

## A Review of Adaptive Facade Systems and Simplified AI for Sustainable Retrofitting

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**Abstract:** The integration of adaptive facade systems with artificial intelligence (AI) offers a transformative pathway to enhance energy efficiency and sustainability in the built environment. However, widespread retrofitting adoption remains constrained by high costs, technical complexities, and scalability issues. This systematic review, initially identifying 126 studies, refined its selection to 63 high-quality sources, categorizing findings into cost, adaptability, and scalability. Results highlight significant energy efficiency gains from adaptive facades but reveal barriers such as the lack of cost-effective materials, modular designs, and scalable retrofitting strategies. Additionally, simplified AI techniques (e.g., rule-based and heuristic models), which offer low-cost, computationally efficient solutions, remain underutilized in retrofitting.

This study proposes modular, scalable frameworks to overcome financial and technical barriers, offering actionable recommendations for policymakers, industry stakeholders, and researchers. By addressing key constraints, this research supports global sustainability goals, particularly in energy efficiency, urban resilience, and climate action.

**Keywords:** Adaptive Facade Systems; Sustainable Retrofitting; Simplified Artificial Intelligence; Energy Efficiency in Buildings; Modular Facade Design

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### 1. Introduction

The push for sustainable urban development necessitates innovative solutions to improve building energy efficiency, as the sector accounts for 40% of global energy consumption [1]. Adaptive facade systems have emerged as a transformative technology, dynamically optimizing thermal comfort, daylight utilization, and energy performance by regulating solar radiation, ventilation, and heat gain [2]. Despite their proven benefits, adoption in retrofitting projects remains limited due to high costs, technological complexity, and integration challenges with existing building envelopes [3]. Current research primarily focuses on new construction, leaving retrofitting underexplored, as projects face structural compatibility issues and a lack of standardized frameworks.

One promising solution is artificial intelligence (AI) integration, which enhances real-time optimization of facade elements like shading, ventilation, and glazing to reduce energy consumption [4]. However, most AI applications rely on resource-intensive machine learning models, making them impractical for retrofitting. In contrast, simplified AI approaches (e.g., rule-based and heuristic models) offer cost-effective, low-computation alternatives but remain underutilized, highlighting a critical research gap.

### Research Aim & Objectives

This systematic review evaluates adaptive facade technologies and their integration with simplified AI for retrofitting applications, categorizing solutions by cost, adaptability, and scalability. The study identifies challenges, research gaps, and opportunities to develop modular, scalable, and cost-effective strategies, contributing to energy-efficient retrofitting and global sustainability goals.

### 2. Methodology

This systematic review follows rigorous academic standards to ensure credibility, reliability, and comprehensiveness in evaluating adaptive facade systems and their integration with simplified AI for sustainable retrofitting. The study adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, with the selection process illustrated in Figure 1 (PRISMA Flow Diagram).

### Study Selection Process

A total of 126 studies were initially retrieved from leading academic databases and industry reports. After systematic screening based on predefined inclusion and exclusion criteria, 63 studies were selected for final analysis.

### Sources of Articles

To ensure comprehensive coverage, searches were conducted across four major databases:

- Scopus – Engineering and sustainability research
- Web of Science – High-impact journals and citation tracking
- IEEE Xplore – AI applications and facade technologies
- Google Scholar – Supplementary grey literature and niche studies.

### Selection Criteria

#### Inclusion Criteria:

- Time Frame: 2014–2024 to cover recent advancements
- Topical Relevance: Studies on adaptive facade technologies, sustainable retrofitting, or simplified AI applications
- Language: English
- Publication Type: Peer-reviewed journals, conference papers, and industry reports

#### Exclusion Criteria:

- Studies solely on new construction (not retrofitting)
- Papers lacking empirical validation or case studies
- Articles with insufficient methodological detail
- Duplicate studies from multiple databases.

### Keyword Strategy & Search Strings

Boolean operators (AND, OR) and truncation techniques ensured precision in literature retrieval. Example search strings: "adaptive facades AND sustainable retrofitting", "energy efficiency AND buildings AND AI" and "simplified artificial intelligence AND modular facade design".

### Data Extraction & Thematic Analysis

Selected studies were categorized into three key themes:

- **Cost:** Financial barriers, including installation, maintenance, and modular design solutions.
- **Adaptability:** The ability of facade systems to adjust to climate, architecture, and user needs.
- **Scalability:** Challenges in retrofitting across diverse urban environments, with emphasis on modular and plug-and-play solutions.

