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Low-Cost Smart Materials for Responsive Building Envelopes

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Abstract

Responsive building envelopes offer an important pathway for reducing heating and cooling demand by allowing walls, roofs, windows, and façade elements to alter their thermal, optical, or physical behavior in response to changing environmental conditions. However, many advanced adaptive-envelope technologies remain difficult to deploy widely because they depend on expensive glazing systems, sophisticated actuators, complex control systems, nanomaterial processing, or high-maintenance mechanical components. This study examines an alternative pathway centered on low-cost or cost-reducible smart materials capable of providing autonomous or minimally powered environmental response.

A structured integrative review was undertaken covering phase-change materials, thermochromic hydrogels and coatings, hygromorphic wood-based systems, biochar-supported thermal-storage composites, dynamic insulation concepts, and selected hybrid responsive envelope technologies. The evidence indicates that phase-change materials are particularly promising for affordable thermal regulation because they can be incorporated into gypsum, concrete, wallboards, façade cavities, or bio-based porous supports while storing and releasing latent heat. Biomass-derived biochar and agricultural-residue carbon can further reduce dependence on expensive support matrices and provide opportunities for circular material development.

Thermochromic hydrogels offer passive solar-control functionality without continuous electrical actuation, although durability, optical stability, freezing resistance, and long-term cycling remain significant barriers. Hygromorphic timber and cellulose-based systems offer a fundamentally different low-energy strategy by using natural dimensional responses to humidity to produce autonomous movement, ventilation, or shading. The paper develops a Low-Cost Responsive Envelope Framework based on five criteria: material affordability, passive responsiveness, manufacturability, climatic suitability, and life-cycle durability. The analysis concludes that the strongest pathway toward affordable responsive buildings is not the indiscriminate replacement of conventional envelopes with highly sophisticated smart façades. Instead, smart functionality should be embedded selectively where material response can reduce thermal loads without imposing excessive capital, maintenance, control, or replacement costs.

Keywords: Smart Materials; Responsive Building Envelope; Phase-Change Materials; Thermochromic Materials; Hygromorphic Materials; Building Energy Efficiency; Adaptive Façade; Bio-Based Materials; Passive Thermal Regulation; Affordable Buildings

1. Introduction

The building envelope forms the principal environmental boundary between occupied indoor space and external climatic conditions. Walls, roofs, windows, foundations, shading elements, and façade assemblies influence conductive heat transfer, solar gains, air leakage, daylight availability, moisture movement, and the heating or cooling demand required to maintain acceptable indoor conditions. The U.S. Department of Energy estimates that envelope technologies are associated with approximately 30% of primary energy consumed in residential and commercial buildings, demonstrating why improvements to envelope performance can influence both energy demand and occupant comfort. Conventional envelope design seeks to resist environmental change through fixed insulation, glazing, mass, and shading. Responsive envelopes instead seek to adapt their properties as external and internal conditions change.

Adaptive-envelope research has expanded considerably through dynamic insulation, movable shading, electrochromic and thermochromic glazing, phase-change materials, responsive ventilation systems, and mechanically transformable façades. Contemporary reviews describe adaptive envelopes as systems capable of altering thermal resistance, solar transmittance, heat-storage behavior, ventilation, or physical configuration according to environmental stimuli or operating requirements. Simulation research has shown that appropriately selected dynamic façade technologies can substantially reduce annual thermal loads in some climatic and building contexts; Attia and colleagues reported reductions reaching approximately 30% under their modeled office-building conditions. Such findings establish the technical potential of adaptive façades, but they do not automatically establish economic accessibility.

Affordability remains one of the principal barriers separating experimental responsive envelopes from widespread construction practice. Electrochromic glazing, vacuum insulation panels, aerogels, motorized façade elements, sensors, control hardware, and advanced nanoengineered coatings can deliver strong performance while increasing initial investment, commissioning complexity, maintenance requirements, or replacement cost. Recent reviews of next-generation building materials continue to identify cost and scalability as important obstacles to large-scale adoption. For low-income housing, rapidly urbanizing regions, educational buildings, small commercial properties, and retrofit markets, an adaptive technology that performs extremely well but cannot be manufactured, repaired, or financed locally may have limited practical value.

