International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Energy Production and Management
Vol. 10, No. 2, June, 2025, pp. 289-303
Journal homepage: http://iieta.org/journals/ijepm

The Role of Smart Technologies in Enhancing Building Energy Efficiency in the Era of Climate Change

Khalid A. Karoon*, Yahya Ibraheem

College of Architectural Engineering, University of Technology – Iraq, Baghdad 10066, Iraq

Corresponding Author Email: ae.21.12@grad.uotechnology.edu.iq

Copyright: ©2025 The authors. This article is published by IIETA and is licensed under the CC BY 4.0 license (http://creativecommons.org/licenses/by/4.0/).

https://doi.org/10.18280/ijepm.100211

Received: 26 April 2025
Revised: 11 June 2025
Accepted: 21 June 2025
Available online: 30 June 2025

Keywords:
climate change, intelligent management, renewable energies, smart envelope

ABSTRACT

The urgent need for a more responsive built environment in the era of climate change has driven architects, researchers, and construction professionals to adopt integrated design solutions that utilize various technologies to improve buildings' energy performance. This effort aims to reduce dependence on fossil fuels, whose combustion significantly contributes to climate change. Notably, the building sector consumes approximately 41% of electrical energy, with most of this energy used for ventilation, cooling in summer, heating in winter, and artificial lighting. This comparative study employs a descriptive methodology, gathering information about energy sources, their types, and their impact on the construction sector. Additionally, it analyses architectural projects that have adopted smart envelopes as a remedial measure to combat climate change. The research then explores modern treatments for contemporary building envelopes and their transformation into smart envelopes by elucidating the concept of intelligence within these systems. Experiments implementing these methods in the Middle East and North Africa (MENA) region are reviewed, highlighting the benefits and lessons learned. The study emphasizes the impact of renewable energies and their integration with the building envelope, as well as negative treatments at the envelope level that contribute to isolating the building from external environmental conditions. The findings provide a comprehensive description of how different variables affect the energy performance of buildings.

1. INTRODUCTION

One of the most pressing global issues today is the excessive consumption of non-renewable energy sources, particularly fossil fuels. This overreliance has significantly contributed to global climate change, manifesting in various environmental risks such as global warming, air pollution, and ozone layer depletion [1, 2]. The extensive use of fossil fuels has led to severe environmental problems, including the emission of toxic gases that have resulted in numerous adverse environmental phenomena, notably global climate change [3]. The extensive use of fossil fuels poses significant economic burdens on nations and threatens the future of the planet. Consequently, oil-dependent countries have become increasingly aware of the necessity to diversify their income sources to mitigate their dependence on a single resource [4]. Globally, there has been a growing interest in seeking alternative energy sources, giving rise to terms like renewable energies. These sources, such as solar and wind energy, have existed since the dawn of humanity and have been utilized to varying extents in primitive ways [5]. These early experiments have formed the foundation for developing these rudimentary methods in line with technological advancements, particularly in the field of architecture [6].

The research problem addressed in this study is that architecture designed without considering how and to what extent it uses energy is a major contributing factor to climate change. The significance of this research lies in improving the energy efficiency of buildings through the application of building envelope treatments as a case study. These treatments have contributed to creating environmentally efficient architecture. The study explores modern techniques used in contemporary architecture and assesses the potential benefits of negative treatments using contemporary methods. It delves into the concept and technical aspects of the smart envelope, examining its practical applications and its role in providing thermal comfort and mitigating climate change. Research Question: How can the integration of smart technologies, including energy efficiency measures, renewable energy systems, and intelligent management of building envelopes, enhance the energy performance of buildings and contribute to mitigating the impacts of climate change?

The research employs a descriptive methodology, gathering information on energy sources, their types, and their impact on the construction sector, as well as the influence of limited and renewable energy consumption on climate change. It also investigates the various approaches adopted in contemporary architectural envelopes. Additionally, an applied methodology is used to analyze contemporary architectural examples that have adopted the smart envelope as a treatment method to combat climate change, aiming to achieve highly environmentally efficient contemporary architecture. The methodology for studying project samples relied on websites and research that discussed them. However, it would be better to visit these projects or contact the executive or designing companies to understand the nature of the technologies used and the obstacles in their implementation and operation, thereby obtaining more accurate and detailed results. However, this process requires time for travel and meetings, as well as funds to pay the companies, which are not feasible within the constraints of a master's study in terms of time and cost.

2. ENERGY SCENARIO

In the 1980s, the international community recognized the severe threat posed by climate change and began establishing institutions and treaties to address it [7]. Emissions resulting from energy consumption in buildings, transportation, and industry are among the leading causes of climate change, with buildings being the largest contributors [8]. The building sector presents the most cost-effective opportunity to reduce these emissions, thereby underscoring the urgent need to shift towards renewable energy sources. Although renewable energy cannot fully replace oil shortly, reducing reliance on carbon-based fuels and diversifying energy sources can significantly alleviate environmental burdens [9]. The following section elucidates the concept of natural energy sources, their types, and the advantages and disadvantages of each source. This serves as a prelude to discussing how architecture can contribute to mitigating the impact of climate change.

2.1 Natural energy sources

This section explores natural energy sources, classifying them into non-renewable and renewable categories. Non-renewable sources like coal, oil, and natural gas are depleting due to high consumption, leading to environmental concerns. In contrast, renewable energy sources, including solar, wind, and hydropower, offer sustainable alternatives by harnessing natural energy flows that are continuously replenished. The section highlights the benefits and limitations of these energy types, emphasizing the critical need for a shift toward renewable energy in architecture. Integrating renewable technologies into building designs can help reduce carbon emissions and contribute to global sustainability efforts in mitigating climate change. Natural energy sources can be classified into two main categories: non-renewable energy and renewable energy.

Table 1. Non-renewable energy source

Source	Description	Key Points
Coal	Emerged during the Industrial Revolution and spread globally. Various types of coal differ in organic composition and energy content.	- Significant fuel sources since the Industrial Revolution. - Currently accounts for about 27% of global energy production. - The largest reserves are in the U.S. (22.3%), Russia (15.2%), and Australia (14%).
Oil	Discovered about a century ago. Initially used in the U.S., expanded globally after WWII due to its transportability and high energy density.	- Became the leading energy source after WWII. - Represents around 31% of global energy consumption. - Largest reserves: Venezuela (17.5%), Saudi Arabia (17.2%), Canada (9.7%), Iran (9.1).
Natural gas	The third most consumed energy source globally, making up 18% of total energy consumption.	- The U.S. holds 6.7% of global reserves. - Arab countries together hold about 15%. - Major reserves: Russia (19.9%), Iran (17.1%), Qatar (13.1%).

Table 2. Renewable energy source

Renewable Energy Source	Description	Key Points
Biomass energy	Derived from organic materials (not covered in detail).	- Renewable energy source. - Reduces dependence on fossil fuels. - Can lead to deforestation if not managed sustainably.
Geothermal energy	Utilizes heat from the Earth's core (not covered in detail).	- Reliable and consistent energy. - Low emissions. - limited to geologically active regions.
Wind energy	Uses wind turbines to convert the wind's kinetic energy into electricity. Composed of turbines, a tower, a control system, and a station. Reduces carbon emissions but faces challenges like weather variability.	- Renewable electricity generation. -Reduces carbon emissions. - Low operational/maintenance costs. - Visual and noise impacts
Solar energy	Solar energy is derived from the sun and can be used for heating homes, pools, and industrial processes, particularly in remote areas. Flat plate collectors are common for electricity and heat generation.	- Homes and industrial heating. - Useful in remote areas. - Major renewable energy source in both developed and developing countries.
Ocean thermal energy	Uses temperature differences between warm surface water and cold deep ocean water to generate electricity through heat exchangers.	- Consistent and renewable sources. - Suitable for tropical regions. - Expensive initial setup and limited to specific regions.
Tidal energy	Harnesses energy from ocean tides using underwater turbines. It is highly predictable compared to other renewable sources.	- Reliable and predictable energy. - Minimal environmental impact. - Limited to coastal regions with significant tidal ranges.

