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SIMULATION-BASED INVESTIGATION OF ETFE AND AUTOHEAL POLYMERS FOR ENERGY EFFICIENCY AND THERMAL COMFORT IN ADAPTIVE BUILDING ENVELOPES

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Abstract

Facades are integral to building design, serving as the aesthetic outer shell and acting as a thermal barrier. The Responsive Kinetic Facades revolutionize the concept of facades changing the dynamism from a static structure to adaptive system, capable of responding to external environmental stimuli of glare, and temperature variation. The study evaluates two unique materials, Ethylene Tetrafluoroethylene (ETFE) and Auto Heal polymer for their performance in adaptive façade systems. A systematic literature review was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) criteria, explaining the data selection process with a PRISMA flow diagram. The study compares the energy efficiency performance and thermal comfort of these materials when applied to the south façade of a high-rise office building in Jaipur, India, which experiences a composite climate. The assessment aligns with Energy Conservation Building Code (ECBC) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommendations [1–3]. The performance metrics include annual energy consumption (kWh/m2), discomfort hours, Fanger Predicted Percentage of Dissatisfied (PPD), and Fanger Predicted Mean Vote (PMV). Simulation test was conducted under identical environmental conditions using Design Builder V7.0 (with an EnergyPlus engine). Results showed that the ECBC base case, without any shading device has recorded the highest annual HVAC energy discomfort hours. The Auto Heal facade achieved significant reduction in energy use and lowered thermal discomfort hours. In comparison, the ETFE facade though contributed to improvements but not as much as AutoHeal. These findings suggest Auto heal as an alternative to ETFE for improving energy efficiency, thermal comfort and sustainable urban development [3].

Keywords: Adaptive Building Envelopes, Indoor Environment Comfort, Building Performance, Energy Simulation, Energy Efficiency

1. Introduction

1.1. Background

High-rise commercial buildings are responsible for most of the global energy consumption and carbon emissions, due to solar heat gains through their façades [2–4]. These structures increase high thermal loads, specifically in hot climates. These facades tend to utilize mechanical

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systems widely, consuming 50% of their yearly electricity for heating and cooling [5]. Building envelopes are not only serving as visual elements but successfully deal with climate change and energy limitation, adaptive and responsive building envelope solutions that can rapidly respond to evolving climatic conditions must be incorporated.

1.2.Identifying the necessity for adaptive building skins

Adaptive systems that may alter their properties which includes thermal conductivity, solar heat gain, and visibility in real-time—are progressively replacing traditional static façades, which are incapable to change in response to changing external environmental stimuli [6–14]. With improving thermal comfort, reduction in HVAC loads, and optimizing daylighting, such facades improve the energy efficiency of the building. In composite climate of Jaipur, with hot summers and cold winters, these adaptive systems can significantly reduce the need to resort on the artificial source of energy. The objective of these innovative shells is to minimize energy use while maintaining all year thermal efficiency for occupants [15].

1.3.Appropriate materials for adaptive building skins

The selection of the material is important to enable façade adaptability. In this context, two advanced materials stand out.

- ETFE is a fluoropolymer with superior thermal properties, and is lightweight, durable and UV -resistant. To adjust with the modifying insulation, ETFE cushions can dynamically inflate and deflate.
- Auto Heal, inspired by bio-regenerative mechanism is a self-healing advanced material that combines a polar stretchable polymer with an ionized salt, to form a stable ion-dipole structures. This material is transparent, and can repair itself when damaged, making it ideal for applications in soft robotics, wearable electronics, and flexible displays.

  In overcoming challenges in material science and building technology, both these unique materials possess the properties that are needed for adaptive systems but differ in thermal comfort impacts for the occupants and energy performance of the building under composite climatic conditions.

1.4.Limitations in developing adaptive building skins

Despite it appears encouraging, there are few concerns in adopting adaptive façade systems. Challenges may involve higher initial expenditure, the need for the professional expertise, and combining with the existing infrastructure. Such issues are progressively addressed as technology evolves and understanding of energy efficient alternatives expand in compliance with the building codes and standards. Soon adaptive facades will become more beneficial and widely employed option with multidisciplinary collaboration and supportive regulatory frameworks.

1.5 Literature Review

Recent studies on responsive kinetic facades show, that by modifying their characteristics in response to varying external climatic conditions, adaptive building skins have the ability to improve the building energy efficiency by lowering energy consumptions and maintain the thermal comfort for the users. The dynamic facades allow buildings to perform at their optimal

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level round the year, by constantly adjusting their solar heat gain co-efficients, transparency and thermal resistance.

Materials like Ethylene Tetrafluoroethylene (ETFE) have grown increasingly proo minent in the pursuit towards environmentally friendly construction owing to their remarkable insulating attributes, excellent visibility, and lightweight design[16–19]. ETFE was originally developed by DuPont in the 1940s and is currently used for notable buildings such as the Media-TIC Building in Barcelona, the Beijing National Aquatics Center, and the Allianz Arena in Munich [20–27].

In accordance to studies, ETFE provides less mechanical stress and installation expenses whilst decreasing energy consumption by up to 30% as when compared with glass [28–31]. However, research indicates substantial holes in ETFE's durability over time across several climatic regions, especially with regard to how it adapts to fluctuations in temperature and degradation in the environment. Additionally, there is still an absence of comprehensive studies on how it affects the environment, notably the implications of the manufacturing process and the end of life outcomes [32]. Scientific data concerning ETFE's thermally and acoustic properties continues to be insufficient, inspite of its strong recognition as sustainable and recyclable material [5,7,33–40]. Furthermore, limited research has been conducted evaluating ETFE with other responsive façade materials [6,8,34,41]. There is an urgent need to extend the study as how effectively this material could be used as adaptive façade system in high-rise structures especially with regards to comfort distribution, management systems, and occupant involvement under different climate zones to assist in build an energy-efficient urban settings [5]. The lack of discussions regarding building standards and regulations that applicable to adapted ETFE building facades limits their widespread adoption [42]. More importantly, the material's maintenance requirements, longevity, and overall visual effectiveness in façade systems have not been established [9,14,42–44].

Simulation tools like as Rhinoceros, Grasshopper, Ladybug, Honeybee, and Radiance are being applied by many researchers to validate the thermal performance advantages related to ETFE [45]. Factors like K-value, transmission of light behavior, melting range, and discomfort hours, yet, remain less thoroughly understood [46–57]. The ability of ETFE as a responsive façade material for enhancing indoor air quality and building energy efficiency has been illustrated [58–61], but its integration with other intelligent technologies, including nanomaterials, has not been fully studied [62]. The inadequate level of assessment of simulation findings with pragmatic case studies is an important issue [63].

Currently, auto-healing polymers have become an enormous breakthrough in the discipline of material science. Self-healing materials, that initially were intended for usage in medical care and aerospace usage, are now an achievable option for the construction industry. Due to their inherent ability to self-heal damage, these materials which include metals, polymers, ceramics, and composites, significantly increase durability, sustainability, and functionality [48][49]. Both architects and engineers are experiencing greater possibilities to reconsider façade techniques with increased lifespan efficiency and robustness in structure [64]. One such development in building construction is self-healing concrete, which minimizes intrusion of water, prolong

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structural resilience, and heals microcracks, all of which cut repair costs [65–78]. In the same manner, building facades treated with self-healing materials may repair surface damage and extend the lifespan of the substrate that supports them. Self-healing polymers, such PMMA, PVC, and polycarbonate, have been considered the most emerging materials in this field. These are presently extensively used due to their adaptability and longevity [79–81]. The effectiveness of smart polymeric coatings for microcrack repair has been improved by the use of natural ingredients such as tung oil and linalyl acetate. Polymer-clay hybrid materials that can self-heal when exposed to water are noteworthy advancements that provide an eco-friendly method of façade durability [68].

An extremely advanced family of self-repairing materials includes auto-healing polymers made from ion-dipoles. They create utilization of strong, reversible interactions which encourage self-healing and adaptation to the environment using dynamic supramolecular connections among charged ions and molecules that are polar [82,83]. This phenomenon is being acquired with both intrinsic (such as reversible covalent or hydrogen bonding) and extrinsic (such as encapsulation) means [65–67]. A significant development is a bio-inspired material that mimics the self-healing abilities of Wolverine, a Marvel comic character material which is transparent, stretchable, and self-repairing. It is developed by integrating an intensely ionized salt with a polar stretchable polymer. These materials heal using interaction where molecules that are polar attract ions that are oppositely charged, retain their structural strength under stress, and exhibit flexibility identical to rubber [84–87]. They additionally offer environmental responsiveness, longevity, and stimulus by electromagnetic fields, amongst other attributes.

The application of auto-healing polymers in adaptive dynamic façades has not received significant consideration in architectural modeling, in spite of their immense potential. Sustainable construction and the indoor environment could be substantially improved through the combination of these materials with dynamic conversion strategies, particularly for high-rise structures in urban environments.

The Ministry of Power (MoP)'s Bureau of Energy Efficiency (BEE) created the Energy Conservation Building Code (ECBC) in India, that defines minimal energy efficiency standards for building components like HVAC systems, lighting, and building facades. ECBC, which launched in 2007, facilitates the execution of advanced simulation modeling techniques in order to promote data-driven design decisions. International regulations like ASHRAE 90.1 (for energy performance) and ASHRAE 55 (for thermal comfort) offer rigorous standards for efficient performance of envelopes for buildings that fall in compliance with ECBC [1,3,88–90].

Following these guidelines, a simulation-based study to evaluate these two smart materials as a Responsive kinetic facade was conducted. A hypothetical building model (benchmarking a prototypical office building) was created in DesignBuilder V7.0 (with an EnergyPlus engine) software, with defined geometry, location, and composite climate data [4,20]. First, a baseline case with a conventional static facade having no external shading or dynamic elements was simulated to establish reference performance for energy consumption and indoor comfort. This base model was calibrated to meet ECBC and ASHRAE guidelines and serves as the reference point. Next, two responsive facade scenarios were implemented on the same model using ETFE

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and Auto Heal as the adaptive materials. In both cases, the facade was assumed to be capable of reacting to identical external climatic conditions, to modulate heat gain and loss. Integrating the study with the established standards and simulating real-world operational conditions, this research paper provides a detailed evaluated analysis of these materials as adaptive façade systems for the building energy efficiency and indoor environment quality.

In summary, numerous studies on ETFE as a responsive adaptive façade material focuses on its sustainability and energy efficiency. Significant issues remain as far as long -term performance under various climatic conditions. Additionally, the integration of self-healing technologies with ETFE remains uninvestigated. There is also a lack of comparative analysis between ETFE and other adaptive façade materials. In this study, in spite of having different chemical compositions, ETFE and Auto heal perform same function as responsive façade to the thermal and optical features in real time. To the best of our knowledge, no previous research has compared these two unique materials for adaptive building envelopes in a whole building simulation test. This study fills the gap between the material characteristics and building energy performance by providing new insights into adaptive material selection for responsive building envelopes. Further by comparing these two materials, impacts on the thermal comfort of the occupants, building energy efficiency and the overall sustainable built environment can be better comprehended.

The research questions listed have been discussed in the various parts of this paper that are synced with the sections of this study: Section 2 explains the structured methodology framework used in this paper; Section 3 describes the two façade scenarios i.e. ETFE and Auto heal being assessed for thermal comfort and energy consumption using advanced DesignBuilder simulation tool; Section 4 explains results and discussion where both materials are compared to the baseline scenario without any shading, depicting AutoHeal's superior performance. Also, a detailed table presents comparisons with the prior ETFE based researches; Section 5 describes the conclusion that AutoHeal is better than ETFE enhancing the thermal comfort and reducing the energy consumption. While future scope promotes the concept of exploring its application in wider scale.