A lower-cost pathway is possible when the material itself performs part of the sensing and response function. Phase-change materials absorb and release latent heat according to temperature. Thermochromic materials alter optical properties as temperature changes. Hygroscopic wood and cellulose composites swell and shrink in response to moisture. Thermoresponsive hydrogels modify light transmission without requiring conventional motors. These material-driven responses can reduce reliance on separate sensors, actuators, electrical motors, and complex control logic. Research on adaptive dynamic envelopes integrated with phase-change materials demonstrates the potential to improve the timing of heat storage and release, while thermochromic smart-window research shows how temperature-responsive optical behavior can regulate solar gains autonomously.

The present paper therefore investigates low-cost smart materials as an enabling layer for responsive building envelopes. Low cost is interpreted broadly rather than as the lowest purchase price. The study considers material cost, fabrication complexity, actuation energy, installation requirements, maintenance, expected lifetime, compatibility with existing construction methods, and the possibility of using locally available or waste-derived feedstocks. Particular attention is given to PCM systems, thermochromic hydrogels, biomass-supported thermal-storage materials, and hygromorphic bio-based components. The study proposes that economically viable responsive envelopes should be evaluated through whole-life affordability and climatic usefulness rather than novelty alone.

2. Objectives of the Study

2.1 To Identify Affordable Smart-Material Pathways

The first objective is to identify smart-material families that can provide responsive thermal, optical, or physical behavior while remaining compatible with cost-sensitive building applications.
The study emphasizes materials capable of operating passively or with very low auxiliary energy and that can potentially be integrated into conventional wall, roof, glazing, or façade construction.

2.2 To Evaluate Performance–Cost Trade-Offs

The second objective is to examine the trade-offs among thermal performance, response speed, material durability, manufacturing complexity, fire safety, structural compatibility, maintenance, and economic accessibility.

The analysis deliberately avoids assuming that the technically highest-performing material is automatically the most appropriate for widespread building deployment.

2.3 To Develop a Low-Cost Responsive Envelope Framework

The third objective is to formulate an evidence-informed framework for selecting responsive materials according to climate, building type, envelope function, manufacturing capability, expected service life, and whole-life affordability.

3. Review of Literature

3.1 Phase-Change Materials as Passive Thermal Regulators

Phase-change materials are among the most extensively investigated smart materials for building envelopes. They store thermal energy through latent heat when changing phase and release that energy when the reverse transition occurs. Properly selected PCMs can therefore absorb excess heat when envelope temperatures rise and release stored energy after temperatures fall.

Wang and colleagues' state-of-the-art review describes the integration of PCM with adaptive dynamic envelopes as a means of improving both heat-storage and heat-release efficiency. More recent reviews continue to report extensive investigation of PCMs in walls, roofs, floors, concrete, insulation systems, and hybrid thermal-storage assemblies.

PCMs are particularly relevant to affordability because several integration methods do not require a mechanically moving façade. Macroencapsulated PCM can be located within wall or ceiling cavities; microencapsulated PCM can be incorporated into construction products; and shape-stabilized composites can use porous matrices to retain the phase-changing component.
Cost reduction is also increasingly linked with waste-derived and bio-based supports. Wang and colleagues developed an economical hydrated-salt/bagasse biomass-derived carbon composite,

demonstrating how agricultural residue can function as a support for phase-change thermal storage. The published study explicitly positions biomass-derived carbon as part of a cost-conscious thermal-storage strategy. Recent biochar research similarly identifies renewable, low-cost biomass-derived carbon as a potentially attractive matrix for composite PCM development.

Nevertheless, PCM integration presents significant challenges. Leakage, supercooling in some salt hydrates, phase segregation, low thermal conductivity, compatibility with construction materials, fire behavior, mechanical-strength reduction, and encapsulation durability can restrict practical deployment. Reviews of PCM-enhanced concrete emphasize the need to balance thermal advantages against mechanical and durability consequences.

3.2 Thermochromic and Hydrogel-Based Solar Control

Thermochromic materials alter their optical characteristics according to temperature. In building applications, the most widely discussed function is dynamic solar control through glazing or coatings.

Aburas and colleagues' major review of thermochromic smart windows discusses multiple material classes and their potential for building-energy conservation. Wang and Narayan similarly review thermochromic materials including vanadium dioxide, hydrogels, and related smart-window systems.

For affordability, thermoresponsive hydrogels are especially interesting because their transition behavior can occur passively. A hydrogel layer can become more or less transparent as temperature crosses a transition threshold, reducing the need for motors or continuously powered switching systems.