2.1.1 Non-renewable energy sources

Non-renewable natural resources, which do not regenerate within a human lifetime and take millions of years to renew, are extracted from the earth's crust and are depleted due to their consumption rate, far exceeding their replenishment rate. They are categorized into three primary sections [10-13], as shown in Table 1.

2.1.2 Renewable energy sources

Renewable energy sources are derived from natural energy flows that recur automatically and periodically in nature. Unlike non-renewable energy, which typically exists in fixed deposits within the earth and requires human intervention for extraction, renewable energy is continuously replenished and accessible through natural processes. The primary types of renewable energy available globally include solar energy, wind energy, hydropower, and biomass energy. We will not cover other renewable sources, such as wave energy and geothermal energy, as we believe their exploitation soon is unlikely or their current investment significance is relatively low [14]. Table 2 displays the renewable energy sources with relevant data extracted from the study [14].

3. ARCHITECTURE AND CLIMATE CHANGE

Buildings are responsible for significant land use, energy and water consumption, and climate change impacts. The construction sector represents 39% of greenhouse gas emissions and 36% of energy consumption. To ensure the long-term safety and normal operation of buildings, it is crucial to understand the impact of climate on buildings and how to address these impacts [15]. Climate change is a complex issue that requires equally complex response measures. The most common strategies are mitigating climate change impacts and adapting to them. In short, the purpose of mitigation is to avoid what cannot be managed, and the purpose of adaptation is to manage what cannot be avoided [16]. Buildings are a major contributor to climate change, accounting for one-third of global energy consumption and one-quarter of CO_2 emissions. Residential buildings are the most consuming, although tertiary expansion requires further analysis to develop sound-specific indicators. Heating, Ventilation, and Air Conditioning (HVAC) systems comprise 38% of building consumption, calling for strengthened standards and incentives for retrofitting [17, 18]. Considering these statistics, the Agency for Environmental Protection (APE) considers reducing the natural resources consumed in construction and the amount of pollution it generates as vital to the future of sustainability.

In recent times, there has been a significant demand for renewable energy, which is increasing due to the rising cost of energy and global environmental changes. The environmental risks associated with fossil fuel-powered power plants are considerable in terms of emissions and fuel consumption. Additionally, the transmission of electric energy from these generation units to customers through the current electricity grid results in significant energy losses. This has led to a global shift away from these plants towards renewable energy sources to preserve the environment and reduce carbon dioxide emissions [17]. According to the Global Renewable Energy Report, renewable energy accounted for 28.3% of the global electricity mix in 2021, with solar and wind power providing more than 10% of the world's electricity for the first time, as shown in Figure 1. The construction sector is one of the most significant sectors that has adopted renewable energy, alongside the transportation, agriculture, industry, and energy sectors [18].

The importance of adopting renewable energy and sustainable building practices in the construction sector to combat climate change. The primary research gap to be reviewed is the simultaneous development and integration of energy efficiency and renewable energy policies in the construction sector to stabilize and reduce carbon dioxide emissions. The focus will be on the next part. What new technologies are available or needed to enhance the integration of renewable energy in construction? How effectively are current building projects integrating renewable energy and energy efficiency measures? By focusing on these areas, research can identify effective strategies to improve the adoption and integration of renewable energy measures and energy efficiency in the construction sector, particularly in building envelope treatments.

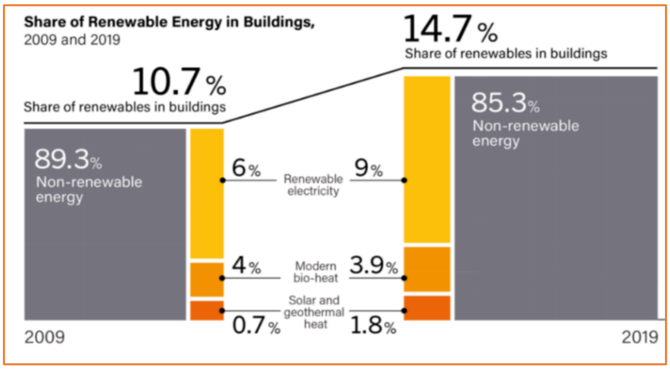


Figure 1. Comparison of renewable energy adoption in buildings between 2009 and 2019 [18]

4. MODERN METHODS IN CONTEMPORARY ARCHITECTURE TO CONFRONT CLIMATE CHANGE

Eco-friendly building requires measures to reduce energy usage and explore the potential of advanced technological applications in contemporary architecture to minimize the impact of climate change [19]. This necessitates enhancing the efficiency of the building envelope, which separates the conditioned interior spaces from the external environment. This can be achieved through various actions, such as using high-insulation windows and applying thermal insulation to walls, roofs, and floors. One commonly adopted measure is passive cooling, especially in low-energy homes, which minimizes the need for energy consumption. Additionally, utilizing solar energy for heating and domestic hot water reduces electricity demand. On-site renewable energy generation, including solar, wind, and hydropower, can significantly mitigate the environmental impact of buildings. Below, we review some of the modern technological solutions used in contemporary architecture that can contribute to improving a building's energy efficiency [18].

4.1 Solar energy in building envelopes

4.1.1 Building-Integrated Photovoltaics (BIPV)

This technology, known as BIPV, assists in generating electrical power by incorporating solar cells into the structures and materials of buildings. The goal of this technology is to transform buildings from mere energy consumers into active electricity generators. Below, we will elucidate this technology, including its benefits, types, applications, challenges hindering its widespread adoption, and examples of projects in the Arab world where this technology has been utilized [20], as shown in Figure 2.

Figure 2. BIPV Technology [20]

The concept of BIPV Technology is a technology that integrates solar cells directly into building structures, whether as exterior façades, roofs, or even windows. BIPV is a crucial part of the concept of green building, where the building itself plays an active role in generating electrical energy from its various components rather than merely serving as a passive structure. Simply put, BIPV Technology can be used as an alternative to traditional roofs, skylights, and building façades [21].

Benefits of BIPV Technology:

- Energy Generation: BIPV systems allow for the direct production of electricity from sunlight, reducing reliance on fossil fuels and decreasing the demand for electricity generated from non-renewable sources.
- Architectural and Aesthetic Integration: Solar panels can be seamlessly integrated into the building's design, enhancing the overall aesthetics and eliminating the need for traditional, prominent solar panel installations. BIPV systems offer a variety of colors and shapes to complement different architectural styles.
- Space Efficiency: Utilizing surfaces such as roofs, walls, and windows for energy generation maximizes the use of available space and leaves ground areas free for other purposes. This approach negates the need for additional structures to support traditional solar panels, reducing the infrastructure requirements.
- Improved Thermal Performance: Integrated solar panels can provide an extra layer of insulation, helping to reduce direct solar heat gain within the building. This contributes to maintaining a moderate indoor temperature, potentially lowering heating and cooling costs.
- Environmental Sustainability: BIPV systems are often made from environmentally friendly materials, contributing to the reduction of the building's overall environmental footprint.

These benefits make BIPV Technology a viable and attractive option for modern, sustainable architecture, aligning energy generation with aesthetic and functional aspects of building design.

4.1.2 Applications for BIPV Technology

BIPV Technology has a wide range of applications in buildings. It can be used as façades for buildings, as shown in Figure 3, roofs for canopies and houses, balconies, as shown in Figure 4, as well as in fences and other structures [20].