2. Methods: A Systematic Literature Review

In order to ensure a transparent approach for an extensive understanding of this study, a Systematic Literature Review (SLR) [91,92] was carried out using PRISMA guidelines [92,93]. Figure1 shows, the structured framework for data processing in three stages: data identification, data screening, and data included.

2.1 Data identification

The initial step was to search documents through scientific databases such as Scopus, ScienceDirect, Google Scholar and PubMed, using specific keywords: ETFE, adaptive facades, self healing, AutoHeal polymer, thermal comfort, energy efficiency and simulation tools. The prime sources of data are the journals and magazines, books and conference proceedings published between 2010 and 2025. The total number of 657 records were identified.

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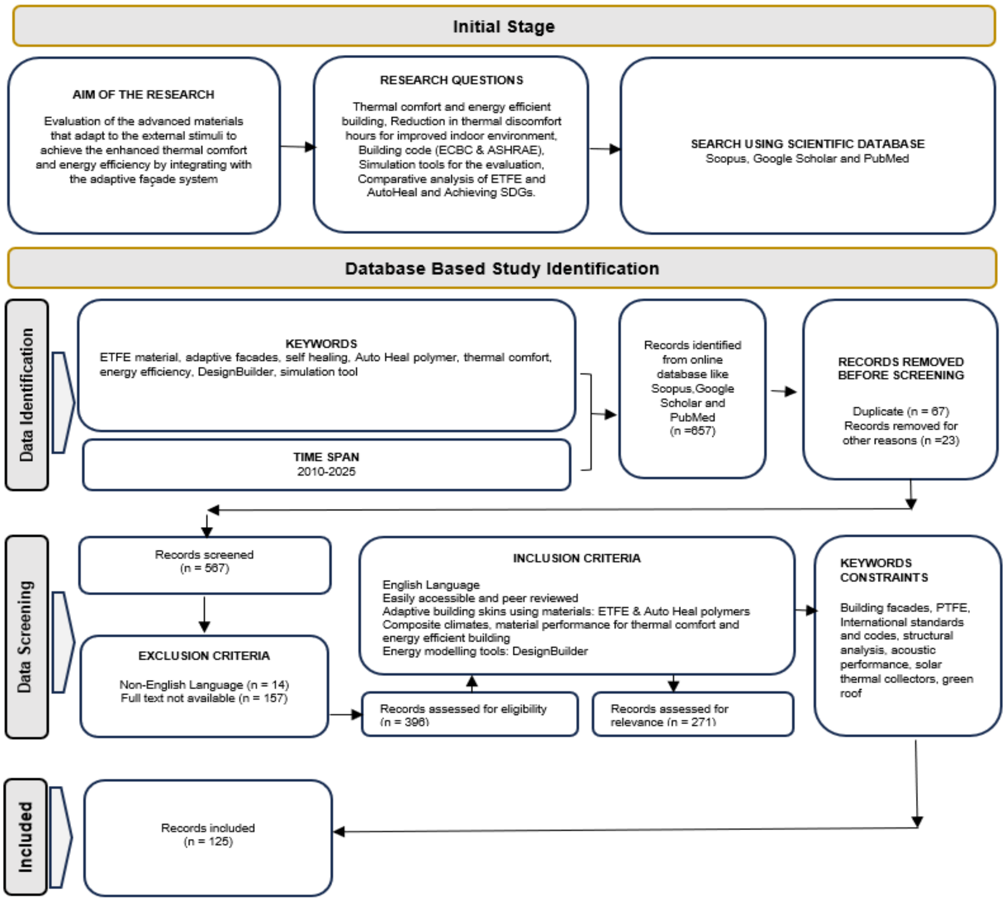

Figure 1. Methodological framework of the research

2.2 Data screening: inclusion and exclusion parameters

The following inclusion and exclusion parameters were defined to proceed further with the screening of the documents identified in the previous stage:

Inclusion parameters:

- The information gathered must be published in English.
- The study must be peer-reviewed and easily available.
- The publication must provide data on the use of ETFE as adaptive building skins, as well as the thermal and mechanical properties of both ETFE and AutoHeal polymers.
- The publication should stress on the material performance in a composite climate specifically about the thermal comfort for occupants and the energy efficiency of the building.
- The publication should focus on the use of energy modelling tools, like DesignBuilder for evaluating material performance under real-world climatic conditions.

Exclusion parameters:

- Irrelevant studies and duplicates
- Non-English language
- Full text not available

The total number of records screened were 561. Using the exclusion criteria stated above, total 171 records were excluded. The records assessed for the eligibility were 396 in number.

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Whereas 271 records were assessed for relevance using Inclusion criteria. Furthermore, researches lacking simulation based evaluation of these materials and without the reference of thermal comfort and energy efficient buildings, were excluded from the data screening method.

2.3 Data included:

Only 125 records were selected as included data from the papers finalized in the data screening. The final papers were opted on the basis of their relevance to thermal properties, and sustainability in the construction industry.

3. Simulation Setup and Tools

After using PRISMA methodology for the systematic review and data processing , the next step included the use of advanced simulation tools for the whole building performance analysis. An extensive simulation was conducted using whole-building energy modeling to evaluate each facade material under uniform conditions [94–98]. Building performance simulation is extensively utilised to optimise building envelopes and systems. This technology enables the assessment of different facade material's impact on energy efficiency and occupant comfort without the need for physical prototypes [99–101]. Design Builder V7.0 (with an EnergyPlus engine) software was chosen for its advanced capabilities in assessing the building energy performance [98,102–105]. Hourly timestep analysis was executed to record the seasonal and diurnal fluctuations in annual simulations i.e. January to December. This tool is well-established for predicting annual energy consumption, thermal comfort indices, and daylighting, aligning with best practices encouraged by ECBC and ASHRAE 90.1/55 standards [5,106]. Figure 2 shows the baseline building model that was utilised for all simulations. The office block, located in Jaipur, Rajasthan, India, is in a composite climate region with hot summers and cool winters. The geometry and orientation of the model were maintained consistently across all simulation runs. Key building parameters (floor area, number of floors, occupancy density, internal loads, etc.) standard reference models [4] were utilized and modified to accommodate the local climate [20]. The building envelope in the base case consisted of typical construction materials meeting ECBC 2017 with prescriptive requirements [106] for wall U-values = 0.630 W/m2K, Roof U-value = 0.330 W/m^2K, Glass U-value = 3.00 W/m^2K and solar heat gain coefficients, SHGC = 0.27, Equipment Power density (W/m^2) = 16.14, Lighting Power density (W/m^2) = 9.5 and Occupancy density ($People/m^2$) = 0.05. In the base case, no shading devices or kinetic features were used, providing a clear performance benchmark under static facade conditions [107,108].

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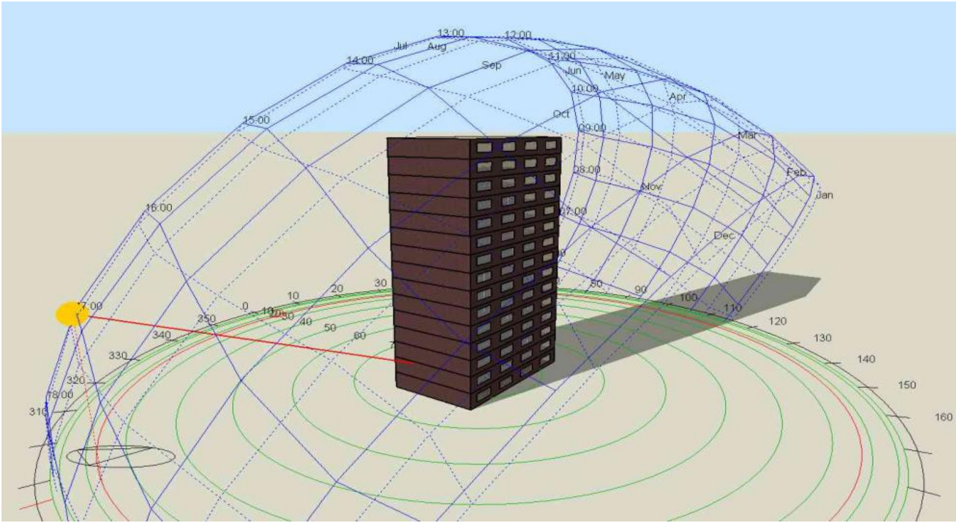

Figure 2. Building 3D view in Design Builder tool Building details for making Building Simulation Model:

- Area : 375m^2 (25m X 15m)
- Floor to floor height : 3.0m
- 15 Storey, office building having glazing on the south wall

For climate data, an EnergyPlus compatible, Jaipur EPW file, representing the composite climate was used. All simulations for the different facade scenarios used the same weather data to ensure comparability. The HVAC system in the model was configured to be a standard efficient system (e.g., variable air volume with economizer) sized according to the building load. Internal thermostat setpoints, occupancy, and lighting schedules were kept consistent in all cases. This uniform setup isolates the effect of the facade material as the primary variable.

3.1 Simulation Inputs and Assumptions

- Occupancy Parameters:
  - Density: 0.05 people/m² (i.e., 20 m²/person), based on ECBC standard.
  - Schedule: ECBC Office_OpenOff_Occ schedule aligned with ECBC 2017 Table 9-13.
  - Activity level: 0.90 (light office work / standing / walking).
- HVAC and Environmental Control:
  - Cooling System: VAV with air-cooled chiller.
    - Fuel: Electricity from grid.
    - Seasonal COP: 3.0
    - Min. Supply Air Temp: 12°C
    - Cooling Setpoint: 26°C (occupied), 32°C (setback).
    - Heating: 22°C setpoint, 12°C setback — minimal in Jaipur climate.
- Ventilation:
  - Fresh Air Rate: 2.5 L/s-person; 0.3 L/s-m² per ASHRAE 62.1/ECBC 2017.
- Internal Loads:

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- Lighting Power Density:
- 9.5 W/m² using ECBC Office_OpenOff_Light schedule.

- Radiant Fraction: 0.42
- Visible Fraction: 0.18
- Luminaire Type: Suspended
  - Equipment Load: 16.14 W/m² with ECBC Office_OpenOff_Equipment schedule.
- Simulation Details:
  - Tool: DesignBuilder v6.1 + EnergyPlus engine.
  - Location: Jaipur (Composite climate zone, India).
  - Weather Data: EnergyPlus TMY2 EPW file.

- Simulation Timeframe: Annual run (8760 hours).

3.2. Performance Metrics

To thoroughly compare the facade options, several key performance metrics from the simulation results, were analysed:

Discomfort Hours: The total number of hours in an entire year when the temperature inside falls beyond a specified comfort range. In this case the comfort range is determined by standard criteria such as the acceptable range of PMV/PPD per ASHRAE 55 [[4,109]].

Energy Use per year :It provides the total building energy consumption per unit floor area, mainly for HVAC (cooling and heating) and fans. It is expressed in kilowatt-hours per square meter for the analysis period.

Fanger Predicted Percentage of Dissatisfied (PPD, %): This index predicts the percentage of users who will experience thermal discomfort in the indoor environment [110,111].

