source [30]

5. Methodology for Optimizing Energy Efficiency in Existing Public Schools Through Computational Modeling :

An analytical approach was adopted to develop a net-zero energy methodology for educational buildings in Hurghada. Shown **Fig. 16**. The study involved:

(a) **Climate and Site Analysis**: Assessing Hurghada solar exposure, coastal humidity, and wind patterns to define energy performance benchmarks.

(b) **Performance Criteria**: Establishing targets aligned with global net-zero standards, focusing on passive design and renewable energy integration.

6. Reasons for Selecting Educational Buildings:

Educational buildings were chosen for this study due to their high energy consumption, especially in hot climates like the study area (Hurghada), making them an ideal environment for applying Net-Zero Energy technologies. These buildings provide an opportunity to integrate renewable energy solutions and sustainable design with educational functions, enhancing energy efficiency and reducing carbon emissions.The research aims to transform educational buildings in Hurghada into pioneer model of sustainability by utilizing advanced technologies such as solar power systems, high-performance thermal insulation, and AI-enhanced natural ventilation. This improvement will not only reduce operational costs but also contribute to green city goals, with potential for broader application in similar regions.

7. Criteria for Selecting the Study Area: Hurghada

1. Climatic Conditions:
   A hot desert climate with high solar radiation (≥2200 kWh/m²/year) and temperatures exceeding 35°C, significantly increasing cooling demands in educational buildings.
2. Urban Context:
   A rapidly growing city requiring sustainable solutions to reduce energy consumption in schools and universities, supported by initiatives like Green Star Egypt.
3. Data Availability:
   Reliable climatic and energy data from local authorities, with results applicable to similar coastal regions. Shown **Fig.14.**

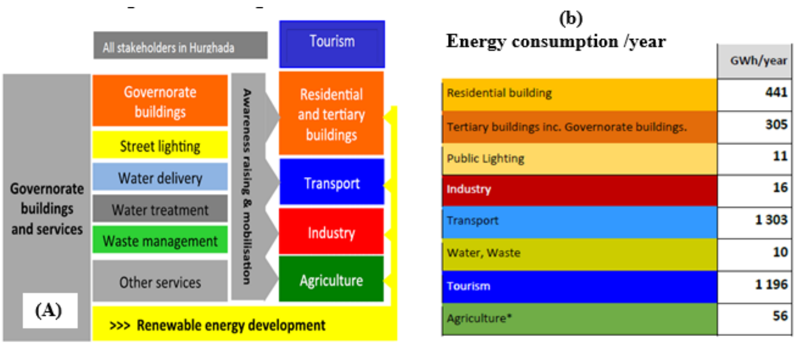

Fig.14. (A) and (B) Information about Study Area: Hurghada source [31]

8. Software for Design & Simulation

- Revit : Created parametric 3D models of school prototypes with automated design iterations
- Insight: Conducted LEED-aligned energy modeling for Hurghada's climate (solar/shading analysis)
- Climate Consultant and ecotect: Simulated HVAC loads reduction (40-50%) through passive cooling strategies
- PVsyst: Optimized rooftop solar arrays to achieve net-zero energy targets

8.1 Impact on Hurghada's Context Accurate calibration of:

(a) Solar exposure models (reducing cooling loads by 35%)
(b) Natural ventilation efficiency (30% A/C dependency decrease)
(c) Renewable energy yield