Figure 3. Applications of BIPV systems can be used as façades for buildings [20]

Figure 4. Applications of BIPV systems can be balconies for buildings [20]

In Arabic countries, there are prominent projects utilizing BIPV Technology [22, 23]. Examples of them are the Research and Development Centre (R&D) – Dubai Electricity and Water Authority (DEWA). The view of the building is shown in Figure 5. This center integrates BIPV Technology into its design, demonstrating the advanced use of solar energy systems within the building's structure [22].

Figure 5. Research and Development Centre (R&D) [22]

Another example of a BIPV-based project in Arab countries is Dubai Frame, as depicted in Figure 6. The Dubai Frame incorporates BIPV [23] technology into its façade, blending innovative solar energy solutions with iconic architectural design.

Figure 6. Dubai Frame [23]

BIPV Technology offers a sustainable and energy-efficient solution for modern buildings, providing multiple benefits, including improved energy efficiency, enhanced architectural aesthetics, and increased property value. By adopting this technology, significant progress can be made in sustainability and in reducing negative environmental impacts.

5. SMART ENVELOPE CRITERIA

Before delving into the concept of the smart building envelope, it is essential to first clarify the notion of smart buildings and their technical and functional characteristics. This will set the stage for a detailed exploration of the smart building envelope.

5.1 The concept of smart buildings

The term "smart buildings" refers to their ability to recognize and perceive changes in external and internal conditions and to respond and adapt appropriately to these changes. The objective is to optimize resource utilization, improve the indoor environment, and enhance occupant comfort. Conversely, non-smart buildings are characterized by their static nature and inability to respond to such changes [24]. Smart buildings are characterized by three main attributes that a building must possess (Awareness, Decision-Making, and Responsiveness) [25].

5.2 Infrastructure and technical requirements for smart buildings

Smart buildings represent an evolution in architecture that integrates advanced technologies to enhance efficiency and comfort. These buildings are based on three core elements, as illustrated in Figure 7 and described in Table 3.

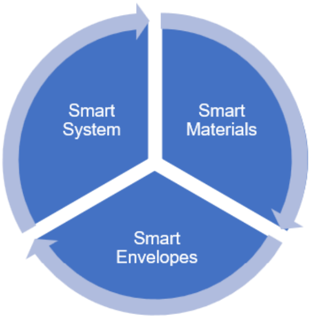


Figure 7. Elements of a smart building

Table 3. Elements of a smart building

Smart Element	Description
Smart systems	Smart systems encompass advanced technologies for automatic control of lighting, heating, ventilation, and security. These systems are interconnected through computing and communication technologies to enable continuous monitoring and performance optimization.
Smart envelopes	Smart envelopes are building façades that dynamically interact with the environment, such as by controlling the flow of heat and light. This interaction enhances energy efficiency and reduces the reliance on artificial heating and cooling systems.
Smart materials	Smart materials can adapt to changing conditions, such as glass that can alter its transparency or thermal coatings that respond to temperature variations. These materials improve occupant comfort and enhance energy efficiency.

These elements are integrated through interconnected systems that allow for efficient resource management, reduced operating and maintenance costs, and the provision of comfortable and healthy environments. This integration enhances productivity and minimizes environmental impact. In this research, and according to the selected case study, smart envelopes will be explored and detailed as one of the most significant of these systems.

5.3 Concept of the smart envelope

The term "smart envelope" is used because it encompasses the façades and roofs of a building. The building envelope is the foremost architectural component that interfaces with the external environment, acting as the boundary between the building's internal spaces and the surrounding environment. It plays a crucial role as the thermal regulator for indoor spaces while also controlling the levels of natural lighting and ventilation. With the rapid advancements in technology and techniques, building envelopes and façades have greatly benefited from this progress [26]. Historically, architects perceived the external envelope of a building as a static element that did not change. However, with the advent of the smart envelope concept, this view has shifted. The smart envelope is now seen as a dynamic, life-like entity capable of movement to meet the needs of users with minimal energy consumption and even contribute to the building's energy requirements [27]. The operating principle of the smart envelope consists of three successive stages [28], as shown in Figure 8.

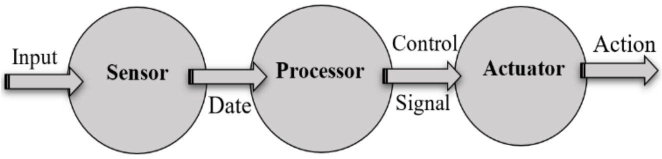


Figure 8. Stages of operation of the smart envelope-prepared by the researcher

- Input: Through various sensors, both external and internal.
- Processing: Managed by the building's central intelligence system (Building Management System).

- Output: Implemented by actuators connected to the building's exterior elements, such as surfaces, walls, and external openings.

5.3.1 Characteristics of the smart envelope

The smart envelope possesses distinctive characteristics, which have become a focal point in architectural theories aimed at leveraging façades to benefit the environment and consider energy-saving measures. These characteristics include [27, 28]

i. Ability to Change, Adapt, and Control

With the evolution of the smart envelope concept, the ability to change has become one of its fundamental characteristics. For instance, the smart envelope can alter its properties according to the climatic seasons throughout the year. In the summer, the exterior envelope functions to block the sun's rays from striking the building and reducing the temperature. Conversely, in the winter, the envelope absorbs as much heat as possible to warm the building, as illustrated in Figure 9. Thus, the envelope acts as a regulator of permeability rather than simply a barrier to keep elements out [21]. Additionally, the envelope can adjust its levels of transparency as needed, achieved through the control of material properties known as smart materials.

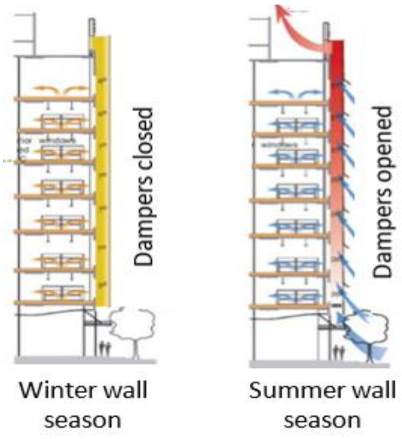


Figure 9. Change in the characteristics of the building envelope with the change of seasons [21]

A simple example of this is the "Hooker Building" in New York City. Its façades have the active ability to adapt to daily and seasonal changes. The exterior envelope responds to these changes by automatically opening and closing the solar shading louvers located between the exterior and interior glass layers. These sun breakers are controlled by solar cells positioned on the upper edge of one of the solar shading louvers in each set [25], as illustrated in Figure 10.

Figure 10. Solar shading louvers in the smart envelope of the Hooker Building, New York [25]

ii. Ability to Learn

Scientists aim for the smart envelope to possess the ability to learn and autonomously make optimal decisions based on past similar experiences. For instance, the system could detect overcast skies and anticipate rain, thereby making the best decision for the building. This goal includes endowing the smart envelope with human-like traits such as acting autonomously without user intervention, self-regulating to adapt to ongoing environmental changes, and having the capability to predict future conditions and find suitable solutions for the occupants [26].

iii. Ability to Meet User Requirements

The smart envelope is designed to provide maximum comfort through autonomous control. It must be capable of accepting new, possibly unconventional user commands based on their preferences. However, the acceptance of such preferences depends on the building's privacy level. In private buildings, the envelope should comply with user desires even if they contradict optimal thermal comfort. In contrast, in public buildings, users are expected to adhere to the general system requirements [27]. The smart envelope dynamically adjusts to seasonal changes, enhancing energy efficiency by blocking or absorbing heat as needed. It teaches us from past experiences to make autonomous decisions and adapt to user preferences, providing comfort while balancing energy use. This makes it essential for sustainable building design, as Figure 11 briefly explains.