Fanger Predicted Mean Vote (PMV): The PMV is an indicator of the average thermal sensation on a scale from -3 (cold) to +3 (hot), with 0 being neutral. It takes several factors like air temperature, radiant temperature, humidity, air speed, metabolic rate, and clothing level. Values close to 0 (between -0.5 and +0.5) are mainly considered comfortable [[4]].
The above-mentioned metrics were calculated for every simulation scenario to provide a detailed picture: energy performance (via annual kWh/m²) and occupant comfort (via discomfort hours, PPD, PMV) [110–117].

3.3. Façade Scenarios

After running the base case simulation to obtain a performance baseline, the simulation test was conducted for the following facades:

- ETFE facade: The building's external skin is replaced or overlaid with an ETFE-based kinetic facade. In simulation terms, this was represented by modifying the envelope properties to mimic ETFE foil cushions. ETFE is highly transparent with relatively low thermal insulating value as a single layer, but in a cushion system (multiple layers of ETFE

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with air cavities) its effective U-value can be much lower [53,118–120]. In our model, the ETFE facade was assumed to dynamically adjust (for instance, by inflating or deflating cushions, or by deploying shading within the cavity) in response to outside conditions. Based on dynamic inflation, effective U-value = 1.6 W/m²K, SHGC = 0.35 was taken as reference values for simulation test [5,121,122]. This setup aims to reduce solar gains on hot days and increase insulation on cold days, following principles observed in prior ETFE dynamic facade research.

- Auto-heal facade: The building facades use Auto heal, a self-healing material, as the kinetic layer. The purpose of including Auto Heal is to test if a material with self-repairing capability and presumably good insulation can outperform ETFE in maintaining comfort and reducing energy demand. To characterize the thermal stability and composition of the material, TGA (Thermogravimetric analysis) was conducted under various temperature conditions up to 600 °C by METS (Middle East Testing Services) Laboratories, Ajman, UAE [123–125].

In both adaptive scenarios, the control strategy for the kinetic facade was simplified in the simulation: the facade was set to fully deploy its maximum shading/insulating state during periods of excessive solar gain (to minimize cooling load), and to retract or become maximally transparent during cold periods or when solar heat is beneficial (to reduce heating load). This on/off control approximates a responsive system, provides a reasonable estimate of potential performance improvement. By keeping the control logic consistent for both ETFE and Auto Heal, we ensured a fair comparison between the materials.

4. Results and Discussions

After running the simulations, the performance of the two smart facade materials, ETFE and Auto Heal, was compared against the ECBC-compliant base case. The subsequent discussion interprets the key findings shown in Table 1 and 2. The total building energy consumption and the percentage of energy savings in Figure 12 and Figure 13.

4.1.Baseline Performance

The ECBC Base Case, without any shading device, noticeably had the highest energy consumption and indoor discomfort values. The annual HVAC energy use was the high load is mainly due to extensive solar gains and thermal losses through the static facade, resulting in greater HVAC demand of about 96 kWh/m². Correspondingly, the base building experienced 1588 discomfort hours over the year, indicating that for nearly 18% of the time in a year, indoor environment fell outside the comfort zone refer Table 1. The PPD was about 25.3%, meaning one in four occupants were predicted to be uncomfortable on average, and the PMV of +0.82 suggests the indoor environment tended to be uncomfortably warm for occupants (near the upper limit of the comfort range). Since the baseline simulation scenario meets the minimum standards, there is a need for improvement for enhancing the building energy efficiency and the indoor comfort for the users. Figure 3, Figure 4 and Figure 5 shows the monthly comfort graph,

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yearly bar chart for comfort and yearly bar chart for energy consumption respectively using ECBC base case.

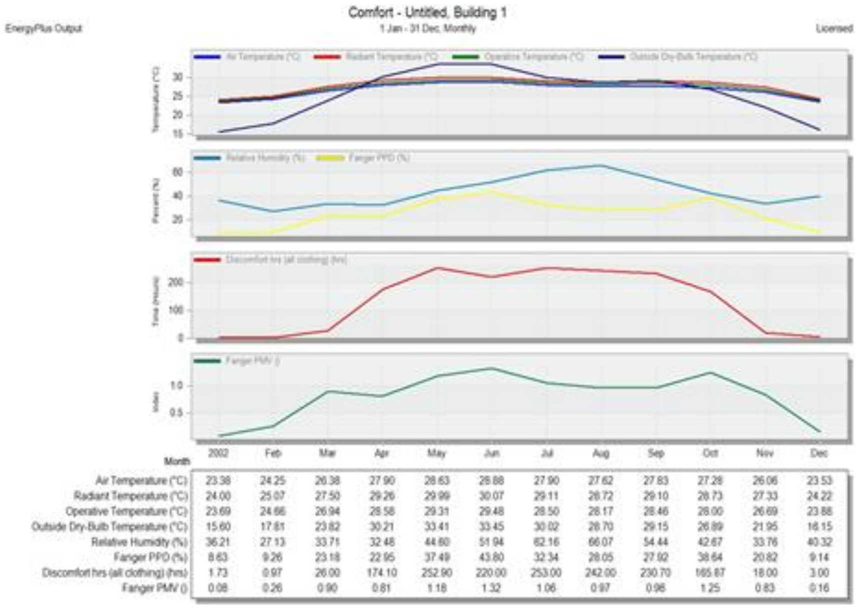

Figure 3. ECBC base case - The comfort graph (Monthly)

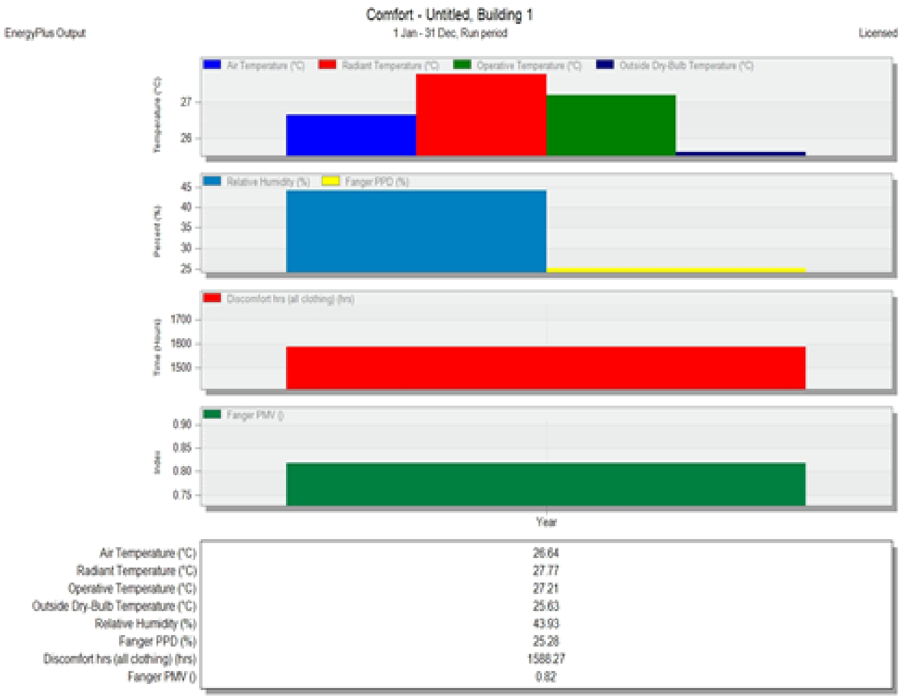

Figure 4. ECBC base case - Bar Chart for the Comfort (Yearly)

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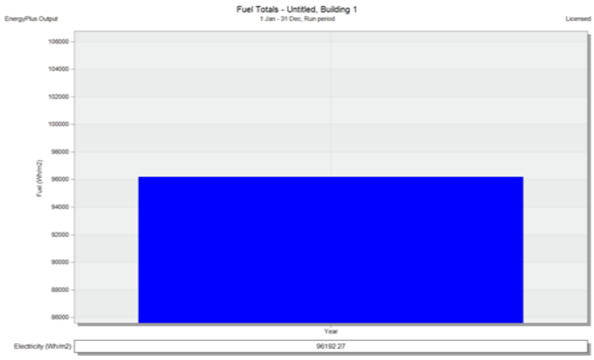
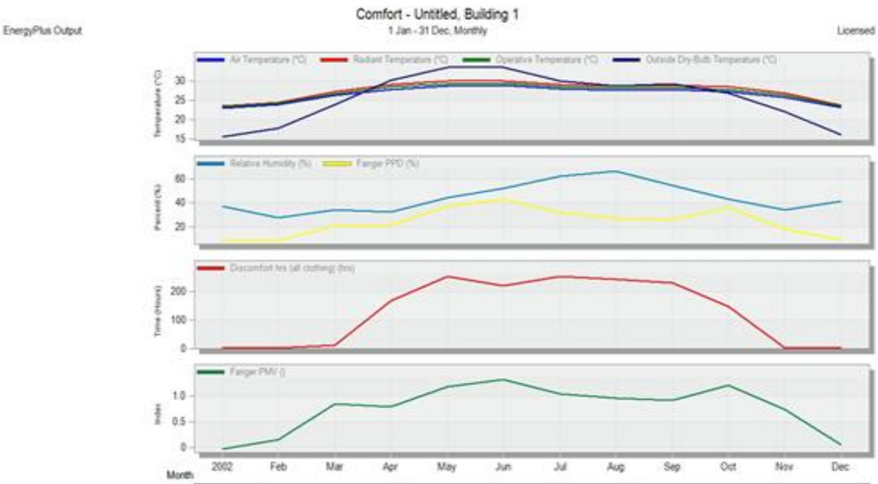


Figure 5. ECBC base case - Bar chart for Energy Consumption (Yearly)

4.2 ETFE façade performance

Incorporating a ETFE facade led to a noticeable improvement over the base case. Annual energy use dropped to 95 kWh/m², which is a 1.36% reduction in HVAC energy consumption relative to the base case. While this energy saving is modest in percentage terms, it reflects the ETFE system's ability to slightly reduce heat gains and losses by adapting to. The discomfort hours decreased to 1530.67 hours, about 58 fewer hours than the base case. This indicates that the ETFE adaptive facade system kept the building in the comfort range for more hours of the year, likely by mitigating extreme thermal conditions. The PPD improved to 24.11%, so fewer occupants are predicted to feel dissatisfied, and the PMV moved to +0.76, closer to the neutral comfort point, referring to Table 1.

The ETFE adaptive facade provided some enhancement in both energy efficiency and indoor environmental comfort, validating the concept that a dynamic envelope can outperform a static one. Figure 6, Figure 7 and Figure 8 show the monthly comfort graph, yearly bar chart for comfort and yearly bar chart for energy consumption respectively using ETFE on the façade as a shading material.