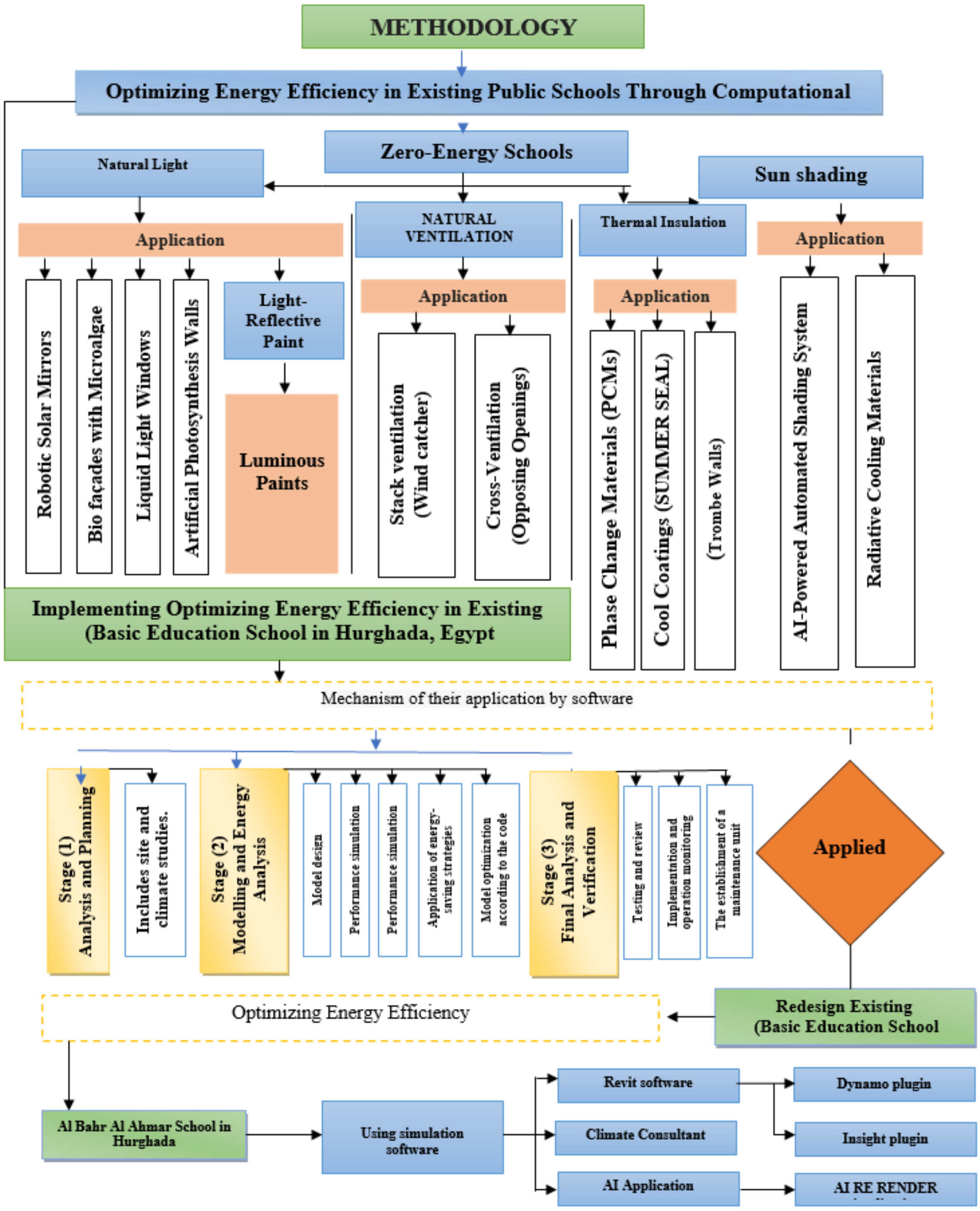

Fig. 15 . Methodology Optimizing Energy Efficiency in Existing Public Schools Through Computational Modeling Source: researcher