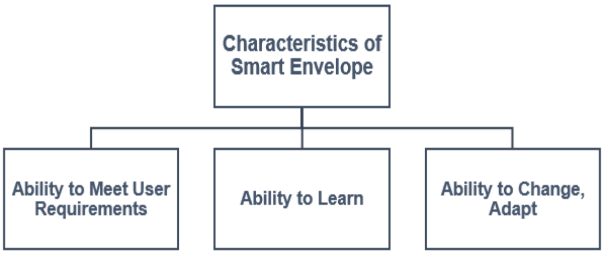


Figure 11. Characteristics of the building envelope

5.3.2 Smart envelop functions

Table 4. Diverse functions of the smart envelope

Element	Function
Sun and light	Natural lighting, light transmittance control, sun protection, and sun glare control.
Vision	Allows see-through (optical contact) and provides privacy by adjusting transparency.
Heat	Insulation and thermal control limit building heat leakage.
Sound	Reduce external noise.
Ventilation	Allows controlled natural ventilation.
Health	It protects against biological damage resulting from fungi, etc., and improves the indoor environment from pollutants and unpleasant Odors.
Safety and protection	Protection from external elements such as rain, wind, and security from intrusion.
Construction and art	Transporting loads, facilitating implementation, operation, and maintenance, and integrating with all building systems.
Oth	Reasonable cost provides privacy and generates energy.

Smart envelopes differ from traditional ones by integrating various devices that enable the external building envelope to adapt and function as a climate-regulating medium. It controls the permeability of the four elements, heat, light, sound, and air, to help meet the fundamental comfort requirements: thermal, visual, acoustic, and ventilation. The automated components of the smart envelope ensure that each comfort requirement stays within a range that optimizes occupant satisfaction. Thus, the smart envelope performs crucial and diverse functions, which are detailed in Table 4.

5.4 Types of smart envelopes

There are two types of smart envelopes: single-skin and double-skin smart envelopes.

5.4.1 Single skin smart envelopes

This type of envelope interacts with the external environment in a single-layer manner, where thermal and light exchanges occur directly regardless of the composition of that single layer. The physical properties of the layer depend on the properties of the material from which it is made. These properties are influenced by the different characteristics, manufacturing processes, and various types of glass used, or they rely on external means to achieve better physical properties, such as shading units, for example.

The single-skin smart envelope achieves thermal regulation and control by advanced types of glass panels, which can be categorized into treated glass and multi-layered glass.

i. Treated Glass

This glass works by managing thermal loads and their transfer into interior spaces. These glass panels can alter their composition to enhance their capability to reduce heat transfer when external temperatures rise or to minimize the loss and transfer of internal heat when external temperatures drop.

ii. Multi-layered Glass

This type of glass relies on the presence of internal layers or an insulating space between the glass layers. These features help in controlling heat transfer by providing additional barriers that slow down thermal exchange [28]. Additionally, solar shading devices, whether fixed or movable, are used to aid in thermal management. However, they do not primarily reduce thermal transfer. They play a supportive role in minimizing the thermal impact of direct solar radiation on heat transfer to internal spaces, as shown in Figure 12.

Figure 12. External solar shading devices [28]

iii. Ventilation Properties

Single-skin smart envelopes are designed to utilize natural ventilation efficiently. Ventilation openings or windows are strategically opened and closed based on the direction of the external wind and temperature. Adjustable louvers or vents can be included to allow fresh air to enter and warm or polluted air to exit. Smart envelopes use anticipated weather data and environmental information to proactively manage ventilation needs. For example, the envelope may open vents before temperatures rise to preemptively cool the building. This approach helps reduce reliance on mechanical cooling systems and enhances energy efficiency [29].

5.4.2 Double skin smart envelopes

The double-skin smart envelope consists of two layers or levels of glass designed to interact with the external environment. The outer layer addresses changes in external conditions, while the inner layer manages the internal environment of space. These two layers are separated by an air gap, which often contains reflectors, movable blinds, and air circulation fans. This air gap serves to adjust and mitigate unfavorable external conditions and acts as an insulator for both heat and sound [30], as illustrated in Figure 13.

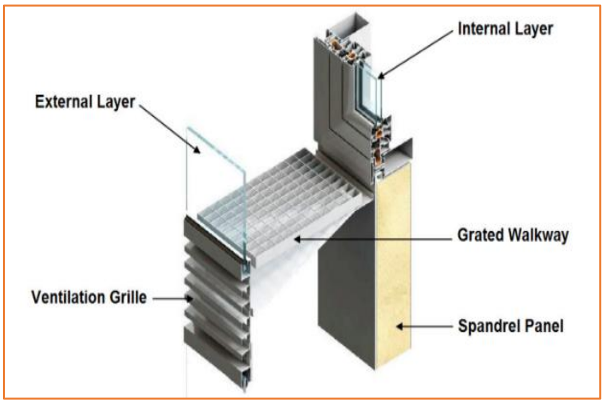


Figure 13. Double skin smart envelope [30]

5.5 Components of the smart envelope

The components of a smart envelope come in various forms and perform a wide range of functions. These components include:

5.5.1 Roof

Smart roofs are a fundamental part of the smart envelope in modern buildings. Their role extends beyond traditional protection against environmental factors like rain and heat. One of the additional advantages of smart roofs is their ability to generate electricity through photovoltaic technology. This can be integrated into the roofs in the form of solar panels or solar cell systems [31], as shown in Figure 14.

5.5.2 Walls

Walls are a fundamental component of the building's exterior envelope, working in conjunction with other envelope elements to protect the building from external factors. There are various types of smart envelope walls, including photovoltaic walls, which operate on the same principle as photovoltaic roofs mentioned earlier. These walls or façades are ideally oriented southward to maximize exposure to sunlight. However, vertically oriented photovoltaic façades typically generate less electricity compared to panels tilted towards the sun. These façades also protect from glare and direct sunlight. Smart envelope walls are often constructed from glass and steel or glass and aluminum [32].

Figure 14. Integration of solar cells on a building roof [31]

5.5.3 Automated control system

The automated control system serves as the brain of the smart envelope, acting as the primary controller for all façade functions. It comprises a vast database with numerous inputs, information, and data that flow into it continuously. It also processes a large number of equations to manage and optimize the performance of the building envelope.

5.5.4 Smart façade

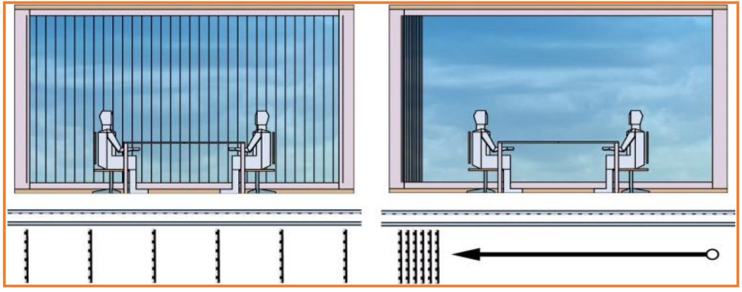
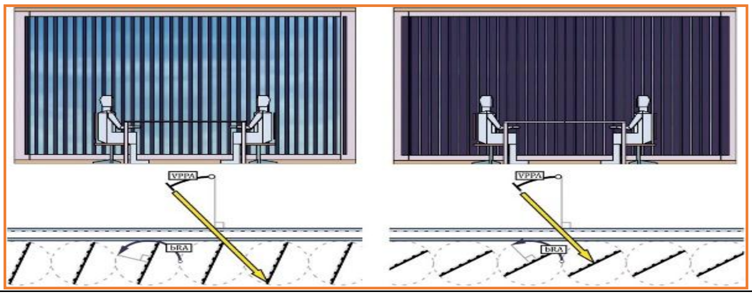
Smart façades can be divided into two types: functional and integrated devices. The functional elements of smart façade devices are opening vents and shading devices. The opening vents include smart windows, which control light transmission by changing the transparency of the glass. The shading devices are of many types, as described in Table 5.