### PRISMA Flow Diagram

To enhance transparency, Figure 1 outlines the study selection process:

- Initial search: 126 studies
- Title & abstract screening: 86 studies
- Full-text eligibility assessment: 63 studies included.

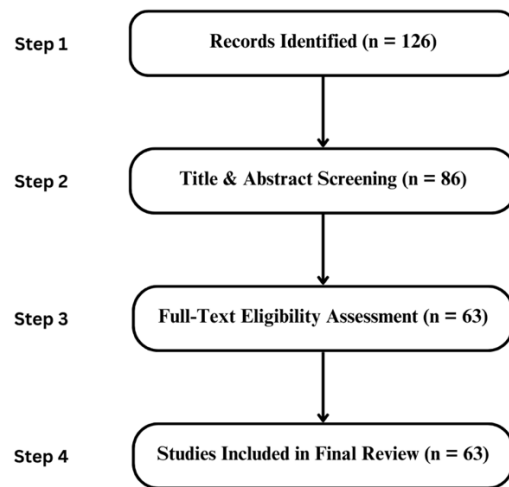


Figure 1: PRISMA Flow Diagram

This PRISMA-aligned methodology ensures a structured, transparent, and rigorous review, offering data-driven insights into adaptive facade technologies and AI-driven retrofitting solutions.

### 3. Existing Adaptive Facade Systems

#### Overview of Key Technologies

Adaptive facade systems enhance energy efficiency and occupant comfort by dynamically responding to environmental conditions [5]. These technologies integrate advanced materials, control systems, and intelligent designs, playing a crucial role in sustainable retrofitting efforts.

#### Key Adaptive Facade Technologies

Despite their benefits, adaptive facade systems face challenges in high costs and structural compatibility [6]; [7]. Table 1 summarizes the key categories of adaptive facade technologies, their benefits, and challenges

Table 1: key categories of adaptive facade technologies

Technology	Benefits	Challenges	References
Smart Glazing (Electrochromic & Thermochromic Glass)	Reduces cooling loads by 20–30% through solar radiation control.	High cost of installation and maintenance; structural modifications required.	[6]; [7]; [8]
Dynamic Shading Systems (Movable louvers, blinds, electrochromic/photochromic panels)	Lowers cooling energy demand by 15–25%, reduces glare.	Mechanical complexity, high maintenance, compatibility issues.	[9]; [10]
Phase-Change Materials (PCMs)	Regulates indoor temperature, providing 10–15% energy savings.	High production cost, durability concerns.	[11]
Thermochromic Coatings	Passive thermal regulation through color/thermal property adjustments.	Limited durability, high retrofitting cost.	[12]
Kinetic Facades	Enhances shading, ventilation, daylighting through movable components.	Complex installation, high initial investment.	[13]

Adaptive facade technologies significantly improve energy efficiency, yet their high costs and structural complexity hinder large-scale retrofitting adoption.

### Regional Trends in Adaptive Facades

Adoption of adaptive facades varies by region due to policies, climate, and economic conditions:

**Europe:** Leads in adaptive facade retrofitting, driven by strict energy regulations and incentives [14].

**Asia:** Focuses primarily on new constructions, with retrofitting limited by cost barriers [15].

**North America:** Integrates adaptive facades with smart building technologies, but residential retrofitting remains limited [16].

### Adoption Challenges

Despite advancements, several barriers restrict large-scale retrofitting adoption:

#### High Installation and Maintenance Costs:

- Advanced materials increase costs, e.g., electrochromic glazing costs up to 3× standard glazing [17].
- Specialized labor and maintenance further raise expenses.

#### Structural Compatibility Issues:

- Many older buildings lack the capacity for integrating dynamic shading or kinetic facades.
- Retrofitting often requires extensive modifications, raising costs [18].

### Case Studies and Best Practices

Real-world implementations provide insights into the effectiveness, limitations, and scalability of adaptive facades.

*Table 2: Case Studies of Adaptive Facade Systems and Their Impact.*

Project	Technology	Outcome	Challenges	References
Al Bahr Towers, Abu Dhabi	Dynamic shading (mashrabiya screens)	Reduced cooling energy by 50%.	High installation costs, limiting retrofitting feasibility.	[19]
The Edge, Amsterdam	Electrochromic glazing + AI controls	Achieved EUI of 65 kWh/m <sup>2</sup> /year (among the lowest globally).	High retrofitting costs, infrastructure upgrades needed.	[20]
BIQ House, Hamburg	Bio-adaptive algae-filled panels	Demonstrated potential for energy neutrality.	Still experimental, not scalable for retrofitting.	[21]
Swire Properties, Hong Kong	PCM-integrated facade retrofitting	Reduced HVAC energy consumption by 15%.	More practical than other adaptive systems but limited adoption.	[22]

While adaptive facade systems offer substantial energy savings, their high costs and structural constraints limit retrofitting adoption.