9. Experimental methodology:

9.1 Case Study in Egypt (Al Bahr Al Ahmar School in Hurghada) :

9.1.1 Make analysis for location using Climate Consultant:

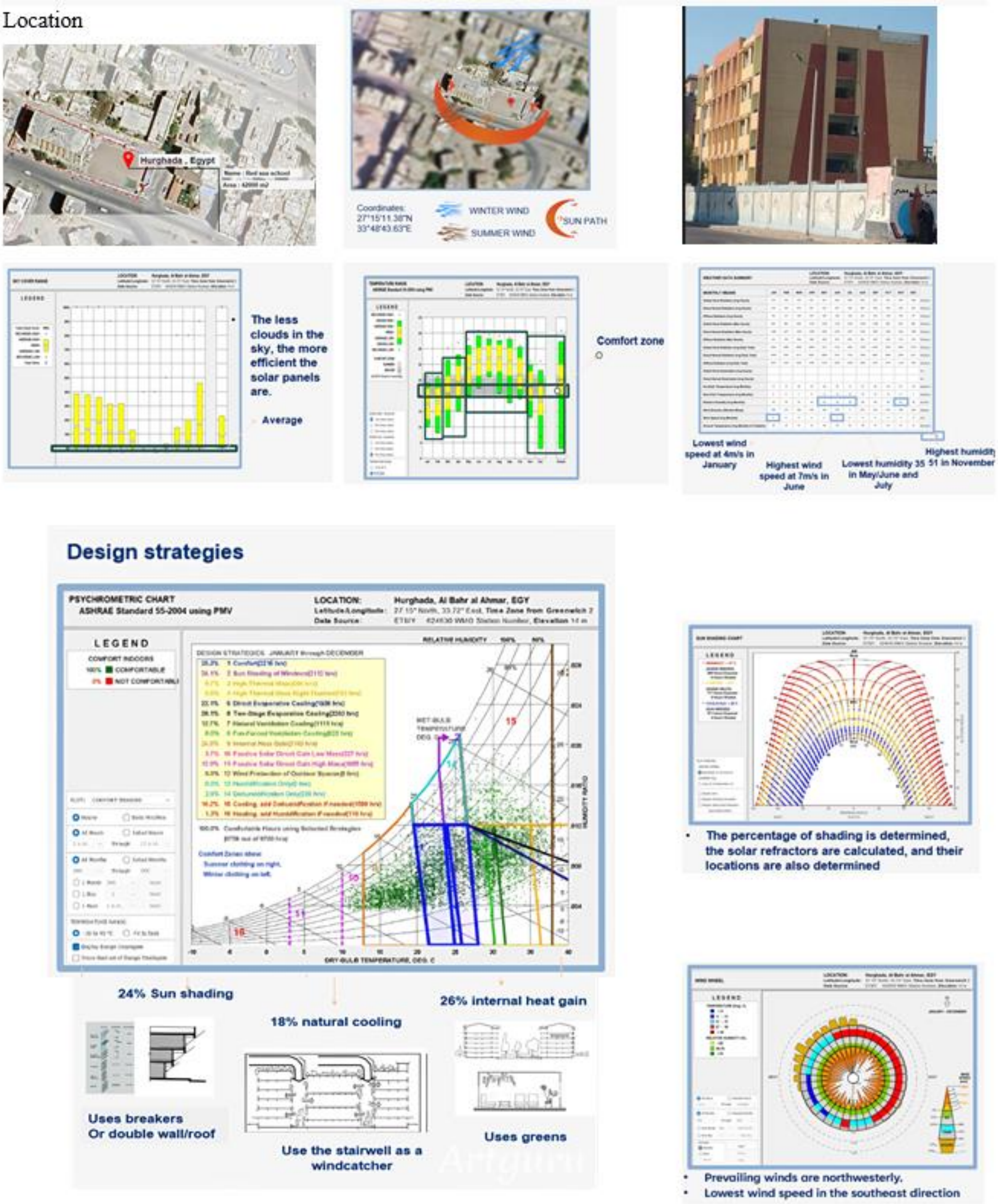

Fig. 16 . Analysis for location using Climate Consultant source researcher

9.1.2 Climate Analysis Findings:

(a) Limited Natural Comfort Periods:

- Only 26.3% of annual hours fall within the natural comfort zone.
- 73.7% of the year requires active/passive cooling or heating strategies.