5.5.5 Shading devices

There are shading methods associated with the smart envelope, including external, internal, and integrated shadings, as described in Table 5, extracted from studies [33-35].

Operation and control of the smart façade requires smart monitoring, sensing, and activation of the façade components. Sometimes, those control components could be adjusted and pre-set by the user. Recently, AI has been applied in some cases to predict the coming events surrounding the building envelope, and the components are self-adjust themselves. Smart façade components are divided into the categories shown in Table 6.

Table 5. Shading devices in the smart façade of the smart building envelope

Shading Devices	Descriptions	Figures
External shading devices [33]	External shading tools are integrated into the façade to reduce the heat gained from direct solar radiation. These devices intercept solar radiation before it reaches the building, effectively minimizing heat accumulation.	
Internal shading devices [34]	Internal shading devices are used to reduce glare caused by solar radiation. These devices are typically adjustable, allowing occupants to regulate the amount of direct light entering the space. The most common internal shading solutions include horizontal or vertical blinds that are attached to the window.'	 

Integrated shading devices [35]	When a building features a double façade, shading devices can be integrated between the two layers within the air gap. This setup helps manage solar gain and glare effectively by placing the shading elements in the intermediate space, enhancing thermal and visual comfort.	

Table 6. Components of smart façade

Smart Façade Components	Description
Motors blind	Mechanical devices powered by an electric motor to easily operate blinds.
Actuation vent	Ventilation systems use electric motors for automatic airflow control in buildings [32].
Network communication	Adding any of the various smart façade's devices require networks of cables that connect them to the system, facilitating the transmission of signals and data to and from these devices. The communication network is a crucial element of the overall system, relying on advancements in information and communication technology for its development [36].
Sensors	Provide automated control systems with data about the surrounding environment, adding functionality and responsiveness to the smart envelope components. These sensors are crucial elements of the automated system, converting various natural changes into electrical signals. Different types of sensors operate by measuring environmental variables such as light levels, temperature, wind conditions, rain, occupancy, and more [33].

5.6 Properties of the smart envelope

The intelligent properties of the smart envelope are what distinguish the exterior composition of a smart building. These properties enable the building to maximize comfort with the highest energy efficiency and the least negative impact on the environment, fulfilling the primary role of the envelope effectively.

The physical properties of the smart envelope are the most critical functional characteristics that form the practical foundation through which the smart envelope performs its environmental regulation and adaptation processes. These properties enable the envelope's ability to change and are divided into thermal properties, ventilation properties, lighting properties, and acoustic properties.

Among these, the thermal properties of the smart envelope are the most crucial in determining its success in interacting with the external environment. Ventilation properties also play a supportive role in thermal regulation, as controlling heat transfer is a significant challenge in using smart glass envelopes. This is due to the increased thermal loads within spaces that have large glass surfaces on their exterior façades [27]. Given their significant impact on energy consumption, thermal comfort, and environmental impact, the focus will be on the thermal and ventilation properties. Their application will be studied concerning both single and double smart envelopes.

The thermal properties of the double-skin smart envelope should not be considered separately from its ventilation properties, as ventilation plays a crucial role in thermal control and regulation. This is achieved through specific elements such as foldable and liftable aluminum blinds, adjustable aluminum louvers, and both fixed and movable solar shading louvers. These shading devices are typically located in the air gap between the two layers of the double skin envelope. Their movement, rotation, and tilt angles are controlled either manually or automatically by the central control system of the smart building [34]. A summary of the smart envelope is shown in Table 7.

Table 7. Summary of the smart envelope concept, types, characteristics, and functionality

Explanation	Smart Envelope
Concept	• The smart envelope encompasses all external parts of the building that surround the internal spaces. It is characterized by its dynamic nature and ability to move. • It acts as the thermal regulator for the building's interior spaces while also controlling natural light and ventilation factors.
Functionality	• Its operation is based on three successive stages: sensing, recognizing the event, and finally, decision-making and execution.
Characteristics	• The smart envelope can adapt to external conditions, facilitating environmental alignment and reducing environmental and climatic impact on human comfort. • It makes autonomous decisions based on previous data and can meet occupant requirements.
Features	• It provides energy savings for the building. Enables connection with the external environment. • It offers a flexible internal structure. Controls the intensity of solar heat and the level of glare.
Types	- Single Skin: Single layer or surface of glass. - Double Skin: Two layers or surfaces of glass, which include variations such as box façades, air column façades, corridor façades, multi-layer façades, and ventilated façades with louvered vents.

6. CASE STUDIES OF ARCHITECTURAL ENVELOPES TO MITIGATE THE IMPACT OF CLIMATE CHANGE

Studying and analyzing smart buildings enhances the understanding of the concept of building intelligence. It reveals the benefits and solutions that smart buildings offer, including occupant comfort, increased worker productivity, energy efficiency, and environmental sustainability. These buildings are not only more energy-efficient but also energy-generating and environmentally considerate, making them more sustainable.

Research into smart buildings contributes to spreading awareness and understanding of their advantages. These buildings have become a focal point for development in advanced countries due to their significant benefits in energy conservation and environmental protection.

The selection of case studies will be based on several criteria examined in the research to analyze and understand their implementation and operation within buildings.

- The building must incorporate a unique characteristic that qualifies it as having a smart envelope (the smart feature).
- The envelope must meet criteria that encompass environmental sustainability and energy efficiency.
- The envelope should have been constructed in the 21st century.
- The building should exemplify contemporary technology by including innovative high-performance materials and systems, as well as technological solutions designed to enhance comfort and control.
- The project must include one or more sources of renewable energy.

6.1 Project Cube Berlin

The building has the general data provided in Table 8 [35].

Table 8. Cube building general data [37]

Item	Information
Architect	3XN-COMPANY
Location	Berlin, Germany
Total area	19,500 m²
Completion date	2020

6.1.1 Building description

It is a modern office building located in a historic area in the heart of Berlin. The building is distinguished by its sculptural architecture, making it a notable architectural landmark and a pioneering smart building in office technology. The location of the building is part of the overall master plan for Europa City, which includes the Berlin train station [37].

The sculptural form of the building provides external balconies on every floor, as shown in Figure 15. Its glass façades reflect the movement of pedestrians around it, enhancing the vibrancy of the city's public space. The design features ten floors of office space, a ground floor with a reception lobby, food and beverage outlets, underground parking, a rooftop terrace, and a flexible space that can be transformed into a lecture hall [37].

Inside, the office spaces feature large, floor-to-ceiling windows that offer expansive views of the historic area. These windows also provide ample natural light and ventilation. Additionally, the façades include solar shading elements that provide shade.

Figure 15. Cube Berlin building [38]

The office spaces feature balconies or external extensions on every floor, resulting from the sculptural formation of the building's cubic façades, each side measuring 42.5 meters in length.

The roof is considered the building's fifth façade, featuring a large, spacious terrace that serves as a public area for employees and visitors to gather [35].

6.1.2 The smart system in the building envelope

The standalone office building in central Berlin is designed in the shape of a cube with multifaceted glass façades. It complements the master plan for the area laid out by German architect OM Unger in the mid-1990s.