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air Temperature (°C)	23.02	23.88	26.19	27.83	28.61	28.85	27.86	27.57	27.73	27.12	25.77	23.17
Radiant Temperature (°C)	23.46	24.49	27.17	29.13	29.94	30.03	29.04	28.63	28.91	28.42	26.83	23.67
Operative Temperature (°C)	23.24	24.19	26.68	28.48	29.27	29.44	28.45	28.10	28.32	27.77	26.30	23.42
Outside Dry-Bulb Temperature (°C)	15.60	17.81	23.82	30.21	33.41	33.45	30.02	28.70	29.15	26.89	21.95	16.15
Relative Humidity (%)	37.02	27.72	34.08	32.59	44.69	52.05	62.34	66.41	54.88	43.10	34.33	41.27
Fanger PPD (%)	8.93	8.70	21.06	21.83	37.02	43.28	31.63	27.01	25.85	36.06	17.84	9.06
Discomfort hrs (all clothing) (hrs)	3.57	1.80	10.23	167.67	252.73	220.00	252.83	241.77	229.03	147.03	0.13	3.87
Fanger PMV ()	-0.03	0.15	0.84	0.78	1.17	1.31	1.04	0.95	0.92	1.20	0.74	0.05

Figure 6. ETFE - The comfort graph (Monthly)

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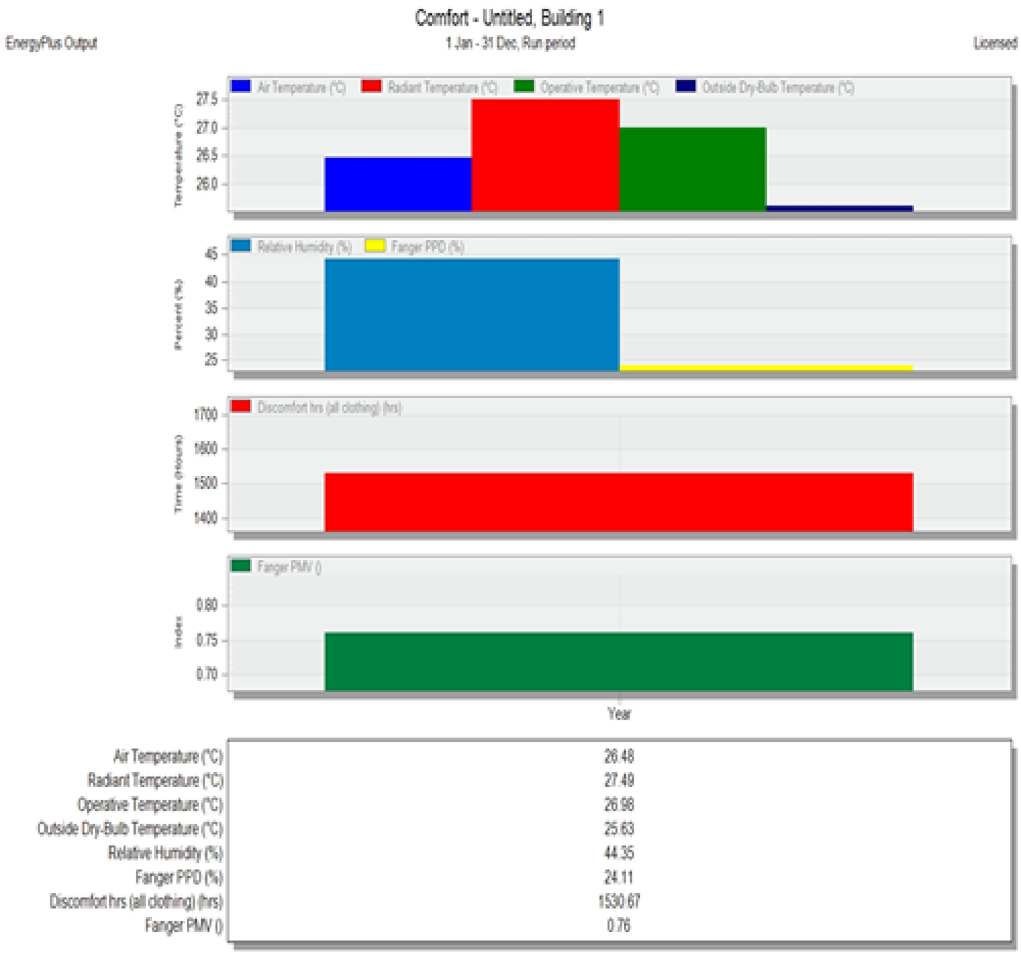

Figure 7. ETFE - Bar Chart for Comfort (Yearly)

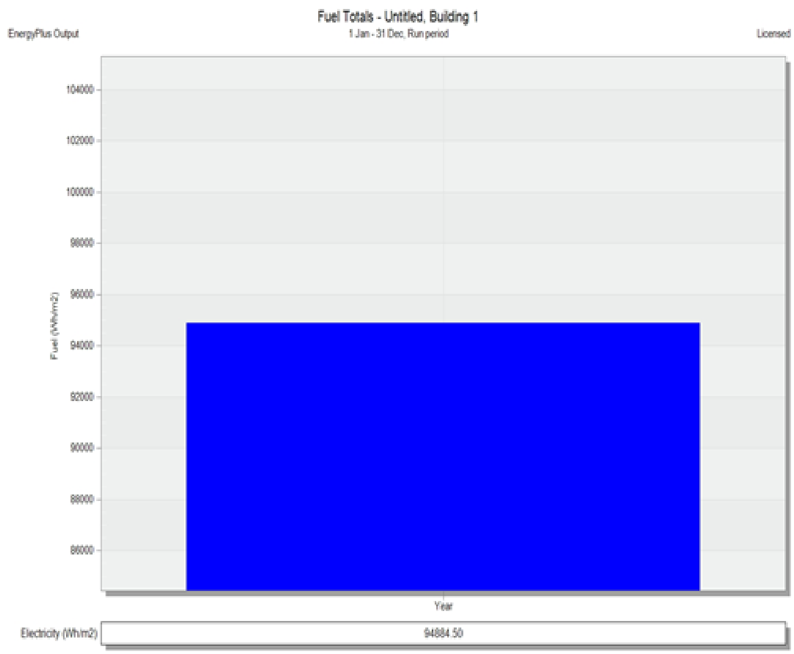

Figure 8. ETFE - Bar chart for Energy Consumption (Yearly)

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4.3 Auto heal façade performance

The facade with the Auto Heal material demonstrated the best performance among the tested scenarios. The annual energy consumption dropped to 93 kWh/m², which is a 3.41% saving compared to the base case and ETFE case. Significantly, the Auto Heal facade had the lowest number of 1477.53 discomfort hours, PPD was 22.64%, and the PMV came down to +0.67, the lowest of all the cases tested, signifying the superior performance of Auto Heal across all the parameters, i.e. lower energy use, fewer discomfort hours, lower PPD, and a PMV enable it as an innovative material for adaptive façade system. Refer Table 1. Figure 9, Figure 10 and Figure 11 show the monthly comfort graph, yearly bar chart for comfort and yearly bar chart for energy consumption respectively using ETFE on the façade as a shading material.

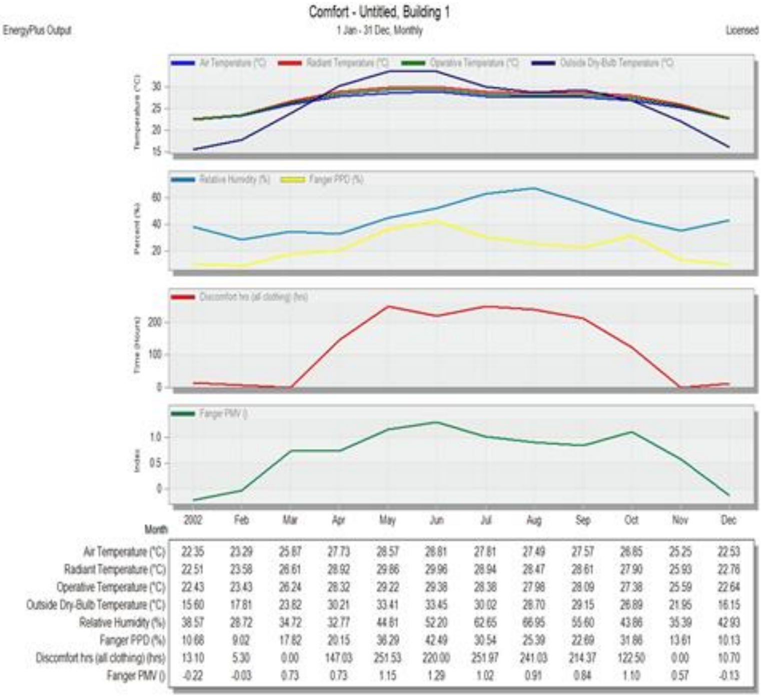

Figure 9. Auto heal - The comfort graph (Monthly)

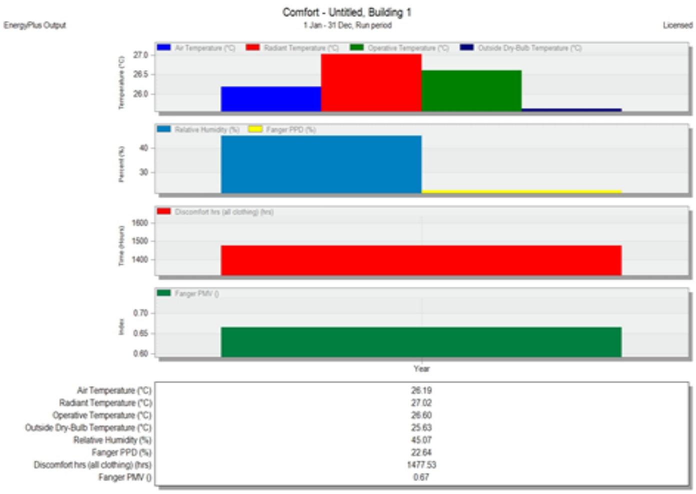

Figure 10. Auto heal - Bar Chart for Comfort (Yearly)

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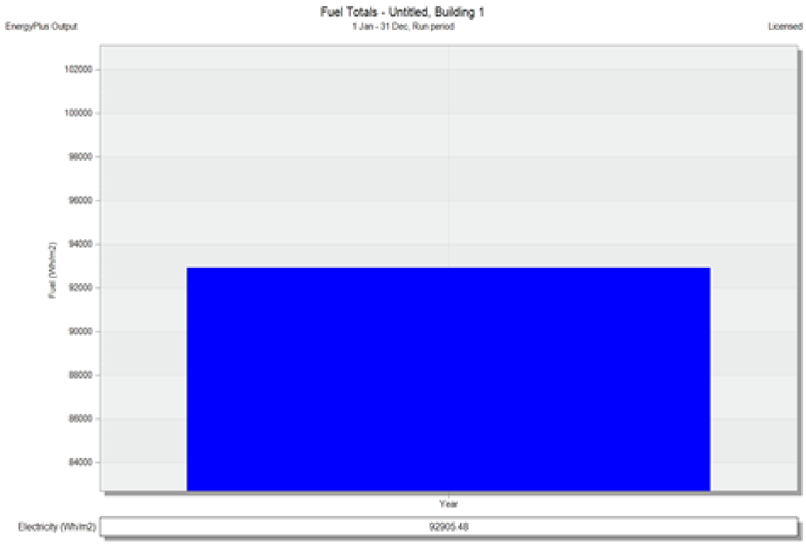

Figure 11. Auto heal - Bar chart for Energy Consumption (Yearly)

Table 1. Performance of Base Case vs. Adaptive Facade Scenarios.
(Annual values are given per square meter of floor area; PPD and PMV are comfort indices.)