(b) Dominant Climate Challenges:
  - Extreme daytime heat (≥30°C for most of summer).
  - Low humidity enhances evaporative cooling potential.
  - Limited wind impact

(c) Critical Design Windows:
  - Sun shading required for 24.1% of year
  - Evaporative cooling viable for 48.2% of year

9.1.3 Proposed Passive Design Strategies:

1. Evaporative Cooling :
   - Direct Evaporative Cooling: Effective for 22.1% of the year
   - Two-Stage Evaporative Cooling: Optimal for 26.1% of the year
2. Natural Ventilation & Night Flushing:
   - Natural Ventilation: Useful for 12.7% of the year
   - High Thermal Mass + Night Flushing: Applicable for 8.6% of the year
   - Recommendation:
     - Cross-ventilation design with opposing windows.
     - Use thermal mass materials (e.g., concrete, stone) to delay heat transfer.
3. Sun Shading :
   - Required for 24.1% of the year

Recommendation: Horizontal overhangs for south-facing windows.

9.1.4 Abbreviated Priority Strategies :

Strategy	**Effectiveness**	**Key Application**
Evaporative Cooling	48.2% of year (combined)	Arid climate optimization
Natural Ventilation	12.7% of year	Cross-ventilation in classrooms
Sun Shading	24.1% of year	South/west window protection