The cube is entirely clad in glass and measures 42.5 meters in all directions. A pattern of triangular membranes surrounds its façade, creating external balconies for the offices on each floor within the building [38].

Although the building is fully covered in glass, 3XN employs a double-skin façade, cross-ventilation, rooftop solar panels, and an automated heating and ventilation system in an attempt to demonstrate that glass buildings can be energy-efficient [38].

The Berlin Cube is 25 percent more energy-efficient than the well-known green building standards require.

Internally, the building boasts high flexibility, with the capability to move structural elements to accommodate changes in the building's use [37].

The floors wrap around a central core for services and vertical circulation. This design allows for the segmentation of office spaces around it, as shown in Figure 16 [39].

Figure 16. Floor plan of the Cube Berlin project [40]

This building represents the new generation of smart office buildings, adopting advanced artificial intelligence features to serve users. These features allow them to control ventilation, air conditioning, maintenance, energy, book meeting rooms, reserve parking spaces, and provide energy for electric cars and bicycles, among other services, enabling each employee to utilize them according to their personal preference [40].

The intelligent system includes a high-capacity electronic brain that caters to the employees' needs, making the building a hub of knowledge and high-efficiency services.

The high thermal efficiency glass façades are enveloped by an osmotic skin that absorbs water, cooling and moisturizing the building externally. This membrane is coated with solar cell pigments and incorporates a system that captures and reuses thermal energy, significantly enhancing the building's energy efficiency [40].

6.2 Bahrain World Trade Center

This building is part of Bahrain's rapidly developing skyline and represents a significant investment in urban infrastructure. The completion in 2008 aligns with a period of extensive growth in the region, driven by the country's economic diversification efforts. The simple building data is provided in Table 9.

Table 9. Bahrain World Trade Center data

Item	Data
Location	Isa Al Kabeer Avenue, Manama, Bahrain
Completion year	2008
Cost	$150 million
Number of floors	50

6.2.1 Building description

The Bahrain World Trade Center is a twin-tower complex standing 240 meters tall, consisting of 50 floors, and located in Manama, Bahrain. Designed by the multinational architectural firm Atkins, the towers were completed in 2008. They are the world's first skyscrapers to integrate wind turbines into their design [41], as shown in Figure 17.

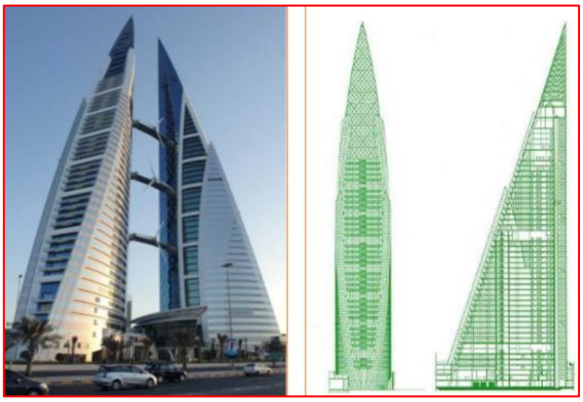


Figure 17. Bahrain World Trade Centre [42]

The Bahrain World Trade Center has provided a prestigious new address for international and regional businesses. The buildings are advanced in both design and operation, the first 'smart' offices in the Kingdom. They feature intelligent systems capable of offering unparalleled security solutions, along with significant competitive advantages and high efficiency in office management [42].

The Twin Towers rest on a three-story podium that houses a recreational resort, restaurants, upscale shopping centers (Moda Mall), and parking facilities. The towers include 34 floors of office space, with an observation deck on the 42nd floor and the five-star Sheraton Hotel. In total, the towers comprise 50 floors [43], as shown in Figure 18.

Figure 18. The smart envelope of the Bahrain World Trade Centre [43]

6.2.2 The smart system in the building envelope

The standout feature of this monumental building lies in its adoption of green technology or sustainable architecture, making it the first skyscraper globally to be partially powered by self-generated wind energy. The wind turbines installed in the towers generate between 11% and 15% of the electrical energy required by the Bahrain World Trade Center, significantly reducing approximately 55,000 kilograms of carbon emissions.

Furthermore, the building is designed to integrate seamlessly with its surrounding environment while minimizing carbon emissions into the atmosphere. This goal is accomplished through a variety of solutions incorporated into the design of the Twin Towers [41-43].

- To counter the scorching Arabian sun, double-glazed and tinted windows reduce 85% of the heat absorbed by the building.
- Efficient air conditioning systems are employed to lower the substantial costs of cooling the building during extreme heat.
- Fluorescent lighting installed on each floor will significantly reduce energy consumption, making the building consume only half the energy compared to other skyscrapers.
- The building design includes substantial gaps between the external environment and the air-conditioned interior to minimize the infiltration of heat and sunlight.
- Deep layers of gravel are used to insulate the roofs, offering enhanced thermal insulation for the building's surfaces.

- Large expanses of sunshades are implemented to provide extensive shading on the exterior surfaces of the towers.
- The building features a dual drainage system that segregates contaminated water and waste, facilitating the recycling of reclaimed water.
- Extensive landscaping is utilized to reduce CO2 emissions and offer shading over the parking areas.
- Balconies are strategically placed to provide shading over the glass surfaces of the building.
- Solar energy is harnessed to power and light the roads around the towers, contributing to electrical energy conservation.

6.3 Results of the case study

Table 10 provides an overview to facilitate the understanding of the application of smart technologies, renewable energies, and energy efficiency in buildings, which contribute to reducing the impact of climate change.

The use of shading systems in the building envelope, along with their role in supporting natural lighting and ventilation, as well as harnessing solar energy for the building's power needs, embodies the principle of integrating renewable energies with the building envelope, which is a crucial strategy in design.

Table 10. Comparison between the cases

Element	Cube Berlin	Bahrain World Trade Centre
Energy efficiency	• Double-skin glass façades provide effective thermal insulation. • Automated heating and ventilation system ensures efficient energy distribution. • Solar panels on the roof help supply part of the building's energy needs.	• Wind turbines generate 11-15% of the building's electrical energy needs. • Double glazing reduces absorbed heat by 85%. • Efficient air conditioning systems reduce high cooling costs. • Fluorescent lighting significantly reduces energy consumption.
Smart technologies	• Advanced AI-based building management system for controlling ventilation, air conditioning, and energy. • Smart reservation system for workspaces and parking. • Multifaceted glass façades provide cross-ventilation and natural lighting.	• Highly efficient smart security and administrative systems. • Dual drainage system for recycling harvested water. • Extensive greenery to reduce CO_2 emissions and provide shading. • Balconies and sunshades offer wide shading areas.
Environmental treatments	• The use of an Osmotic Skin absorbs moisture to cool the exterior of the building and reduce heat. • The membrane is coated with solar cell pigments to absorb and reuse thermal energy. • A sculptural building design enhances natural ventilation and provides outdoor balconies on each floor.	• The streamlined design of the towers reduces wind resistance and enhances natural ventilation. • Deep thermal insulation layers on the roofs. • Buffer zones between the external environment and air-conditioned spaces to minimize heat transfer. • Solar energy is used for lighting the roads surrounding the towers.
Environmental impact reduction	• Energy efficiency is 25% higher than the standards known. • Reduced need for artificial air conditioning due to a design that enhances natural lighting and ventilation.	• Reduction of carbon emissions by approximately 55,000 kg annually. • Design compatible with the local environment minimizes negative environmental impact. • Consumes half the energy compared to traditional skyscrapers.
Operational flexibility	• Movable structural elements allow for changing the building's uses as needed. • Interior design permits flexible partitioning of office spaces.	• Flexibility in facility and service management through smart building management systems. • The provision of open spaces and balconies allows for versatile uses.