Recent research describes thermochromic hydrogel glazing as comparatively easy to produce and potentially cost-effective while remaining highly temperature-sensitive. Other work shows continued progress in thermochromic hydrogels integrated with energy-storage or smart-window functions.

However, several limitations remain critical. A façade material must survive repeated daily and seasonal cycles, ultraviolet radiation, freezing conditions, water loss, mechanical stresses, sealing failures, and long exposure to fluctuating temperatures. A laboratory optical response is therefore only the first requirement. Long-term stability, visible-light quality, hysteresis, switching temperature, response time, environmental safety, and replacement complexity determine whether a thermochromic system is genuinely economical over its service life.

3.3 Hygromorphic and Bio-Based Responsive Materials

Hygromorphic materials offer a different type of smart behavior. Wood and cellulose-based composites naturally undergo dimensional change as environmental humidity changes. Instead of suppressing this characteristic completely, adaptive design can exploit it to create passive movement.

Recent research on humidity-responsive façades has used timber, cellulose-based materials, hydrogels, and biopolymers to create systems whose geometry changes according to moisture conditions. The Hygroflex prototype, for example, combines timber and a chitosan-based hydrogel composite to explore water-responsive façade behavior. Other recent work on hygroscopic façade tiles uses cellulose-based materials to create reversible deformation without conventional powered actuators.

The economic attraction is conceptual as well as material. If environmental humidity itself functions as the stimulus and the material supplies the actuation, electrical sensors and motors may become unnecessary for certain shading or ventilation functions.

Bio-based responsive systems can also use waste streams. Sawdust, agricultural residues, cellulose, biochar, and other low-value biomass resources can potentially become components of responsive assemblies, connecting smart-envelope research with circular construction.

The primary challenge is predictability. Natural materials exhibit variability, hysteresis, fatigue, creep, biological degradation, anisotropy, and sensitivity to manufacturing conditions. Responsive movement must remain controlled after thousands of environmental cycles. Consequently, low initial cost should not justify poor durability or uncontrolled performance.

4. Research Methodology

4.1 Research Design

The study adopts a structured integrative literature-review and conceptual-synthesis methodology.
No original building experiment, climate-chamber test, occupant survey, or material-cost dataset was supplied for this manuscript. Therefore, no fabricated energy savings, material prices, building simulations, or thermal measurements are reported as original empirical findings.

The paper synthesizes peer-reviewed research on adaptive envelopes, phase-change materials, thermochromic systems, hydrogels, bio-based smart materials, and dynamic façade technologies.

4.2 Literature Identification and Selection

The principal evidence base covered literature published primarily between 2019 and August 2026, supplemented by earlier influential research where necessary.

Evidence was prioritized when a study addressed at least one of the following:

- material responsiveness;
- building-envelope application;
- energy or thermal performance;
- material affordability or scalable feedstocks;
- manufacturing feasibility;

or service-life constraints.

4.3 Evaluation Criteria

Materials were interpreted through a five-part evaluation framework covering affordability, autonomous responsiveness, thermal or optical contribution, manufacturability, and long-term durability.

Table 1: Methodological Evaluation Framework

Evaluation Dimension	Principal Question
Material affordability	Can the material or its supporting matrix be produced from accessible commercial, mineral, polymeric, bio-based, or waste-derived inputs?
Passive	Can meaningful response occur without continuous

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Evaluation Dimension	Principal Question
responsiveness	external actuation?
Envelope compatibility	Can the system be integrated into walls, roofs, glazing, insulation, façade cavities, or shading components?
Manufacturing scalability	Does the concept depend on highly specialized laboratory fabrication or can it potentially use established construction processes?
Climate suitability	Does the response temperature or humidity range correspond to actual climatic conditions?
Durability	Can repeated thermal, optical, or moisture cycles occur without unacceptable performance deterioration?
Safety	Are fire, toxicity, leakage, structural, moisture, and occupant-safety risks manageable?
Maintenance requirement	Can the system operate without frequent specialist servicing?
Retrofit suitability	Can it be added to existing envelopes without complete façade replacement?
Whole-life affordability	Do energy, maintenance, replacement, and durability benefits justify initial cost?

5. Analysis

5.1 Material Selection for Low-Cost Responsiveness

The literature indicates that affordability should be evaluated according to the function required.
For opaque wall and roof systems, PCM integration appears particularly promising because the response occurs thermally and does not require visible optical quality. Existing wallboard, concrete, panel, and cavity systems can potentially provide the physical host.