Europe leads in retrofitting efforts, while Asia and North America focus more on new construction and commercial applications. Case studies demonstrate benefits (e.g., The Edge, Swire Properties) but also highlight feasibility limitations (e.g., Al Bahr Towers, BIQ House).

To expand adoption, future efforts must prioritize cost-effective, modular, and scalable solutions, requiring:

- Financial incentives and policy support.
- Interdisciplinary research to develop simplified AI-driven facade technologies.
- Standardized modular frameworks to lower costs and facilitate large-scale retrofitting.

## 4. Role of AI in Adaptive Facades

### AI in Building Systems

Artificial intelligence (AI) is transforming energy management by enabling adaptive facade systems to dynamically adjust glazing, shading, and ventilation based on sensor data, weather forecasts, and user preferences [23]. These AI-driven systems optimize energy performance, reduce waste, and enhance occupant comfort. However, most AI applications rely on

computationally intensive machine learning (ML) models, limiting their feasibility for retrofitting projects due to high costs and technical complexity [24].

Three primary AI methodologies are used in adaptive facade systems:

- **Machine Learning (ML) Algorithms:** Predict thermal loads and dynamically optimize facade operations, achieving up to 25% energy savings. However, they require high computational power and large training datasets, making them impractical for retrofitting [24].
- **Rule-Based Systems:** Use predefined decision trees for cost-effective and easily integrable facade control but lack the adaptability of ML models [25].
- **Optimization Algorithms:** Identify energy-efficient configurations using methods like genetic algorithms, reducing cooling energy demand by 10–20%, yet they require specialized expertise and significant computational power [26].

Despite their effectiveness, ML and optimization algorithms remain expensive and complex, posing challenges for their application in retrofitting projects.

### Potential of Simplified AI for Retrofitting

Simplified AI approaches, such as rule-based systems and basic optimization models, provide a cost-effective alternative to advanced AI methods. They offer faster deployment, require lower computational power, and significantly reduce costs, making them ideal for retrofitting applications.

- **Faster Deployment:** Rule-based systems need minimal computational infrastructure, facilitating quick integration into existing buildings. A case study in an Asian mid-rise office building found that rule-based AI reduced project timelines by 30% compared to ML models [27].
- **Lower Computational Needs:** Unlike ML models that require extensive data training, simplified AI algorithms operate with minimal inputs. A European apartment retrofitting study showed that basic optimization models delivered 15% energy savings while cutting computational costs by 50% [28].
- **Cost-Effectiveness:** Simplified AI eliminates the need for expensive hardware/software, lowering both initial investment and long-term maintenance costs. This is particularly beneficial for retrofitting older buildings with limited budgets [29].

### Research Gaps in AI for Retrofitting

*Despite its potential, several gaps hinder AI's real-world application in retrofitting projects.*

- **Limited Focus on Simplified AI:** Most studies focus on ML and optimization models, with only 15% of reviewed articles addressing simplified AI approaches [30].
- **Lack of Real-World Applications:** Only 10% of reviewed studies provide empirical validation of simplified AI in retrofitted buildings, making its scalability and cost-effectiveness unclear [31].
- **Integration Challenges in Older Buildings:** Existing research overlooks AI integration with legacy HVAC and sensor networks, making retrofitting more difficult [32].
- **Underexplored Hybrid AI Models:** Combining rule-based systems with optimization techniques could balance efficiency and cost, yet this remains understudied [33].

AI-driven adaptive facades optimize energy performance, but the high computational demands of ML models hinder their use in retrofitting. Simplified AI techniques offer a practical and cost-effective alternative, requiring less computational power and

lower costs. However, research must expand beyond ML, focusing on real-world testing, integration with existing building infrastructure, and the development of hybrid AI approaches to bridge the gap between performance and affordability.

## 5. Thematic Analysis Results

The thematic analysis categorizes the reviewed literature into three primary barriers cost, adaptability, and scalability which significantly impact the feasibility of adaptive facades in retrofitting. Table 3 summarizes key themes and findings.