7. KEY FINDINGS

The integration of smart systems and renewable energy in building envelopes is a key advancement in sustainable architecture. These innovations enhance passive strategies, allowing buildings to adapt to environmental changes, reduce energy consumption, improve occupant comfort, and lower environmental impact. Key findings include:

i. Smart systems have enhanced the efficiency of passive strategies and their ability to interact and respond to environmental changes by adapting passive solutions to meet the current environmental requirements. The integration of smart systems in passive building strategies represents a significant advancement in sustainable architecture .

ii. Relying on one or more sources of renewable energy in the building envelope, such as wind and solar energy, contributes to reducing carbon emissions by decreasing dependence on fossil fuel energy sources. (This approach not only helps mitigate the environmental impacts of fossil fuels but also aligns with global sustainability goals, making buildings more energy-efficient, resilient, and environmentally responsible).

iii. Operational flexibility in managing the building's facilities and services allows for the movement or addition of elements as needed to change the building's usage. This principle of flexibility is incorporated into the initial planning and design stages to accommodate future expansion, thereby reducing the environmental impact associated with demolition and construction.

iv. The use of double façades has helped reduce internal heat loss and insulate the building from external heat. These façades represent passive solutions enhanced by contemporary smart technologies. Double façades also enhance the overall sustainability of buildings by improving indoor comfort and reducing the need for artificial lighting and HVAC systems. This aligns with global sustainability goals, such as those outlined in the Paris Agreement, which aim to mitigate the impacts of climate change by promoting energy-efficient building practices.

v. Smart technology has emerged at the level of materials, structure, and treatments in building envelopes, ensuring integrated performance in terms of operation, maintenance, and management. By incorporating smart technologies, building envelopes can be designed to require less maintenance and offer longer lifespans, to develop materials and systems that are self-sustaining and require minimal intervention, thereby reducing maintenance costs and environmental impact.

8. CONCLUSIONS

The Middle East and North Africa (MENA) region, like many parts of the world, currently faces an energy shortage crisis due to reliance on non-renewable sources and the lack of comprehensive energy conservation plans. The building sector is one of the highest energy-consuming sectors. Therefore, after studying the effects of climate change and the importance of renewable energy and smart technologies in building design and applying these to global project samples, the following conclusions could be drawn:

- Integration of smart technologies by incorporating smart technologies into building design ensures a comprehensive approach that meets both environmental and functional needs.
- Thermal Efficiency of smart envelopes through the use of smart glass and solar cells regulates natural light and serves as thermal barriers, reducing heating and cooling needs.
- Smart envelopes are adaptive to environmental change and respond to temperature, light, and wind, adjusting to create an optimal indoor climate.
- AI-based systems using autonomous technologies enhance energy efficiency by automatically managing heating, cooling, and lighting.
- Renewable Energy Uses, like PV solar panels and wind turbines on-site within the building envelope, reduce reliance on traditional electric grids and boost sustainability.
- Long-term Sustainability: Smart envelopes help build adaptability to future needs and environmental changes, extending their lifespan for long-term sustainability.
- Although initially costly, smart technologies reduce operational expenses through efficient energy and resource management, and hence, they are economically feasible.

Based on the study, the importance of incorporating smart technologies in building design to enhance thermal efficiency is evident. This includes using smart glass and integrated solar cells to regulate natural light, autonomous control through AI-based management systems, and the utilization of renewable energy. These measures achieve long-term sustainability, reduce operational costs, and extend the lifespan of buildings.

9. RECOMMENDATIONS AND FUTURE DIRECTIONS

The authors propose a set of recommendations to leverage this study in two parallel directions: practical application and research.

9.1 Practical applications direction

i. Encouraging Innovation and Technological Advancement: Promote the continuous innovation and technological development in our contemporary buildings as a solution to their various challenges.

ii. Leveraging Natural Resources and Characteristics: Utilize natural resources and features (such as rainwater, natural lighting, and ventilation) and do not neglect traditional solutions (such as orientation, size, and openings). These enhance the building's performance, reducing the need for advanced technologies and making the building more sustainable.

iii. Learning from Global Expertise: Draw from the global expertise in the field of smart buildings to start where others have ended, rather than reinventing the wheel.

iv. Integrating Renewable Energy Technologies at the Design Stage: To provide comprehensive and sustainable energy solutions for new and existing buildings.

v. Focusing on Effective Thermal Insulation: Use advanced thermal insulation materials and technologies to improve energy efficiency.

vi. Adopting Smart Control Systems: Implement smart control systems to enhance resource management, reduce operational costs, and increase user comfort.

vii. Encouraging the Use of Smart Materials, Such as variable transparency glass and integrated solar panels, to improve the environmental and thermal performance of buildings.

viii. Flexible and Sustainable Design: Design buildings to be flexible and adaptable for different future uses, enhancing the building's longevity and environmental effectiveness.

ix. Conducting Interdisciplinary Research: Foster collaborative research between different engineering disciplines to achieve optimal results and a better understanding of this field.

x. Providing Financial Incentives and Supportive Legislation: To encourage developers to adopt smart envelope technologies in new buildings and existing projects.

xi. Enacting legislation to promote the adoption of smart envelope technologies in new and existing buildings: Enact policies that incentivize the integration of smart envelope technologies in both new and retrofitted buildings to improve energy efficiency and sustainability- Updating Codes and Standards to Include requirements for smart envelope technologies- funding research and studies focused on the development and improvement of smart envelope technologies- designing buildings with smart technologies as an integral part of the architectural framework.

9.2 Future research directions

i. Explore the application of AI and machine learning in building management systems for real-time energy optimization.
ii. Analyze how occupant behavior and interaction with smart building systems influence overall energy consumption.
iii. Investigate the role of advanced energy storage solutions in enhancing the efficiency and reliability of smart building systems.
iv. Assess the cost-effectiveness and long-term operational benefits of implementing smart technologies in buildings.

ACKNOWLEDGMENT

The authors acknowledge the help and support from the Department of Architecture at the University of Technology – Baghdad, Iraq, to complete this work.

REFERENCES

[1] Kuru, A., Oldfield, P., Bonser, S., Fiorito, F. (2019). Biomimetic adaptive building skins: Energy and environmental regulation in buildings. Energy and Buildings. 205: 109544. https://doi.org/10.1016/j.enbuild.2019.109544

[2] UN. (2023). Causes and effects of climate change. https://www.un.org/ar/climatechange/science/causes-effects-climate-change.

[3] Kartal, M.T., Kılıç Depren, S., Ayhan, F., Depren, Ö. (2022). Impact of renewable and fossil fuel energy consumption on environmental degradation: Evidence from USA by nonlinear approaches. International Journal of Sustainable Development & World Ecology, 29(8), 738-755. https://doi.org/10.1080/13504509.2022.2087115

[4] Al-Kayiem, H.H., Mohammad, S.T. (2019). Potential of renewable energy resources with emphasis on solar power in Iraq: An outlook. Resources 8(1), 42. https://doi.org/10.3390/resources8010042

[5] Hafez, F.S., Sa'di, B., Safa-Gamal, M., Taufiq-Yap, Y.H., et al. (2023). Energy efficiency in sustainable buildings: A systematic review with taxonomy, challenges, motivations, methodological aspects, recommendations, and pathways for future research. Energy Strategy Reviews, 45: 101013. https://doi.org/10.1016/j.esr.2022.101013

[6] Hrabovszky-Horváth, S., Pálvölgyi, T., Csoknyai, T., Talamon, A. (2013). Generalized residential building typology for urban climate change mitigation and adaptation strategies: The case of Hungary. Energy and Buildings. 62: 475-485. https://doi.org/10.1016/j.enbuild.2013.03.011

[7] UNFCCC. (1992). United Nations framework convention on climate change. https://unfccc.int/sites/default/files/conveng.pdf.