Facade Scenario	**Annual HVAC Energy (kWh/m^2)**	**Discomfort Hours**	**PPD (%)**	**PMV**
ECBC Base Case	96	1588.27	25.28	+0.82
ETFE Facade	95	1530.67	24.11	+0.76
Auto Heal Facade	93	1477.53	22.64	+0.67

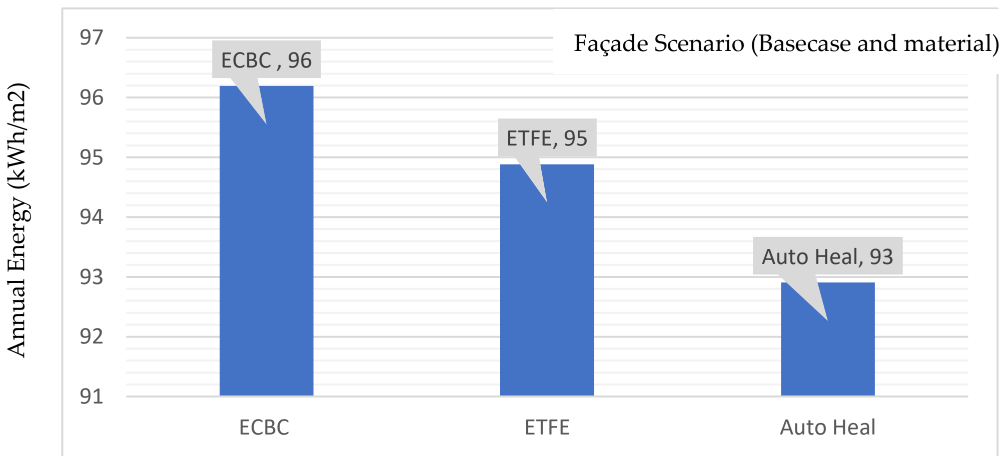

Figure 12. Illustrates these comparisons in terms of energy savings (kWh/m^2) in relative to the base case, highlighting that Auto Heal achieved the highest reduction in energy use.

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Table 2. Percentage savings of Base Case vs. Adaptive Facade Scenarios.

S.No	Material	Fuel totals (kWh/m²)	Percentage Savings (%)
1	ECBC	96	Base Case
2	ETFE	95	1.36
3	Auto Heal	93	3.41

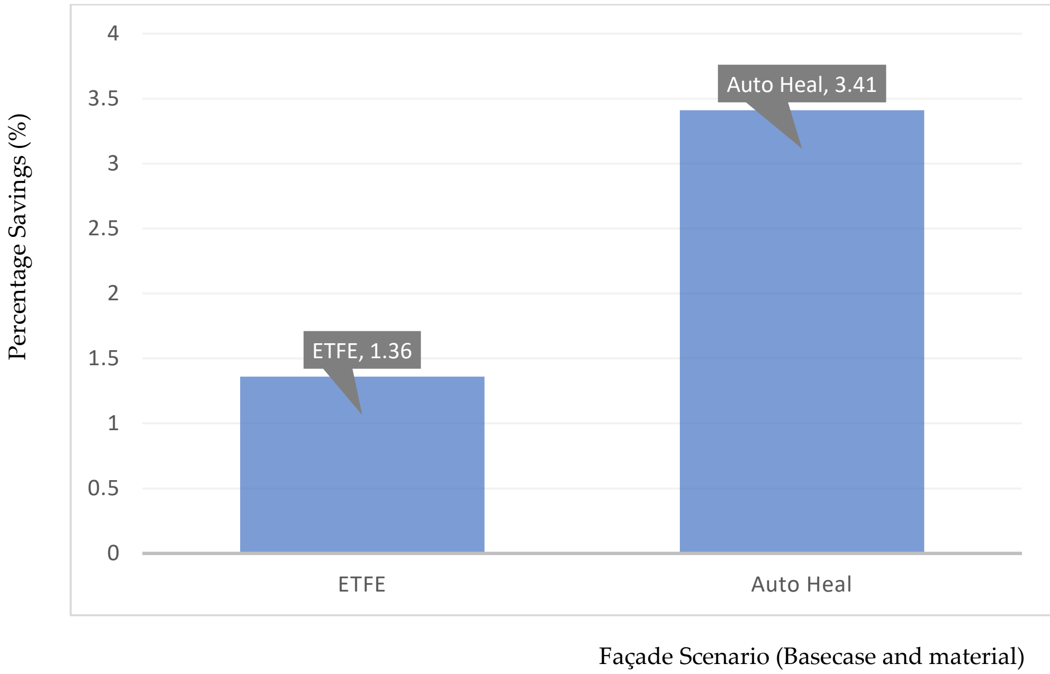

Figure 13. Illustrates Energy savings achieved by each facade material compared to the ECBC base case. The Auto Heal facade showed ~3.4% reduction in annual HVAC energy consumption, more than double the ~1.36% reduction achieved by the ETFE facade.

Based on the quantitative findings of the simulation test conducted, in reference to the ECBC base case, ETFE when used in dynamic façade system resulted in a 1.36% reduction in yearly HVAC energy consumption. Whereas, the façade with Auto heal achieved a more substantial reduction of 3.41%. This prominent difference can be linked to the integral properties of Auto heal polymer, which provides more adaptability and resistance under varied climatic conditions.

The thermal comfort analysis conducted further supports the higher efficacy of Auto Heal in terms of occupant satisfaction. The base case façade scenario recorded 1,588 discomfort hours, a PPD of 25.3%, and a PMV of +0.82, the ETFE façade system revealed improved metrics to 1,530 discomfort hours, a PPD of 24.1%, and a PMV of +0.76. The Auto Heal, validated the most improved benefits, reducing the thermal discomfort hours to 1,477, a PPD of

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22.6%, and PMV of +0.67for Auto Heal. These substantial gains not only are statistically important but also indicate real advantages in user comfort and reduced energy consumption.

The existing literature on responsive façade material has largely focused on ETFE, highlighting its optical modulation and structural characteristics, with limited attention to long-term reliability or self-healing properties. However the exploration of materials like Auto heal, originally used for robotics and wearable electronics, in this domain represents a noticeable gap. It brings in a new aspect by bringing together resilience with adaptive thermal performance thereby improving the energy efficiency of the building. This comparative study provides valuable insights into the performance of conventional and advanced materials in adaptive facades. The findings offer a strong basis for expanding this research across varied climates to further explore the potential of such materials in addressing energy use and comfort challenges. This research focuses on the first critical performance comparison of ETFE and Auto Heal polymers by running a simulation test for façades, filling a critical knowledge gap and contributing to the enhanced progress in the field. Table 3, provides a data based evidence to promote the application of Auto Heal polymer in responsive building envelopes, for sustainable and energy efficient built environment.

Table 3. A comparative analysis between the current research and previous study on building efficiency using ETFE as a material for adaptive facades.
(AutoHeal polymer has never been used previously in building skins)

Paper Title	Façade Material	Quantified HVAC Reduction %)	Discomfort Hours	PPD (%)	PMV	Remarks
Current Study (ETFE)	ETFE	Calculated 1.36% HVAC reduction ✓	Analysed 1,530 ✓	Included 24.1 ✓	Included+0.76 ✓	Quantified via simulation based on ECBC reference case. Comparison with Auto Heal polymer
Current Study (Auto Heal)	Self-adaptive Auto Heal Polym	Calculated 3.41% HVAC reduction	Analysed 1,477	Included 22.6	Included +0.67	Outperforms all others in both energy and thermal comfort. Exhibites for the

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	er	✓	✓	✓	✓	first time the high adaptability and efficient performance of Auto-Heal. Best suited for the adaptive building skins.
Seasonal Optimization of Dynamic Thermo-Optical ETFE Façade System	Thermo-optical Dynamic ETFE	Not Calculated	Not Analysed	Not Included	Not Included	Proposed control strategy, analyzed U-value variability, but no HVAC energy results
Analysis of Building Envelope for Energy Consumption and Indoor Comfort in a Near-Zero-Energy Building in Northwest China	ETFE Facade	No (Only heating load given)	Not Analysed	Not Included	Not Included	Paper focuses on energy use in the heating season, and propose envelope optimizations like insulation and window-to-wall ratios. No comparison with any other material.
Application and validation of eco-efficiency principles to assess the design of lightweight structures: case studies of ETFE	ETFE Building skins	Not Calculated	Not Analysed	Not Included	Not Included	Eco-efficiency & sustainability of ETFE membranes in reference to architectural case studies. No comparison with any other material.

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building skins						
Fabric Façade: An Intelligent Skin	ETFE Building Fabric	Not Calculated	Not Analysed	Not Included	Not Included	Discusses lightweight nature and potential of the fabric for sustainability. No comparison with any other material.
Buildings with ETFE foils: A review on material properties, architectural performance and structural behavior	ETFE Foils	Not Calculated	Not Analysed	Not Included	Not Included	Focuses on the mechanical/structural properties and review the architectural performance. No comparison with any other material.
Can Ethylene Tetra Fluoro Ethylene cushions double-skin façade applications improve building envelope performance, reduce energy consumption and enhance visual and thermal comfort in UAE	ETFE Cushions	Calculated	Not Analysed	Not Included	Not Included	Simulation-based study using IES-VE and validated against real electrical load data. No comparison with any other material.

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buildings?						
Ellipsoidal Shape and Daylighting Control for the ETFE Pneumatic Envelope of a Winter Garden"	ETFE Cushions	Not Calculated	Discussed qualitatively but without any measured comfort data	Not Included	Not Included	The study is based on the ETFE cushion technology. No comparison with any other material.
Environmental load of ETFE cushions and future ways for their self-sufficient performances	ETFE Cushions	Not Calculated	Not Analysed	Not Included	Not Included	The study stress on the evaluation of the ETFE material on the environment, structural behaviour. No comparison with any other material but integration with photovoltaic cells.
Ethylene tetrafluoroethylene (ETFE) material: Critical issues and applications with emphasis on buildings	ETFE	Not Calculated	Not Analysed	Not Included	Not Included	Analysis on material and it's use as an envelope. No comparison with any other material

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Importance of Smart Materials Application In Building Skins	Case study on ETFE	Not Calculated but described energy efficiency gains	Not Analysed but mentioned qualitatively	Not Included	Not Included	Focus on the different smart materials. No comparison with any other material
Optimal control of switchable ethylene-tetrafluoroethylene (ETFE) cushions for building façades	ETFE Facade	Calculated	Not Analysed	Not Included	Not Included	Discusses the use of ETFE as façade with kinetic mechanism. No comparison with any other material
Transparent architecture-building with ETFE membranes	ETFE Facade	Not Calculated	Not Analysed	Not Included	Not Included	The study validates the material use as facades. No comparison with any other material

5. Conclusion

This study offers a comparative performance analysis of two dynamic façade materials - ETFE and Auto Heal, a novel self-healing polymer, assessed using comprehensive whole-building energy simulations under identical environment and operational conditions for yearly building energy consumption and occupant thermal comfort. The performance of ECBC static façade, ETFE façade and AutoHeal façade based on the simulation.

Data is as follows:

- Compared to the ECBC static baseline, annual HVAC energy consumption reduced by 3.4%
- Indicating enhanced indoor thermal comfort due to the lowest 1,477 discomfort hours
- PPD at 22.6% and PMV of +0.67, promotes better thermal comfort metrics
- Due to its better thermal properties, it is suitable for high-performance building envelopes.
- Achieved 1.3% energy savings over the static baseline.
- Contributes to improved comfort performance by reducing discomfort hours to 1,530

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- Exhibits that it can outperform static façades under challenging environmental conditions but less than Autoheal.
- Demonstrates the highest energy use of 96,192.27 kWh/m² and greatest 1,588 discomfort hours.