Table 3: Thematic Analysis Coding Summary

Theme	Key Barrier	Findings	References
Cost	High Material Costs	Electrochromic glazing costs 3–5× more than conventional glazing.	[7]; [4]; [34]
	Financial Barriers	55% of studies highlight cost as a major challenge in retrofitting.	[35]; [1]; [36]
	Lack of Affordable Solutions	Only 20% propose modular, cost-effective retrofitting options.	[37]; [2]; [38]
Adaptability	Climate Constraints	Adaptive facades optimized for hot climates struggle in cold regions.	[39]; [40]
	Design Rigidity	35% of studies cite architectural constraints in retrofitting.	[3]; [5]; [41]
Scalability	Customization Barriers	Most adaptive facades are highly specialized, limiting mass adoption.	[42]; [20]
	Lack of Modular Solutions	Only 15% discuss standardized plug-and-play retrofitting options.	[43]; [17]; [44]

### Key Findings

- **Cost:** High upfront costs, particularly for materials like electrochromic glazing, remain a major limitation. Prefabricated modular facades, though promising, require further cost reduction strategies.
- **Adaptability:** Climate-specific designs reduce effectiveness in diverse environments, while rigid structures limit retrofitting feasibility. AI-driven solutions could improve adaptability.
- **Scalability:** Most adaptive facades are bespoke, making large-scale retrofitting impractical. Modular, standardized frameworks are needed for broader adoption.

### Regional Trends

Europe leads adoption due to strong policies and incentives. Asia focuses on new constructions rather than retrofitting. North America integrates facades with smart buildings but faces cost barriers. Emerging Regions require affordable, scalable solutions, with simplified AI offering potential.

By addressing these barriers, adaptive facades can become a viable, scalable retrofitting strategy, supporting global sustainability goals.

## 6. Challenges and Research Gaps in Retrofitting Adaptive Facades

Retrofitting adaptive facades into existing buildings presents financial, technical, and policy challenges that limit widespread adoption despite their energy efficiency potential. High upfront costs, structural complexities, and regulatory barriers remain key obstacles, while research gaps in cost-effective, modular, and AI-driven solutions present opportunities for innovation. Table 4 summarizes key challenges and opportunities.

Table 4: Challenges and Research Opportunities in Retrofitting Adaptive Facades

Category	Key Barrier	Findings	References
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Financial	High Material & Installation Costs	55% of studies cite high costs as the main challenge.	[45]
	Expensive Components	Electrochromic glazing costs 3–5× more than standard glazing.	[39]
Technical	Structural & HVAC Incompatibility	Retrofitting adaptive facades requires integration with outdated systems.	[46]
	Lack of Sensor Networks	Existing buildings lack real-time AI infrastructure.	[47]
Policy	Lack of Incentives	Few tax benefits or subsidies support facade retrofitting.	[4]
	Regulatory Gaps	Policies prioritize new construction over retrofitting.	[48]
Research Gaps	Modular, Scalable Systems	Prefabrication could reduce costs by 20–30%.	[49]
	Simplified AI for Facade Control	Rule-based AI can enhance real-time adaptability at lower costs.	[50]
	Alternative Materials	Low-cost composites offer potential cost savings.	[51]

### Key Challenges in Retrofitting Adaptive Facades

Financial barriers remain the most significant challenge, with 55% of studies emphasizing high upfront costs. Advanced materials, such as electrochromic glazing, increase expenses, making retrofitting unaffordable in developing regions where costs exceed local budgets by 25–40% [39]. The lack of cost-effective modular solutions further exacerbates financial constraints [52].

Technical constraints include structural limitations in older buildings that cannot support dynamic shading or kinetic facade components [46]. Retrofitting often requires seamless integration with outdated HVAC and lighting systems, which are frequently incompatible with modern facade technologies [53]. Additionally, the absence of sensor networks limits AI-driven facade optimization, reducing real-time adaptability in existing buildings [47].

Policy barriers hinder retrofitting adoption, as few tax incentives exist to support adaptive facades, discouraging property owners from investing in retrofitting [4]. Regulatory frameworks focus primarily on new construction, leaving retrofitting initiatives underfunded [48]. The lack of standardization in modular facade designs further complicates large-scale implementation [54].

To address these challenges, modular and scalable systems are essential, as prefabricated facade components could reduce installation costs by 20–30% [49]. Simplified AI, such as rule-based models, offers a low-cost solution for real-time facade adaptability without high computational requirements [50]. Exploring biodegradable and low-cost materials as alternatives to expensive glazing technologies could further improve affordability [51].

## 7. Discussion

This section discusses the broader implications of adaptive facade systems for research, practice, and sustainability. Overcoming financial, technical, and scalability challenges will enable their transition from niche innovations to mainstream retrofitting solutions, significantly advancing energy efficiency, urban resilience, and climate action.