[8] United Nation Climate Change. (2016). The Paris Agreement: Intended Nationally Determined Contributions (INDCs). https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/indcs.

[9] Al-Kayiem, H.H., Koh, K., Riyadi, T.W.B., Effendy, M. (2020). A comparative review on greenery ecosystems and their impacts on sustainability of building environment. Sustainability, 12(20): 8529. https://doi.org/doi:10.3390/su12208529

[10] Yergin, D. (2009). The Prize: The Epic Quest for Oil, Money and Power. Simon and Schuster. https://archive.org/details/prizeepicquestfo0000yerg_g3v1.

[11] International Energy Agency (IEA). (2024). Oil 2024: Analysis and forecast to 2030. https://www.iea.org/reports/oil-2024.

[12] International Energy Agency (IEA). (2020). Coal 2020: Analysis and forecast to 2025. https://www.iea.org/reports/coal-2020.

[13] BP. (2021). Statistical review of world energy. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-oil.pdf.

[14] Selin, N.E. (2024). Renewable energy. Encyclopaedia Britannica. https://www.britannica.com/science/renewable-energy.

[15] Cheng, C. (2021). Adaptation of buildings for climate change: A literature review. Master's thesis. Department of Building Engineering, Energy Systems and Sustainability Science, University of Gävle, Sweden. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1564191&dswid=1000.

[16] NASA. (2009). Golden state at risk California adapting to climate change. https://climate.nasa.gov/ask-nasa-climate/136/golden-state-at-risk/.

[17] Rehmani, M.H., Reisslein, M., Rachedi, A., Erol-Kantarci, M., et al. (2018). Integrating renewable energy resources into the smart grid: Recent developments in information and communication technologies. IEEE Transactions on Industrial Informatics. 14(7): 2814-2825. https://doi.org/10.1109/TII.2018.2819169

[18] REN21. (2023). Renewables 2022 global status report. https://www.ren21.net/reports/global-status-report/.

[19] Oladosu, T.L., Al-Kayiem, H.H., Gilani, S.I.U.H., Baheta, A.T., et al. (2023). Performance enhancement of electrodialysis regeneration of deep eutectic solvent for liquid desiccant air conditioning systems. Journal of Building Engineering, 70: 106343. https://doi.org/10.1016/j.jobe.2023.106343

[20] Kamal, S. (2024). Building-integrated solar cell technology. https://g-thumb.com/?p=1653.

[21] Öztürk, B., Mutlu-Avinç, G., Arslan-Selçuk, S. (2024). Enhancing energy efficiency in glass facades through biomimetic design strategies. Revista Hábitat Sustentable, 14(1): 34-43. https://doi.org/10.22320/07190700.2024.14.01.03

[22] Dubai Electricity and Water Authority (DEWA). (2023).

Research and Development Centre (R&D). https://www.dewa.gov.ae/en/about-us/media-publications/photo-gallery/dewa-projects/r-and-d.

[23] Aparna. (2021). Old and modern Dubai city tour with Dubai Frame. https://www.dhowcruiseindubai.com/blog/dubai-frame-a-guide-to-seeing-old-new-dubai/.

[24] Al-Mutawali, S.M.A.-S. (2004). Smart technology in contemporary architecture. Faculty of Engineering, Ain Shams University, Egypt. https://books.google.iq/books?id=hIP2oQEACAAJ.

[25] Boake, T.M. (2024). Occidental chemical building: Cannon associates. https://www.tboake.com/hooker.html.

[26] Alanne, K., Sierla, S. (2021). An overview of machine learning applications for smart buildings. Sustainable Cities and Society, 76: 103445. https://doi.org/10.1016/j.scs.2021.103445

[27] Abu Dabous, S., Hosny, F. (2025). A review of building envelope retrofitting methods for improving energy efficiency, aesthetic, and indoor environmental quality. Energy Nexus. 18: 100407. https://doi.org/10.1016/j.nexus.2025.100407

[28] Stazi, F. (2019). Advanced Building Envelope Components: Comparative Experiments. Butterworth-Heinemann. https://doi.org/10.1016/C2018-0-01555-8

[29] Jedinák, R. (2014). Energy efficiency of building envelopes. Advanced Materials Research, 855: 39-42, https://doi.org/10.4028/www.scientific.net/AMR.855.39

[30] Barbosa, S., Ip, K. (2014). Perspectives of double skin façades for naturally ventilated buildings: A review. Renewable and Sustainable Energy Reviews, 40: 1019-1029. https://doi.org/10.1016/j.rser.2014.07.192

[31] Sinopoli, J. (2006). Smart Buildings: A Handbook for the Design and Operation of Building Technology Systems. Spicewood Publishing. https://books.google.iq/books?hl=ar&lr=&id=5WOvPZDAM00C&oi=fnd&pg=PA1.

[32] Balog, V. (2020). The closed cavity facade – A high performance building skin. WFM Media Pvt. Ltd. https://wfmmedia.com/closed-cavity-facade-a-type-of-double-skin-facade/.

[33] de Vries, S.B., Loonen, R.C.G.M., Hensen, J.L.M. (2021). Multi-state vertical-blinds solar shading – Performance assessment and recommended development directions. Journal of Building Engineering, 40: 102743. https://doi.org/10.1016/j.jobe.2021.102743

[34] Abtar, A.N. (2021). A Review of the development and applicability of double-skin façades in hot climates. ARO-The Scientific Journal of Koya University, 9(2): 96-106. https://doi.org/10.14500/aro.10859

[35] Diekow, M. (2018). CA Immo feiert richtfest für Cube Berlin – Das smart building erhält wiredscore-zertifizierung in platin für beste konnektivität. CA IMMO. https://www.caimmo.com/de/presse/news/artikel/ca-immo-feiert-richtfest-fuer-cube-berlin-das-smart-building-erhaelt-wiredscore-zertifizierung-in-platin-fuer-beste-konnektivitaet/.

[36] Elbadawy, N.A., Elagami, M. (2021). Generations of Intelligent architecture and the future of smart schools in Egypt between reality and hope. JES. Journal of Engineering Sciences. 49(2): 131-155. https://doi.org/10.21608/jesaun.2021.59088.1029

[37] Tilley, J. (2020) Case study: Cube Berlin. Architecture Magazine. https://architecturemagazine.co.uk/2020/02/04/case-study-cube-berlin/.

[38] Pintos, P. (2020). Cube Berlin smart office building / 3XN. ArchDaily. https://www.archdaily.com/935777/cube-berlin-smart-office-building-3xn.

[39] GlassonWeb. (2019). Cube Berlin: Double skin façade that meets complex aesthetic and technical performance requirements. https://www.glassonweb.com/news/cube-berlin-double-skin-facade-meets-complex-aesthetic-and-technical-performance-requirements.

[40] Fântână, G.I., Oae, S.A. (2021). Evolution of smart buildings. International Journal of Energy, 15: 41-43. https://doi.org/10.46300/91010.2021.15.7

[41] Al-Kodmany, K. (2014). Green towers and iconic design: Cases from three continents. ArchNet-IJAR: International Journal of Architectural Research. 8(1): 11-29. https://doi.org/10.26687/archnet-ijar.v8i1.336

[42] Szolomicki, J., Golasz-Szolomicka, H. (2019). Technological advances and trends in modern high-rise buildings. Buildings, 99: 193. https://doi.org/10.3390/buildings9090193

[43] Lomholt, I. (2008). Bahrain WTC building: Architecture. e-architect. https://www.e-architect.com/bahrain/bahrain-wtc-wind-turbines?expand_article=1.