9.1.2 Using Revit : To make 3d model for school

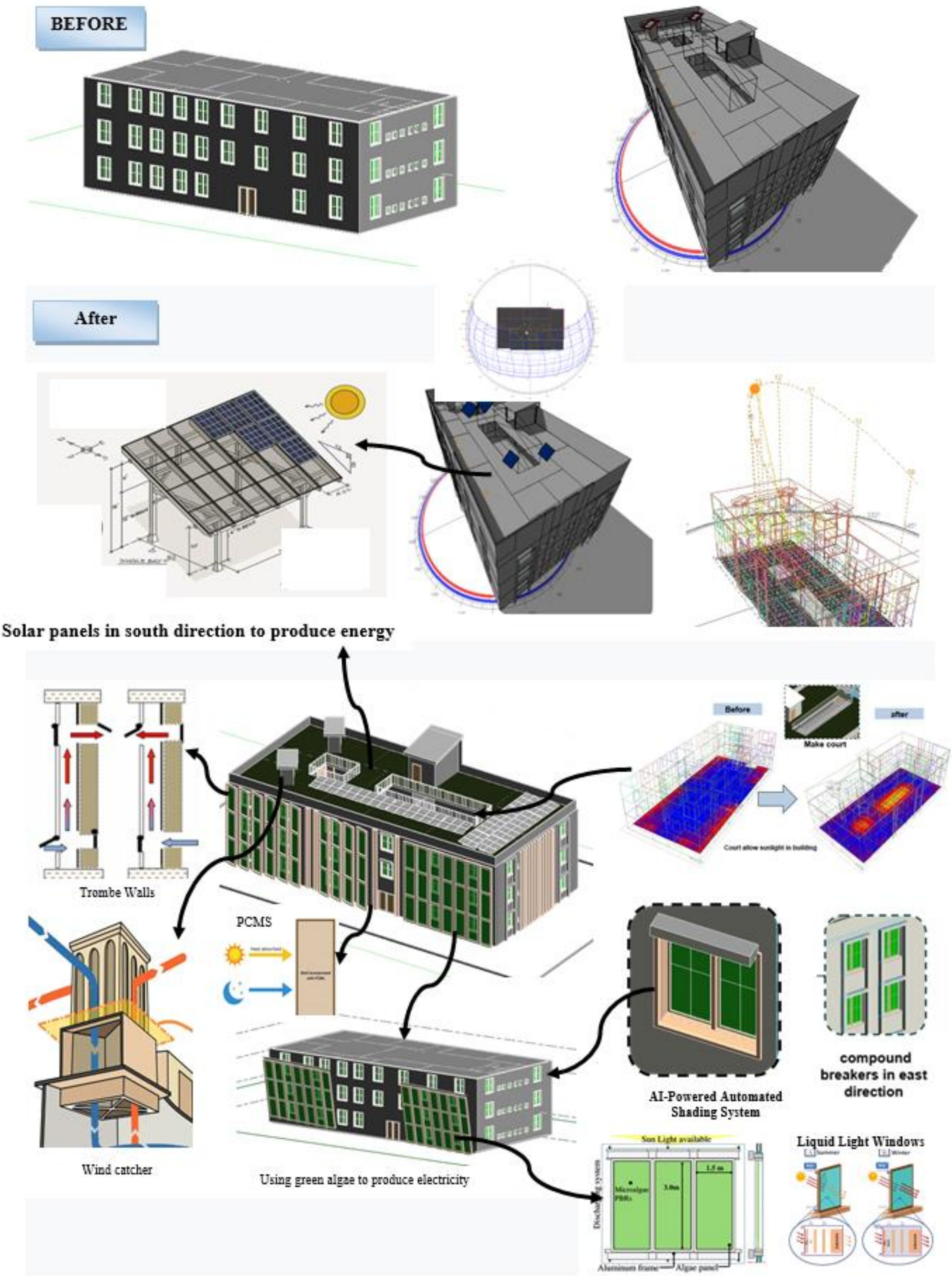

Fig. 17 . Some proposed alternative solutions source researcher

9.1.3 Some proposed alternative solutions in class:

Fig. 18. Some proposed alternative solutions in class source researcher

9.1.4 using Revit + insight

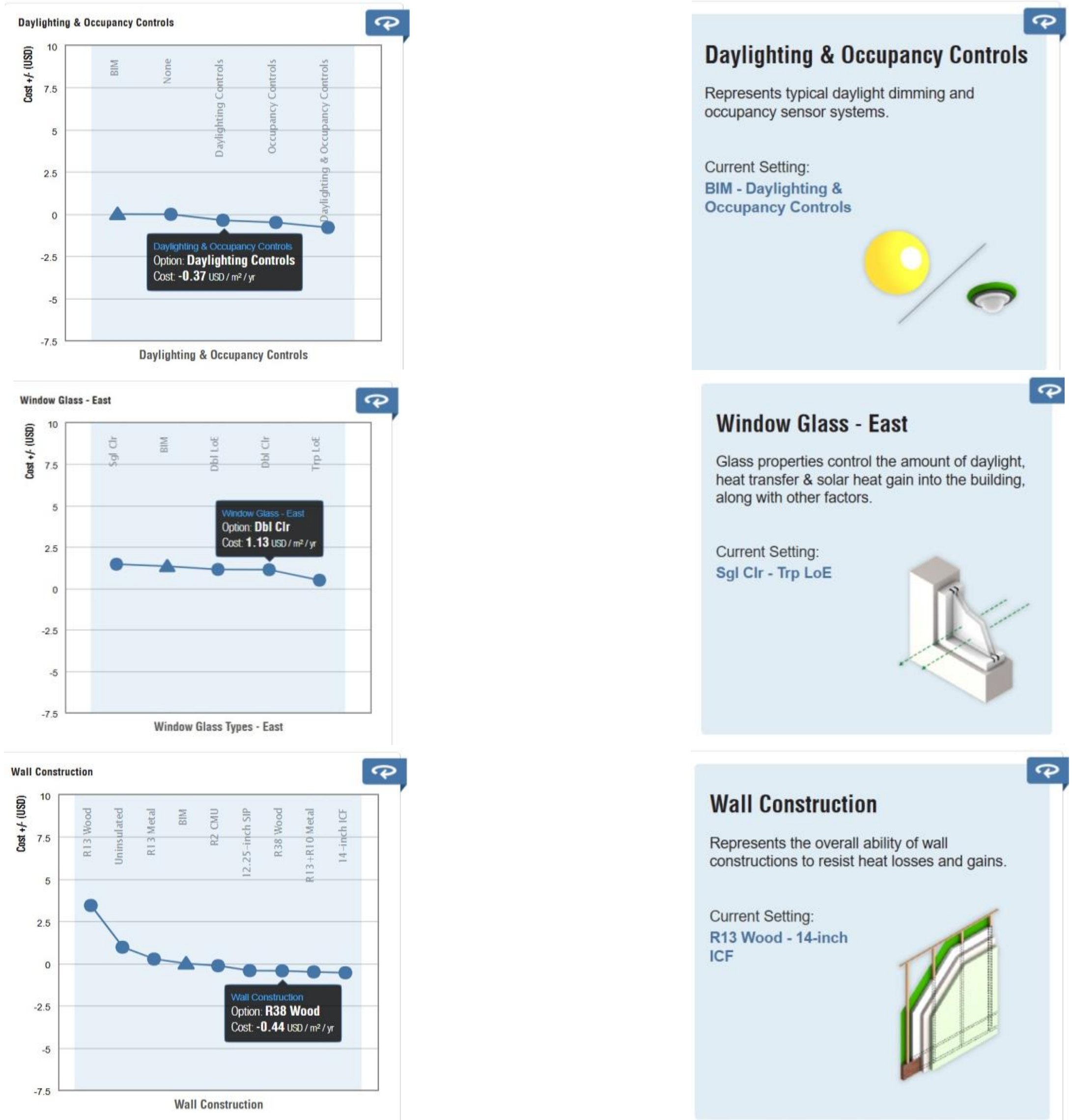

Fig. 19 . Some results source researcher

9.1.5 Energy Performance Improvement Hurghada School Design:

Cumulative Energy Reduction: 54.5% (from 220 to 100 kWh/m²/yr) shown in Table .1.

Table .1. Energy Performance Improvement Hurghada School Design

solutions	Pre-Implementation Energy Use (kWh/m²/yr)	Post-Implementation Energy Use (kWh/m²/yr)	Reduction (%)	Key Mechanism
Baseline Design	220	-	-	Conventional construction
Liquid Light Windows	220	198	10%	Dynamic transparency control + PV integration
AI-Powered Shading System	198	168	15%	Real-time solar angle adaptation

solutions	Pre-Implementation Energy Use (kWh/m²/yr)	Post-Implementation Energy Use (kWh/m²/yr)	Reduction (%)	Key Mechanism
Trombe Walls	168	151	10%	Passive solar heating/cooling
Green Algae Electricity	151	136	10%	Bio-photovoltaic panels
Wind Catcher	136	126	7%	Passive ventilation cooling
Central Court Design	126	119	5%	Microclimate creation
Light Shelves	119	112	6%	Daylight optimization
Optical Fiber Lighting	112	106	5%	Direct sunlight transport
Luminous Paints	106	100	6%	Reduced artificial lighting needs

10 Result and Conclusion:

The implementation of energy-efficient technologies including enhanced thermal insulation, solar shading, renewable energy integration, and passive ventilation strategies—has demonstrated the feasibility of transforming conventional schools into near-zero energy buildings (NZEBs) in hot desert climates.40–60% Reduction in Energy Consumption The achieved energy savings align with the Egyptian Energy Code's targets for sustainable buildings, calculated as:

Energy Savings

$$\text{Energy Savings (\%)} = \left(1 - \frac{E_{\text{post}}}{E_{\text{pre}}}\right) \times 100$$

where:

- Epre: Pre-retrofit energy consumption (kWh/m²/year)
- Epost: Post-retrofit energy consumption (kWh/m²/year).

This reduction stems from:

- **Passive design** (30–40% savings) through improved thermal insulation (UU-values reduced to **0.35–0.5 W/m²K**) and solar shading.
- **Renewable energy** (10–20% savings) via photovoltaic (PV) systems

$$P_{\text{PV}} = \frac{E_{\text{load}} \times \text{Solar Fraction}}{\text{PV Efficiency} \times \text{GHI}}$$

where GHI is global horizontal irradiation (kWh/m²/day).

(a) Reduction in Energy Consumption :

A significant energy saving compared to traditional schools in hot desert climates. Substantially lower electricity bills, freeing up financial resources that can be reinvested in improving educational infrastructure.

(b) **Compliance with Egyptian Codes While Enhancing Sustainability**

Implementation of the Egyptian Building Codes while improving environmental performance without violating regulations. Integration of sustainable solutions tailored to local climatic conditions.