For windows, thermochromic hydrogel systems may represent a lower-energy alternative to mechanically controlled shading or electrically switched glazing where durability and optical requirements can be satisfied.

For external shading or ventilation elements, hygromorphic cellulose or timber systems offer the possibility of material-driven physical movement.

Table 2: Low-Cost Smart-Material Matrix for Responsive Envelopes

Material / System	Environmental Response	Main Envelope Function	Cost-Reduction Pathway	Principal Limitation
Paraffin PCM	Temperature / phase transition	Thermal buffering	Commercial availability and simple encapsulation	Flammability and low conductivity
Hydrated-salt PCM	Temperature / phase transition	Thermal-energy storage	Relatively inexpensive raw materials	Supercooling, segregation and corrosion
Biochar-supported PCM	Temperature / phase transition	Thermal buffering	Waste biomass as porous support	Processing consistency and fire performance
PCM-enhanced gypsum / panels	Temperature	Interior thermal mass	Compatibility with familiar construction products	Encapsulation and cycling durability
Thermochromic hydrogel	Temperature	Dynamic solar transmittance	Passive switching without motorized actuator	UV durability, water retention and sealing
Thermochromic coating	Temperature	Solar absorption/reflection control	Thin-layer application	Long-term color and switching stability
Hygromorphic timber	Humidity	Passive shading / ventilation movement	Natural material acts as sensor and actuator	Moisture cycling and dimensional variability

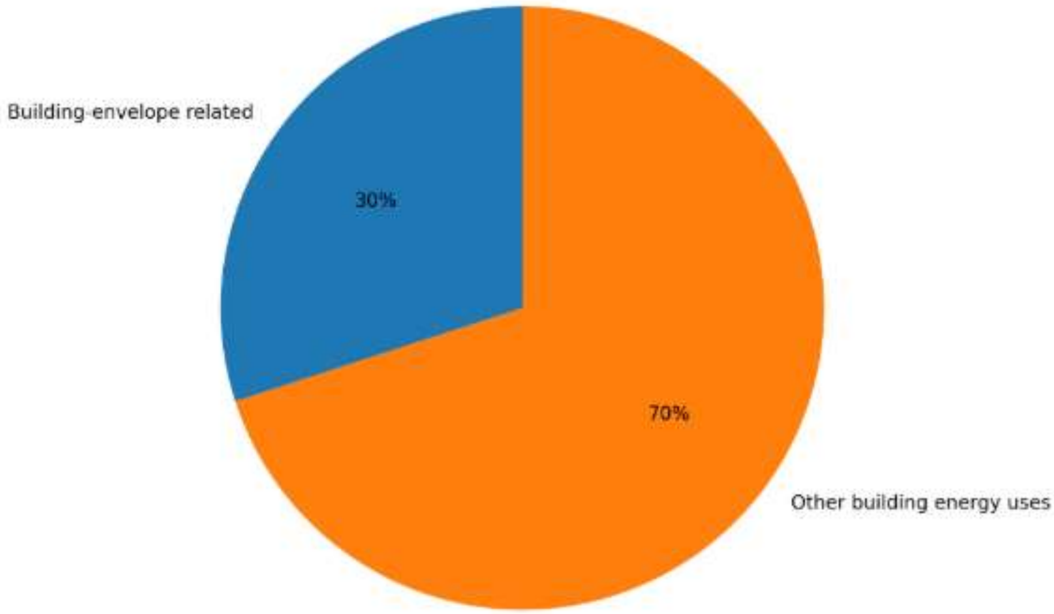
Note: The table presents a qualitative design comparison, not market-price measurements. Local price, climatic suitability, codes, labor, manufacturing volume, and service life can materially change the economic ranking.

5.2 Why Envelope Innovation Matters

The economic relevance of low-cost responsive materials is amplified by the contribution of the envelope to overall building energy performance.

The U.S. Department of Energy reports that building-envelope technologies—walls, windows, roofs, and foundations—are associated with approximately 30% of primary energy consumption in residential and commercial buildings.

Figure 1: Approximate Share of Primary Building Energy Associated with the Envelope



5.3 Proposed Low-Cost Responsive Envelope Framework

The analysis supports a six-stage design process.

Stage 1 — Identify the Dominant Climatic Load

The designer should first identify whether the building problem is dominated by daytime overheating, nocturnal heat loss, high solar gains, humidity, peak cooling loads, or seasonal temperature swings.

A material should not be selected simply because it is responsive.