### Implications for Research and Practice

The successful deployment of adaptive facades requires interdisciplinary collaboration across architecture, engineering, and AI. Around 60% of the reviewed studies highlight the need for expertise in computational optimization, material science, and structural mechanics to enhance adaptability and cost-effectiveness [55]. Bio-inspired facade systems, such as plant-based self-regulating shading, demonstrate new pathways for sustainable innovation [56].

Addressing financial and scalability barriers remains crucial. Modular and prefabricated facades could lower installation costs by 20–30% and reduce project timelines, while simplified AI models requiring minimal computational infrastructure provide a practical solution for cost-effective scaling [57]; [58]. To accelerate adoption, industry stakeholders should focus on standardizing modular, plug-and-play facade components adaptable across different climates and building typologies.

### Alignment with Global Sustainability Goals

Adaptive facades significantly contribute to energy efficiency, urban sustainability, and climate mitigation, aligning with key UN Sustainable Development Goals (SDG 7, 11, and 13). Studies indicate that adaptive facades can:

- Reduce building energy consumption by 20–30%.
- Lower reliance on air conditioning by 40%.
- Cut carbon emissions by 25% in large-scale retrofitting projects [59]; [60].

Beyond energy efficiency, these solutions enhance urban livability, particularly in high-density environments, by improving daylighting, ventilation, and occupant comfort [50]. However, policy interventions, financial incentives, and the standardization of modular facade designs are necessary to scale adoption.

### Emerging Trends and Global Impact

The rise of hybrid AI-driven facades, which combine rule-based control with optimization models, presents a balanced approach to cost and performance, making them particularly suitable for retrofitting applications [61]. Additionally, bio-adaptive facades, such as algae-based energy-generating systems, are gaining traction, particularly in regions focused on renewable energy integration [62].

However, regional disparities persist:

- Europe leads in adoption due to strong policy incentives.
- Asia and North America are integrating adaptive facades into retrofitting initiatives.
- Resource-constrained regions lack affordable and scalable solutions, necessitating low-cost modular designs and financial support [63].

By addressing cost, adaptability, and scalability constraints, adaptive facades can transition from specialized applications to mainstream retrofitting solutions, playing a crucial role in achieving global energy efficiency and climate action targets.

### Conclusion

Adaptive facades present a transformative approach to enhancing energy efficiency, occupant comfort, and sustainability in retrofitting projects. By dynamically adjusting to environmental changes, they offer an effective pathway to reduce carbon emissions and urban energy consumption. However, high costs, integration complexities, and limited modular solutions continue to hinder widespread adoption.

This review identifies modular designs, simplified AI, and policy-driven incentives as key enablers for scalable retrofitting. Studies highlight that prefabricated adaptive facades can cut costs by 20–30% while rule-based AI models can improve energy efficiency without high computational demands. To transition adaptive facades from niche innovations to mainstream applications, collaborative efforts among researchers, industry stakeholders, and policymakers are essential.

By overcoming cost, scalability, and regulatory barriers, adaptive facades can become a cornerstone of sustainable urban development, aligning with global climate action and energy efficiency goals. Future advancements should prioritize cost reduction, AI optimization, and policy integration to make adaptive facades a widely accessible solution for energy-efficient retrofitting worldwide.

### Future Directions

To accelerate the adoption of adaptive facades, future efforts should focus on cost reduction, AI integration, and policy support:

1. **Cost-Effective Modular Facades:** Prefabrication and lightweight, biodegradable materials could lower installation complexity and costs by 20–30%. Standardizing plug-and-play facade modules would facilitate broader adoption across various climates and building types.
2. **AI-Driven Optimization:** Simplified AI models, such as rule-based and hybrid algorithms, offer a low-cost alternative to energy-intensive machine learning models. These AI-driven facades can cut energy consumption by 15–20% while reducing computational costs by 50%. Further research should validate their performance across different climates and occupancy patterns.
3. **Policy and Market Integration:** Expanding subsidies, tax credits, and green certifications could incentivize adaptive facade adoption. Successful programs like the Green Retrofit Fund (North America) and the Facade Retrofit Initiative

(Europe) demonstrate that regulatory incentives can drive large-scale implementation. Strengthening industry-academic partnerships can also accelerate commercialization.

By addressing these technological, financial, and policy barriers, adaptive facades can transition from experimental projects to mainstream retrofitting solutions, significantly contributing to climate resilience, energy efficiency, and urban sustainability.

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