This comparative study introduces valuable insights into the performance of conventional and advanced materials in kinetic façades. With rising global temperatures and the growing demand for thermally comfortable buildings, adaptive façades designed with innovative materials like Auto Heal polymers show significant promise. Auto Heal demonstrates dual benefits—dynamic thermal modulation and long-term durability—positioning it as a progressive solution for energy-efficient, sustainable urban development. The material also offers potential for future research in adaptive façade systems, especially in enhancing thermal control, endurance, and system sustainability. While this study focuses on a single climate zone—chosen for its high glare and solar radiation—it serves as a critical testbed for evaluating the effectiveness of adaptive façades in harsh conditions. The findings provide a strong basis for expanding this research across varied climates to further explore the potential of such materials in addressing energy and comfort challenges. In conclusion, the integration of Auto heal materials into adaptive façades offers a promising pathway to enhance energy efficiency, occupant comfort, and building envelope durability. This research lays the groundwork for future exploration of novel materials in kinetic façade technology and sustainable building design. Additionally, future research can examine the scalability and economic efficiency of Auto Heal polymer in large scale building projects.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ETFE	Ethylene Tetrafluoroethylene
ECBC	Energy Conservation Building Code
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
PMV	Fanger Predicted Mean Vote
PPD	Fanger Predicted Percentage of Dissatisfied
PMMA	Polymethyl methacrylate

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PVC	Polyvinyl chloride
HVAC	Heating, Ventilation, and Air Conditioning.
METS	Middle East Testing Services
TGA	Thermogravimetric analysis
BPS	Building Performance Simulation
SHGC	Solar Heat Gain Co-efficient

References

[1] Emmerich, S. J., Hedrick, R. L., Robin, D., Brundage, D. M., Heiden, R. M., Simmonds, P., Bidstrup, N., Humble, J., Stanke, D. A., Corbat, M. D., Katipamula, S., Stoppelmoor, W. H., Crawley, D. B., Kim, K. W., Swierczyna, R. T., Ferguson, J. M., Kouma, L., Zarour, J. H., Gallagher, M. W., … Reiniche, S. C. (n.d.). ASHRAE STANDARDS COMMITTEE 2017–2018.

[2] Standards 62.1 & 62.2. (n.d.). Retrieved April 18, 2025, from https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2

[3] 2019 Update of Standard 90.1 | ashrae.org. (n.d.). Retrieved April 18, 2025, from https://www.ashrae.org/news/hvacrindustry/2019-update-of-standard-90-1

[4] Azima, M., & Seyis, S. (2022). Evaluating the impact of building envelope on energy performance: Cooling analyses. Journal of Construction Engineering, Management & Innovation. https://www.researchgate.net/profile/Senem-Seyis/publication/359714427_Evaluating_the_impact_of_building_envelope_on_energy_performance_Cooling_analyses/links/62501566d726197cfd46b095/Evaluating-the-impact-of-building-envelope-on-energy-performance-Cooling-analyses.pdf

[5] Han, J. M., & Park, D. (n.d.). Seasonal Optimization of Dynamic Thermo-Optical ETFE Façade System. 4887–4893. https://doi.org/10.26868/25222708.2019.210642

[6] Zhen, X., Li, S., Peng, J., Zhao, Z., Zhang, X., Tan, C., Jiao, R., & Wenbing Wu, W. W. (2024). Analysis of Building Envelope for Energy Consumption and Indoor Comfort in a Near-Zero-Energy Building in Northwest China (SSRN Scholarly Paper No. 5062015). Social Science Research Network. https://doi.org/10.2139/ssrn.5062015

[7] Hosseini, S. M., Mohammadi, M., Rosemann, A., Schröder, T., & Lichtenberg, J. (2019). A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review. Building and Environment, 153, 186–204. https://doi.org/10.1016/j.buildenv.2019.02.040

Received: July 21, 2025

Volume 38 No. 1s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

[8] Li, S., & Wen, Z. (2021). Improving Energy Efficiency and Indoor Thermal Comfort: A Review of Passive Measures for Building Envelope. In G. Ye, H. Yuan, & J. Zuo (Eds.), Proceedings of the 24th International Symposium on Advancement of Construction Management and Real Estate (pp. 1719–1732). Springer. https://doi.org/10.1007/978-981-15-8892-1_121

[9] Sureshkumar Jayakumari, S. D., Imalka, S. T., Yang, R. J., Liu, C., Yang, S., Marschall, M., Corradini, P. S., Benito, A. F., & Williams, N. (2024). Energy and Daylighting Performance of Kinetic Building-Integrated Photovoltaics (BIPV) Façade. Sustainability, 16(22), Article 22. https://doi.org/10.3390/su16229739

[10] (PDF) The Role of Kinetic Envelopes to Improve Energy Performance in Buildings. (2024). ResearchGate. https://www.researchgate.net/publication/286639908_The_Role_of_Kinetic_Envelopes_to_Improve_Energy_Performance_in_Buildings

[11] (PDF) Responsive Kinetic Facades: An Effective Solution for Enhancing Indoor Environmental Quality in Buildings. (n.d.). ResearchGate. Retrieved April 18, 2025, from https://www.researchgate.net/publication/330347504_Responsive_Kinetic_Facades_An_Effective_Solution_for_Enhancing_Indoor_Environmental_Quality_in_Buildings

[12] Abdelwahed Mekhamar, A., & Halim Hussein, A. (2021). BRIEF OVERVIEW OF CLIMATE RESPONSIVE FACADES & ITS KINETIC APPLICATIONS. Engineering Research Journal, 171(0), 16–34. https://doi.org/10.21608/erj.2021.193461

[13] (PDF) Adaptive Facades' Technologies to Enhance Building Energy Performance and More, A literature review and case-based analysis. (n.d.). ResearchGate. Retrieved April 18, 2025, from https://www.researchgate.net/publication/366921619_Adaptive_Facades'_Technologies_to_Enhance_Building_Energy_Performance_and_More_A_literature_review_and_case-based_analysis

[14] Alotaibi, F. (2015). The Role of Kinetic Envelopes to Improve Energy Performance in Buildings. Journal of Architectural Engineering Technology, 04(03). https://doi.org/10.4172/2168-9717.1000149

[15] Razaz, Z. E. (2010). Sustainable vision of kinetic architecture. Journal of Building Appraisal, 5(4), 341–356. https://doi.org/10.1057/jba.2010.5

[16] Gregoris, C. (2016). Colour and light in communication of fabric façades. Cultura e Scienza Del Colore - Color Culture and Science, 6, 37–46. https://doi.org/10.23738/ccsj.i62016.03

Received: July 21, 2025

Volume 38 No. 1s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

[17] Velikov, K., Thün, G., O'Malley, M., & Junghans, L. (2015). Computational and Physical Modeling for Multi-Cellular Pneumatic Envelope Assemblies. International Journal of Architectural Computing, 13(2), 143–168. https://doi.org/10.1260/1478-0771.13.2.143

[18] Dialogue Social Science Review. (2025). Textile Architecture in Transition: Global Trends and Emerging Applications in Pakistan. https://doi.org/10.5281/ZENODO.15757298

[19] Shareef Al-Azzawi, R. A., & Al-Alwan, H. A. S. (2025). Eco-friendly Textile Architecture: A Review of Concepts, Terms and Sustainable Applications. IOP Conference Series: Earth and Environmental Science, 1440(1), 012009. https://doi.org/10.1088/1755-1315/1440/1/012009

[20] Mirrahimi, S., Mohamed, M. F., Haw, L. C., Ibrahim, N. L. N., Yusoff, W. F. M., & Aflaki, A. (2016). The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot–humid climate. Renewable and Sustainable Energy Reviews, 53, 1508–1519. https://doi.org/10.1016/j.rser.2015.09.055

[21] Karádi, D. T., & Hegyi, D. (2021). An Extensive Review on the Viscoelastic-plastic and Fractural Mechanical Behaviour of ETFE Membranes. Periodica Polytechnica Architecture, 52(2), 121–134. https://doi.org/10.3311/PPar.18403

[22] (PDF) Transparent architecture-building with ETFE membranes. (n.d.). Retrieved April 18, 2025, from https://www.researchgate.net/publication/312969070_Transparent_architecture-building_with_ETFE_membranes

[23] Gonçalves, A. (n.d.). Case study: Munich Allianz Arena Stadium.

[24] Koyaz, M. (2017). ADAPTABILITY LEVEL OF FACADE SYSTEMS REGARDING FACADE PERFORMANCES.

[25] Shareef, R. A., & Al-Alwan, H. A. S. (2021). Sustainable textile architecture: History and prospects. IOP Conference Series: Materials Science and Engineering, 1067(1), 012046. https://doi.org/10.1088/1757-899X/1067/1/012046

[26] Liu, Q., Han, X., Yan, Y., & Ren, J. (2023). A Parametric Design Method for the Lighting Environment of a Library Building Based on Building Performance Evaluation. Energies, 16(2), Article 2. https://doi.org/10.3390/en16020832

[27] Orr, K. (2007). THINKING BEYOND THE SQUARE: INNOVATION THEORY AND TECHNOLOGY TRANSFER AS THEY APPLY TO THE BEIJING WATER CUBE. https://opus.lib.uts.edu.au/handle/10453/19683

Received: July 21, 2025

[28] Architectural Designs using ETFE film are Friendlier to the Environment—AGC Chemicals. (2017, May 1). https://www.agcchem.com/blog/blog/etfe-film/architectural-designs-using-etfe-film-are-friendlier-to-the-environment/

[29] Yap, S. (2025, January 17). ETFE Membrane Structure: A Cost-Effective Revolution in Modern Architecture. Tensile Membrane Structure. https://temembrane.com/etfe-membrane-structure-a-cost-effective-revolution-in-modern-architecture/

[30] development@squarebird.co.uk. (2024, August 15). Passive Energy Efficiency with ETFE and Polycarbonate Structures. ARC Structures. https://arcstructures.co.uk/passive-energy-efficiency-with-etfe-and-polycarbonate-structures/

[31] Lisco, F., Bukhari, F., Jones, L. O., Law, A. M., Walls, J. M., & Ballif, C. (2023). ETFE and its Role in the Fabrication of Lightweight c-Si Solar Modules. IEEE Journal of Photovoltaics, 13(3), 349–354. https://doi.org/10.1109/JPHOTOV.2023.3242212

[32] Scorpio, M., Ciampi, G., Spanodimitriou, Y., Laffi, R., Rosato, A., & Sibilio, S. (n.d.). Double-Skin Facades With Semi-Transparent Modules For Building Retrofit Actions: Energy And Visual Performances. 464–471. https://doi.org/10.26868/25222708.2019.210989

[33] Biloria, N. (2009). Adaptive Building Skin Systems: A Morphogenomic Framework for Developing Real-Time interactive Building Skin Systems. Proceedings of the 2009 Computation World: Future Computing, Service Computation, Cognitive, Adaptive, Content, Patterns, 119–125. https://doi.org/10.1109/ComputationWorld.2009.24

[34] Spanodimitriou, Y., Ciampi, G., Tufano, L., & Scorpio, M. (2023). Flexible and Lightweight Solutions for Energy Improvement in Construction: A Literature Review. Energies, 16(18), 6637. https://doi.org/10.3390/en16186637

[35] Chiu, S. K., & Lin, E. S. (n.d.). Transformable Tensile Façade: Performance assessment on energy, solar and daylighting.