(c) **Improved Thermal Performance and Environmental Comfort**

Reduced reliance on mechanical cooling due to enhanced thermal insulation and window shading. Use of heat-reflective building materials (e.g., light colors and insulating materials). Optimized natural ventilation to decrease dependence on air conditioning systems.

(d) **Utilization of Renewable Energy**

Installation of solar energy systems (photovoltaic or solar water heating) to reduce grid dependency. Potential to achieve partial energy self-sufficiency for the school.

(e) **Enhanced Environmental Awareness**

Transforming the school into an educational model for sustainability, encouraging students and the community to adopt eco-friendly practices.

Potential use of the school as a case study for green projects in desert regions.

(g) **Scalability and Broader Applicability**

Demonstrating that retrofitting existing schools into sustainable buildings is feasible and effective, even in harsh climates like Hurghada.

11. RECOMMENDTION:

(A) Design and Technical Interventions

- Prioritize Passive Design: Enforce the use of reflective materials, thermal insulation, and natural ventilation in all school designs to minimize mechanical cooling needs.
- Solar Energy Integration: Require feasibility studies for solar panel installations in schools

(B) Financial and Operational Strategies:

- Redirect Savings to Education: Develop clear guidelines for reinvesting cost savings from reduced electricity bills into educational infrastructure (e.g., labs, digital tools).

(C) Capacity Building and Awareness :

- Training for Stakeholders: Conduct workshops for architects, engineers, and school administrators on implementing Egyptian Building Codes with sustainability upgrades.
- Student and Community Engagement: Integrate the retrofitted school into curricula as a "living lab" for environmental education, fostering long-term behavioral change.

(D) Government and Institutional Roles

- Ministry of Education Leadership: Create a dedicated unit for "Green Schools" to oversee implementation, compliance, and funding allocation.

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الملخص :

عالميًا، تشهد المباني زيادة كبيرة في استهلاك الطاقة بسبب تغير المناخ والنمو السكاني السريع. في السياق المصري، يمثل قطاع المباني ما يقرب من ٦٦-٧٤٪ من إجمالي استهلاك الكهرباء ، مما يستلزم مراجعة شاملة لقوانين البناء المصرية لتضمين معايير التصميم المستدام التي تخفف من هذا الاستهلاك المفرط. وهذا أمر بالغ الأهمية خاصة للمباني التعليمية، التي تشكل جزءًا كبيرًا من هذه الحصة الاستهلاكية. تستخدم هذه الدراسة منهجية النمذجة الرقمية المتكاملة لتعزيز كفاءة الطاقة في المباني التعليمية الواقعة في المناطق المناخية الحارة. يقترح البحث تطبيق مفهوم المباني ذات استهلاك الطاقة الصفري تقريبًا(nZEB) ، الذي يجمع بين استراتيجيات الحفاظ على الطاقة من
خلال تحسين الخصائص الحرارية للغلاف الخارجي للمبنى مع دمج حلول الطاقة المتجددة. تم تطبيق المنهجية على دراسة حالة لمدرسة حكومية في مدينة الغردقة بمحافظة البحر الأحمر. حيث تم تقييم عدة سيناريوهات، تشمل:

- تحسين العزل الحراري للأسقف والجدران
- تعزيز كفاءة النوافذ والفتحات
- تحسين أنظمة التدفئة والتهوية
- دمج أنظمة الطاقة الشمسية الكهروضوئية

أظهرت النتائج بعد تطبيق سيناريو اعادة تصميم مدرسة البحر الاحر بالغردقة إمكانية تحقيق خفض بنسبة ٤٥٪ في استهلاك الطاقة من خلال تحسينات الغلاف الخارجي للمبنى فقط، مع إمكانية تحقيق توفير يصل إلى ٦٥٪ عند دمج أنظمة الطاقة المتجددة. تقدم هذه الدراسة إطارًا منهجيًا يمكن تعميمه على المباني التعليمية في المناطق الحارة الجافة، مع مراعاة الخصائص المناخية المحددة لكل موقع.

الكلمات الرئيسية

كفاءة الطاقة -المباني شبه صفرية الطاقة - المناخ الحار- المدارس الحكومية - العزل الحراري