Its response must correspond to the actual building problem.

Stage 2 — Select the Simplest Useful Response

Where thermal buffering is required, PCM may provide sufficient responsiveness without moving components.

Where solar transmission is the problem, thermochromic glazing may be more appropriate.

Where humidity correlates with desired ventilation or shading movement, hygromorphic materials may provide a passive mechanical response.

The least complex system capable of achieving the required function should be preferred.

Stage 3 — Match Transition Conditions to Climate

Smart materials possess characteristic switching conditions.

A PCM with an inappropriate melting temperature may remain permanently solid or permanently liquid.

A thermochromic window with the wrong transition temperature may darken too early or too late.

Responsive materials therefore require climate-specific tuning.

Stage 4 — Design for Conventional Construction

Affordability improves when the smart material can be incorporated into existing construction processes. Examples include PCM plasterboards, PCM-enhanced concrete elements, retrofit coatings, replaceable smart-glazing layers, façade cartridges, and timber shading units.

Highly specialized assemblies requiring complete building redesign are less suitable for mass adoption.

6. Discussion

6.1 Low Cost Should Mean Low Whole-Life Complexity

1. A central finding of the review is that affordable responsive design cannot be evaluated through material purchase price alone.
2. A cheap active façade element may become expensive if it requires sensors, motors, control software, specialist commissioning, frequent calibration, and difficult replacement.
3. Conversely, a moderately more expensive passive material may provide a better whole-life proposition when the environmental stimulus itself drives its response.
4. This is where PCMs, thermochromic hydrogels, and hygromorphic materials become particularly interesting.
5. The smart functionality is embedded within the material.
6. The material can therefore perform part of the sequence conventionally assigned to separate sensing, control, and actuation technologies.
7. This does not eliminate complexity entirely, but it can shift complexity away from electromechanical systems.

6.2 Bio-Based and Waste-Derived Supports Can Improve Affordability

The emerging use of biomass-derived carbon as a supporting structure for PCMs creates a promising link among responsive building materials, affordability, and circularity.

Wang and colleagues' hydrated-salt/bagasse carbon composite demonstrates a pathway in which agricultural residue becomes part of a thermal-storage material rather than a waste stream. Biochar is also increasingly investigated because its porous structure can retain PCM while its feedstock can originate from renewable biomass.

Collection, drying, pyrolysis, chemical treatment, impregnation, encapsulation, quality control, fire protection, and transport can all contribute to cost.

The strongest future studies should therefore report actual manufacturing cost per unit of usable thermal-storage capacity rather than describing a material as low-cost solely because its raw feedstock is inexpensive.

6.3 Performance, Durability, and Affordability Must Be Evaluated Together

Smart-material literature often emphasizes peak optical modulation, latent-heat capacity, response amplitude, or simulated energy reduction.

Thousands of daily heating and cooling cycles, seasonal humidity changes, solar radiation, pollution, cleaning, impact, water penetration, and temperature extremes can alter material performance.

PCM concrete research already identifies leakage, mechanical-strength reduction, and encapsulation durability as major barriers. Thermochromic research similarly identifies long-term optical stability and environmental adaptability as continuing challenges.

Consequently, future low-cost smart-envelope research should use a cost-per-service-year and cost-per-unit-energy-saved perspective rather than a laboratory material-price comparison.

A material that costs half as much but survives only a small fraction of the building's expected life may not represent an affordable solution.

7. Conclusion

Low-cost smart materials provide a promising route toward responsive building envelopes capable of adapting to environmental conditions without the capital and maintenance burden associated with highly mechanized façade systems.

The literature reviewed in this study demonstrates three particularly important material pathways. First, phase-change materials can provide passive thermal regulation by absorbing and releasing latent heat. Their compatibility with walls, roofs, concrete, panels, and cavities makes them especially attractive for both new construction and selected retrofit applications. Biomass-derived carbon and agricultural-residue supports may further improve resource efficiency and offer pathways toward lower-cost composite PCM systems.

Second, thermochromic materials and hydrogels can regulate solar transmission according to temperature without requiring continuous electrical actuation. Their potential is particularly strong for windows and transparent façade components, although optical quality, UV durability, water stability, switching temperature, and long-term cycling must be improved before low initial cost can reliably translate into low life-cycle cost.