[36] Gómez-González, A., Neila, J., & Monjo, J. (2011). Pneumatic Skins in Architecture. Sustainable Trends in Low Positive Pressure Inflatable Systems. Procedia Engineering, 21, 125–132. https://doi.org/10.1016/j.proeng.2011.11.1995

[37] Keshmiri, P. (n.d.). Biomimicry for a Sustainable Built Environment.

[38] Yum, M. S. (2020). Exploration of smart buildings shell systems centered on sustainability. https://hdl.handle.net/11467/4816

[39] Environmental Sustainability of Textile Architecture: A Review of the Thermal, Optical, and Acoustic Properties of Textile Membranes. (2024). International Society for the Study of Vernacular Settlements, 11(2), 423–441. https://doi.org/10.61275/isvsej-2024-11-02-27

[40] Elattar, S., Hu, X., Golzad, H., & Banihashemi, S. (2025). Environmental Sustainability of Advanced Structures: A Descriptive and Thematic Analysis. Buildings, 15(12), Article 12. https://doi.org/10.3390/buildings15122027

[41] Monticelli, C., Campioli, A., Zanelli, A., di Milano, P., & Bonardi, V. (2009). Environmental load of ETFE cushions and future ways for their self-sufficient performances.

[42] Monticelli, C., Zanelli, A., & Centrulli, M. (2017). Application and validation of eco-efficiency principles to assess the design of lightweight structures: Case studies of ETFE building skins.

[43] Nahar, S., Dos Santos, J. G., Freire, J., & Almeida, P. P. (2023). ETFE Characteristics in Architecture: The Case of Large-Scale Construction Project. Key Engineering Materials, 970, 79–86. https://doi.org/10.4028/p-gusz3w

[44] Nazim, Mohd. A., Rahman, T., Rahman, R., & Hossain, R. (2017). Evaluating the potential of low-e coated 3-layer ETFE pillows as an energy efficient building material. 2017 2nd International Conference for Convergence in Technology (I2CT), 993–997. https://doi.org/10.1109/i2ct.2017.8226278

[45] Qahtan, A. M., Bahdad, A. A. S., Al-Tamimi, N., & Syed Fadzil, S. F. (2024). Optimizing daylighting in lecture halls within hot-arid climates through modification of glazing systems with light-shelves: A parametric design approach. Indoor and Built Environment, 33(5), 929–956. https://doi.org/10.1177/1420326X241226651

[46] Flor, J.-F., Liu, X., Sun, Y., Beccarelli, P., Chilton, J., & Wu, Y. (2022). Switching daylight: Performance prediction of climate adaptive ETFE foil façades. Building and Environment, 209, 108650. https://doi.org/10.1016/j.buildenv.2021.108650

[47] Zolfagharpour, A., Shafaei, M., & Saeidi, P. (2022). Responsive Architecture Solutions to Reduce Energy Consumption of High-Rise Buildings. International Journal of Architectural Engineering & Urban Planning, 32(3). https://doi.org/10.22068/ijaup.679

[48] Freitas, J. de S., Cronemberger, J., Soares, R. M., & Amorim, C. N. D. (2020). Modeling and assessing BIPV envelopes using parametric Rhinoceros plugins Grasshopper and Ladybug. Renewable Energy, 160, 1468–1479. https://doi.org/10.1016/j.renene.2020.05.137

Volume 38 No. 1s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

[49] Shan, R. (n.d.). INTEGRATING RHINOCEROS/GRASSHOPPER WITH GENETIC ALGORITHM IN WHOLE BUILDING ENERGY SIMULATION.

[50] Harry, S. (2016). Dynamic Adaptive Building Envelopes – an Innovative and State-of-The-Art Technology. Creative Space, 3(2), 167–184. https://doi.org/10.15415/cs.2016.32011

[51] Dikou, C. (2023). Innovative Applications for Net-zero Buildings in Architecture, Based on the Principles of Bioinspiration. In Prof. F. Balo (Ed.), Research Highlights in Science and Technology Vol. 4 (pp. 25–42). B P International (a part of SCI-ENCEDOMAIN International). https://doi.org/10.9734/bpi/rhst/v4/5188B

[52] Li, Y., Zhao, Y., Chi, Y., Hong, Y., & Yin, J. (2021). Shape-morphing materials and structures for energy-efficient building envelopes. Materials Today Energy, 22, 100874. https://doi.org/10.1016/j.mtener.2021.100874

[53] Moritz, K., & Hafner, A. (2010). Transparency Carried by Air—Pneumatic ETFE-Foil Cushion Technology. Structures Congress 2010, 2518–2529. https://doi.org/10.1061/41130(369)227

[54] Aditra, R. F., Beccarelli, P., & Wilson, R. (2023). Pneufin: A switchable foil cushion inspired soft pneumatic adaptive shading. Journal of Building Engineering, 77, 107521. https://doi.org/10.1016/j.jobe.2023.107521

[55] Faramarzi, A., Stephens, B., & Heidarinejad, M. (2021). Optimal control of switchable ethylene-tetrafluoroethylene (ETFE) cushions for building façades. Solar Energy, 218, 180–194. https://doi.org/10.1016/j.solener.2021.01.059

[56] Façade-Integrated Sustainable Technologies for Tall Buildings. (n.d.). Docslib. Retrieved April 22, 2025, from https://docslib.org/doc/10137166/fa%C3%A7ade-integrated-sustainable-technologies-for-tall-buildings

[57] Lamnatou, Chr., Moreno, A., Chemisana, D., Reitsma, F., & Clariá, F. (2018). Ethylene tetrafluoroethylene (ETFE) material: Critical issues and applications with emphasis on buildings. Renewable and Sustainable Energy Reviews, 82, 2186–2201. https://doi.org/10.1016/j.rser.2017.08.072

[58] Kuda, A., Yadav, M., & Kuda, A. (2023). Importance of Smart Materials Application In Building Skins: An Overview. 2023 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE), 167–171. https://doi.org/10.1109/ICCIKE58312.2023.10131871

Received: July 21, 2025

Volume 38 No. 1s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

[59] Aziz, H. N. A., & Abdelall, M. I. (2021). RESPONSIVE FAÇADES DESIGN USING NANOMATERIALS FOR OPTIMIZING BUILDINGS' ENERGY PERFORMANCE. 397–408. https://doi.org/10.2495/SC210331

[60] Mansy, A. A. Y. (2019). Can Ethylene Tetra Fluoro Ethylene cushions double skin façade applications improve buildings envelope performance, reduce energy consumption and enhance visual and thermal comfort in UAE buildings? https://bspace.buid.ac.ae/handle/1234/1446

[61] Srisuwan, T. (2017). Article Review: Fabric Façade: An Intelligent Skin.

[62] Lee, J., & Lee, H. (2018). Pneumatic Skin with Adaptive Openings—Adaptive Façade with Opening Control Integrated with CFD for Natural Ventilation. 143–151. https://doi.org/10.52842/conf.caadria.2018.2.143

[63] Monticelli, C., Lombardi, S., Würfl, C., & Ibrahim, H. M. (n.d.). ELLIPSOIDAL SHAPE AND DAYLIGHTING CONTROL FOR THE ETFE PNEUMATIC ENVELOPE OF A WINTER GARDEN.

[64] Ghosh, S. K. (n.d.). Self-healing Materials: Fundamentals, Design Strategies, and Applications.

[65] Choi, K., Noh, A., Kim, J., Hong, P. H., Ko, M. J., & Hong, S. W. (2023). Properties and Applications of Self-Healing Polymeric Materials: A Review. Polymers, 15(22), Article 22. https://doi.org/10.3390/polym15224408

[66] Javeed, Y., Goh, Y., Mo, K. H., Yap, S. P., & Leo, B. F. (2024). Microbial self-healing in concrete: A comprehensive exploration of bacterial viability, implementation techniques, and mechanical properties. Journal of Materials Research and Technology, 29, 2376–2395. https://doi.org/10.1016/j.jmrt.2024.01.261

[67] Jonkers, H. M. (2007). Self Healing Concrete: A Biological Approach. In S. van der Zwaag (Ed.), Self Healing Materials: An Alternative Approach to 20 Centuries of Materials Science (pp. 195–204). Springer Netherlands. https://doi.org/10.1007/978-1-4020-6250-6_9

[68] Liao, C.-Y., Zhang, L., Hu, S.-Y., Xia, S.-J., & Li, D. M. (2024). Recent Advances of Self-Healing Materials for Civil Engineering: Models and Simulations. Buildings, 14(4), Article 4. https://doi.org/10.3390/buildings14040961

[69] Adhikary, S. K., Rathod, N., Adhikary, S. D., Kumar, A., & Perumal, P. (2024). Chemical-based self-healing concrete: A review. Discover Civil Engineering, 1(1), 119. https://doi.org/10.1007/s44290-024-00130-7

[70] Van Tittelboom, K., & De Belie, N. (2013). Self-Healing in Cementitious Materials—A Review. Materials, 6(6), 2182–2217. https://doi.org/10.3390/ma6062182

Received: July 21, 2025

[71] Reinhardt, H.-W., & Jooss, M. (2003). Permeability and self-healing of cracked concrete as a function of temperature and crack width. Cement and Concrete Research, 33(7), 981–985. https://doi.org/10.1016/S0008-8846(02)01099-2

[72] Nijland, T. G., Larbi, J. A., & de Rooij, M. (2007). SELF HEALING PHENOMENA IN CONCRETES AND MASONRY MORTARS: A MICROSCOPIC STUDY.

[73] Amran, M., Onaizi, A. M., Fediuk, R., Vatin, N. I., Muhammad Rashid, R. S., Abdelgader, H., & Ozbakkaloglu, T. (2022). Self-Healing Concrete as a Prospective Construction Material: A Review. Materials, 15(9), Article 9. https://doi.org/10.3390/ma15093214

[74] Ortega Del Rosario, M. D. L. Á., Beermann, K., & Chen Austin, M. (2023). Environmentally Responsive Materials for Building Envelopes: A Review on Manufacturing and Biomimicry-Based Approaches. Biomimetics, 8(1), 52. https://doi.org/10.3390/biomimetics8010052

[75] Xi, B., Al-Obaidi, S., & Ferrara, L. (2023). Effect of different environments on the self-healing performance of Ultra High-Performance Concrete – A systematic literature review. Construction and Building Materials, 374, 130946. https://doi.org/10.1016/j.conbuildmat.2023.130946

[76] Xi, B., Huang, Z., Al-Obaidi, S., Monte, F. L., & Fer, L. (n.d.). Investigation of self-healing property of UHPC with sus- tained loads under aggressive exposure environments.

[77] De Belie, N., Gruyaert, E., Al-Tabbaa, A., Antonaci, P., Baera, C., Bajare, D., Darquennes, A., Davies, R., Ferrara, L., Jefferson, T., Litina, C., Miljevic, B., Otlewska, A., Ranogajec, J., Roig-Flores, M., Paine, K., Lukowski, P., Serna, P., Tulliani, J.-M., … Jonkers, H. M. (2018). A Review of Self-Healing Concrete for Damage Management of Structures. Advanced Materials Interfaces, 5(17), 1800074. https://doi.org/10.1002/admi.201800074

[78] Alzard, M. H., El-Hassan, H., El-Maaddawy, T., Alsalami, M., Abdulrahman, F., & Hassan, A. A. (2022). A Bibliometric Analysis of the Studies on Self-Healing Concrete Published between 1974 and 2021. Sustainability, 14(18), Article 18. https://doi.org/10.3390/su141811646

[79] Blaiszik, B. J., Kramer, S. L. B., Olugebefola, S. C., Moore, J. S., Sottos, N. R., & White, S. R. (2010). Self-Healing Polymers and Composites. Annual Review of Materials Research, 40(1), 179–211. https://doi.org/10.1146/annurev-matsci-070909-104532

Volume 38 No. 1s, 2025

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

[80] Wang, S., & Urban, M. W. (2020). Self-healing polymers. Nature Reviews Materials, 5(8), 562–583. https://doi.org/10.1038/s41578-020-0202-4

[81] Peng, L., Lin, M., Zhang, S., Li, L., Fu, Q., & Hou, J. (2019). A Self-Healing Coating with UV-Shielding Property. Coatings, 9(7), Article 7. https://doi.org/10.3390/coatings9070421

[82] Yan, J., Li, M., Wang, Z., Chen, C., Ma, C., & Yang, G. (2020). Highly tough, multi-stimuli-responsive, and fast self-healing supramolecular networks toward strain sensor application. Chemical Engineering Journal, 389, 123468. https://doi.org/10.1016/j.cej.2019.123468

[83] D. Bergman, S., & Wudl, F. (2008). Mendable polymers. Journal of Materials Chemistry, 18(1), 41–62. https://doi.org/10.1039/B713953P

[84] Nield, D. (2016, December 26). This New Self-Healing, Stretchable Material Is Perfect For Wolverine. ScienceAlert. https://www.sciencealert.com/this-new-self-healing-stretchable-material-is-perfect-for-wolverine

[85] A wolverine-inspired material. (n.d.). ScienceDaily. Retrieved April 22, 2025, from https://www.sciencedaily.com/releases/2016/12/161225231953.htm

[86] Wolverine-style self-healing, stretchable material developed | Technology News—The Indian Express. (n.d.). Retrieved April 22, 2025, from https://indianexpress.com/article/technology/science/wolverine-regeneration-stretchable-material-developed-4445785/

[87] Cao, Y., Morrissey, T. G., Acome, E., Allec, S. I., Wong, B. M., Keplinger, C., & Wang, C. (2017). A Transparent, Self-Healing, Highly Stretchable Ionic Conductor. Advanced Materials, 29(10), 1605099. https://doi.org/10.1002/adma.201605099

[88] Chembolu, S. V. V. (n.d.). Enhancing Building Resilience Through Climate-Adaptive Design: A Case Study of ECBC Implementation in Delhi. International Journal of Engineering Research, 13(07).

[89] Sendrayaperumal, A., Mahapatra, S., Parida, S. S., Surana, K., Balamurugan, P., Natrayan, L., & Paramasivam, P. (2021). Energy Auditing for Efficient Planning and Implementation in Commercial and Residential Buildings. Advances in Civil Engineering, 2021(1), 1908568. https://doi.org/10.1155/2021/1908568

[90] Anjanappa, J. (2025). Affordable Energy Efficiency in India: Overcoming Financial and Policy Barriers in Building Upgrades (SSRN Scholarly Paper No. 5185165). Social Science Research Network. https://doi.org/10.2139/ssrn.5185165

Received: July 21, 2025

Volume 38 No. 1s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

[91] Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. Health Information & Libraries Journal, 26(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

[92] Sommese, F., Badarnah, L., & Ausiello, G. (2023). Smart materials for biomimetic building envelopes: Current trends and potential applications. Renewable and Sustainable Energy Reviews, 188, 113847. https://doi.org/10.1016/j.rser.2023.113847

[93] Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. Journal of Clinical Epidemiology, 62(10), e1–e34. https://doi.org/10.1016/j.jclinepi.2009.06.006

[94] Tabadkani, A., Roetzel, A., Li, H. X., & Tsangrassoulis, A. (2022). Simulation-based personalized real-time control of adaptive facades in shared office spaces. Automation in Construction, 138, 104246. https://doi.org/10.1016/j.autcon.2022.104246

[95] Chen, P., & Tang, H. (2024). A Framework for Adaptive Façade Optimization Design Based on Building Envelope Performance Characteristics. Buildings, 14(9), Article 9. https://doi.org/10.3390/buildings14092646

[96] Nabil Barakat, P. (2024). Benefits of High-Performance Facades to improve building performance and achieve Sustainable Designs. Engineering Research Journal, 182(2), 376–397. https://doi.org/10.21608/erj.2024.361632

[97] Shan, R., & Junghans, L. (2023). Multi-Objective Optimization for High-Performance Building Facade Design: A Systematic Literature Review. Sustainability, 15(21), Article 21. https://doi.org/10.3390/su152115596

[98] Pan, Y., Zhu, M., Lv, Y., Yang, Y., Liang, Y., Yin, R., Yang, Y., Jia, X., Wang, X., Zeng, F., Huang, S., Hou, D., Xu, L., Yin, R., & Yuan, X. (2023). Building energy simulation and its application for building performance optimization: A review of methods, tools, and case studies. Advances in Applied Energy, 10, 100135. https://doi.org/10.1016/j.adapen.2023.100135

[99] Favoino, F. (Ed.). (2018). Building performance simulation and characterisation of adaptive facades adaptive facade network. TU Delft Open.

[100] Tuniki, H. P., Jurelionis, A., Rupp, R. F., Valančius, R., & Bekö, G. (2025). Thermal Comfort and Adaptive Occupant Behaviour in Open Plan Offices in India and Lithuania. Buildings, 15(5), Article 5. https://doi.org/10.3390/buildings15050766

[101] Hensen, J. L. M., & Lamberts, R. (2019). Building performance simulation – challenges and opportunities. In J. L. M. Hensen & R. Lamberts (Eds.), Building Perfor-

Received: July 21, 2025

Volume 38 No. 1s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

mance Simulation for Design and Operation (2nd ed., pp. 1–10). Routledge. https://doi.org/10.1201/9780429402296-1

[102] Tanzeel N.M. Adam. (2023). Evaluation of Adaptive Facades within Context of Sustainable Building in Northern Cyprus. https://doi.org/10.5281/ZENODO.7781064

[103] Adam, T. N. M. (n.d.). Evaluation of Adaptive Facades within Context of Sustainable Building in Northern Cyprus.

[104] Andarini, R. (2014). The Role of Building Thermal Simulation for Energy Efficient Building Design. Energy Procedia, 47, 217–226. https://doi.org/10.1016/j.egypro.2014.01.217

[105] (PDF) Simulation-Based Building Envelope Design Optimization Methodologies for Indoor Thermal Comfort -A Review. (n.d.). ResearchGate. https://doi.org/10.9790/1684-1502053945

[106] Energy Conservation Building Code (ECBC) | BUREAU OF ENERGY EFFICIENCY, Government of India, Ministry of Power. (n.d.). Retrieved April 22, 2025, from https://beeindia.gov.in/en/energy-conservation-building-code-ecbc

[107] Juaristi, M., & Monge-Barrio, A. (2016). Adaptive façades in temperate climates. An in-use assessment of an office building. https://doi.org/10.13140/RG.2.2.29634.99527

[108] Shahin, H. S. M. (2019). Adaptive building envelopes of multistory buildings as an example of high performance building skins. Alexandria Engineering Journal, 58(1), 345–352. https://doi.org/10.1016/j.aej.2018.11.013

[109] Sadeghi, M., Chen, D., & Wright, A. (2024). A Critical Review of Overheating Risk Assessment Criteria in International and National Regulations—Gaps and Suggestions for Improvements. Energies, 17(24), Article 24. https://doi.org/10.3390/en17246354

[110] Kaushal, A. A., Anand, P., & Aithal, B. H. (2023). Assessment of the Impact of Building Orientation on PMV and PPD in Naturally Ventilated Rooms During Summers in Warm and Humid Climate of Kharagpur, India. Proceedings of the 10th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, 528–533. https://doi.org/10.1145/3600100.3627034

[111] Kaihoul, A., El Youssef, M., Pitzalis, E., Sriti, L., Dechouk, Y., Amraoui, K., & Khelil, A. E. (2025). Optimising Thermal Comfort in Algerian Reference Hotel Across Eight Climate Zones: A Comparative Study of Simulation and Psychrometric Chart Results. Sustainability, 17(14), Article 14. https://doi.org/10.3390/su17146249

[112] Yao, R., Liu, J., & Li, B. (2010). Occupants' adaptive responses and perception of thermal environment in naturally conditioned university classrooms. Applied Energy, 87(3), 1015–1022. https://doi.org/10.1016/j.apenergy.2009.09.028

Received: July 21, 2025

Volume 38 No. 1s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

[113] Yang, L., Yan, H., & Lam, J. C. (2014). Thermal comfort and building energy consumption implications – A review. Applied Energy, 115, 164–173. https://doi.org/10.1016/j.apenergy.2013.10.062

[114] de Dear, R., & Brager, G. S. (1998). Thermal Adaptation in the Built Environment: A Literature Review. https://doi.org/10.1016/S0378-7788(97)00053-4

[115] Van Hoof, J. (2008). Forty years of Fanger's model of thermal comfort: Comfort for all?Abstract. Indoor Air, 18(3), 182–201. https://doi.org/10.1111/j.1600-0668.2007.00516.x

[116] Ole Fanger, P., & Toftum, J. (2002). Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy and Buildings, 34(6), 533–536. https://doi.org/10.1016/S0378-7788(02)00003-8

[117] Cheung, T., Schiavon, S., Parkinson, T., Li, P., & Brager, G. (2019). Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II. Building and Environment, 153, 205–217. https://doi.org/10.1016/j.buildenv.2019.01.055

[118] Hu, J., Chen, W., Zhao, B., & Yang, D. (2017). Buildings with ETFE foils: A review on material properties, architectural performance and structural behavior. Construction and Building Materials, 131, 411–422. https://doi.org/10.1016/j.conbuildmat.2016.11.062

[119] Lau, B., Masih, D. A. A., Ademakinwa, A. A., Low, S. W., & Chilton, J. (2016). Understanding Light in Lightweight Fabric (ETFE Foil) Structures through Field Studies. Procedia Engineering, 155, 479–485. https://doi.org/10.1016/j.proeng.2016.08.051

[120] Afrin, S., Chilton, J., & Lau, B. (2015). Evaluation and Comparison of Thermal Environment of Atria Enclosed with ETFE Foil Cushion Envelope. Energy Procedia, 78, 477–482. https://doi.org/10.1016/j.egypro.2015.11.706

[121] Fabrix360. (2022, April 24). What is ETFE G-value (Solar Heat Gain Coefficient SHGC). Home. https://www.fabrix360.com/post/what-is-etfe-g-value-solar-heat-gain-coefficient-shgc

[122] Fabrix360. (2020, April 1). U-value ETFE cushion, the rout to precise determination. Home. https://www.fabrix360.com/post/u-value-etfe-cushion-the-rout-to-precise-determination

[123] Wool, R. P. (2008). Self-healing materials: A review. Soft Matter, 4(3), 400. https://doi.org/10.1039/b711716g

Received: July 21, 2025

Volume 38 No. 1s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

[124] Srivastava, A., Usha, P., Al-Alawachi, S. F. A., Kansal, L., K, A., & Arora, D. (2024). Self-Healing Materials: Mechanisms, Characterization, and Applications: A detailed Review. E3S Web of Conferences, 505, 01019. https://doi.org/10.1051/e3sconf/202450501019

[125] Testing Services | METS Laboratories. (n.d.). Testing Laboratory in UAE - Middle East Testing Lab Services Dubai. Retrieved April 22, 2025, from https://metslab.com/services/

Received: July 21, 2025