Third, hygromorphic wood and cellulose-based materials provide an alternative form of passive responsiveness in which humidity drives physical movement. Such systems are especially relevant to bio-based shading, ventilation, and façade components because the material can simultaneously function as environmental sensor and actuator. Recent prototypes demonstrate the growing feasibility of such approaches, although durability and controlled long-term movement remain research priorities.

The study proposes a Low-Cost Responsive Envelope Framework based on climate diagnosis, minimum-complexity response, climate-matched switching conditions, conventional-construction compatibility, whole-life cost, and durability validation.

The principal conclusion is that responsive building envelopes do not need to become mechanically or digitally complex in order to become intelligent.

References

1. P. Wang, Z. Liu, X. Zhang, M. Hu, L. Zhang, and J. Fan, "Adaptive dynamic building envelope integrated with phase change material to enhance the heat storage and release efficiency: A state-of-the-art review," *Energy and Buildings*, vol. 286, Art. no. 112928, 2023, doi: 10.1016/j.enbuild.2023.112928.
2. N. Zhangabay, T. Tursunkululy, U. Ibraimova, and U. Abdikerova, "Energy-efficient adaptive dynamic building facades: A review of their energy efficiency and operating loads," *Applied Sciences*, vol. 14, no. 23, Art. no. 10979, 2024, doi: 10.3390/app142310979.
3. S. Attia, S. Bertrand, M. Cuchet, S. Yang, and A. Tabadkani, "Comparison of thermal energy saving potential and overheating risk of four adaptive façade technologies in office buildings," *Sustainability*, vol. 14, no. 10, Art. no. 6106, 2022, doi: 10.3390/su14106106.
4. M. A. Mohammed, I. M. Budaiwi, M. A. Al-Osta, and A. A. Abdou, "Thermo-environmental performance of modular building envelope panel technologies: A focused review," *Buildings*, vol. 14, no. 4, Art. no. 917, 2024, doi: 10.3390/buildings14040917.
5. M. Aburas, V. Soebarto, T. Williamson, R. Liang, H. Ebendorff-Heidepriem, and Y. Wu, "Thermochromic smart window technologies for building application: A review," *Applied Energy*, vol. 255, Art. no. 113522, 2019, doi: 10.1016/j.apenergy.2019.113522.
6. X. Wang and S. Narayan, "Thermochromic materials for smart windows: A state-of-art review," *Frontiers in Energy Research*, vol. 9, Art. no. 800382, 2021, doi: 10.3389/fenrg.2021.800382.
7. M. Sun, H. Sun, R. Wei, and W. Li, "Energy-efficient smart window based on a thermochromic hydrogel," *Gels*, vol. 10, no. 8, Art. no. 494, 2024, doi: 10.3390/gels10080494.
8. T. Wang, W. Cui, X. Li, T. Ma, and Q. Wang, "Economical and shape-stabilized hydrated salt/bagasse biomass-derived carbon phase change composite for thermal energy storage," *Journal of Energy Storage*, vol. 85, Art. no. 111083, 2024, doi: 10.1016/j.est.2024.111083.
9. S. J. Osibodu et al., "Phase change material integration in concrete for thermal energy storage: Techniques and applications in sustainable building," 2024, doi: 10.1186/s40807-024-00138-8.
10. S. K. Jha et al., "Incorporation of phase change materials in buildings," *Construction Materials*, vol. 4, 2024.
11. Y. Jiang et al., "A highly visible-transparent thermochromic smart window with enhanced solar regulation," 2024.
12. Y. Shi and S. Gyanchandani, "Hygroflex: A prototype of a water-responsive facade system with an innovative integration of timber and biopolymer," in *Computational Design and Robotic Fabrication*, Springer, 2025.
13. S. Bal et al., "Next generation building materials for energy efficiency and sustainable construction," 2025.
14. S. Barbhuiya et al., "Smart materials, energy efficiency and environmental impact," 2025.
15. Laafer et al., "Comprehensive review of phase change materials for building applications," *Energies*, vol. 19, no. 5, Art. no. 1151, 2026.
16. K. Jiao et al., "Towards passive building thermal regulation: A state-of-the-art review of phase change materials in building envelopes," *Sustainability*, vol. 16, 2024.

17. U.S. Department of Energy, “Building Envelope,” Better Buildings & Better Plants Initiative. The agency reports that envelope technologies are associated with approximately 30% of primary energy consumed in residential and commercial buildings.
18. U.S. Department of Energy, “Opaque Envelope,” Building Technologies Office. DOE reports that opaque-envelope elements influence approximately 28% of building energy use.