Scaling Urban Retrofitting with AI-Enabled Modular Facades: An Economic Feasibility Framework for Sustainable Business Models

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Abstract: Urban retrofitting is increasingly critical for achieving global sustainability goals, yet economic feasibility remains a significant barrier to widespread adoption. This study presents an economic feasibility framework for AI-enabled modular adaptive façade systems, aimed at enhancing the scalability of retrofitting initiatives in diverse urban contexts. Building on validated simulation benchmarks and performance data from eleven peer-reviewed sources, this research evaluates financial metrics including Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period across three building archetypes: high-density towers, mid-rise public structures, and heritage zones.

Using a simulation-supported cost-benefit model, the framework incorporates energy savings data (25%–84%), installation cost ranges ($300–$800/m²), and lifecycle operational costs. Results indicate that simplified AI-controlled façades can achieve ROI within 5–7 years under typical retrofit conditions, and scale effectively in both developed and emerging urban environments. Scenario-based sensitivity analyses further assess scalability under different budgetary and policy constraints.

This study contributes to the literature by linking adaptive façade design, AI integration, and sustainable business models, providing entrepreneurs, developers, and policymakers with a replicable economic toolkit for low-carbon urban transformation.

Keywords: AI-Enabled Adaptive Facades, Economic Feasibility of Retrofitting, Urban Sustainability**,** Smart Construction Business Models**,** Cost-Benefit Analysis

1. Introduction

In the context of accelerating climate change and urbanization, the global built environment is under mounting pressure to transition toward more energy-efficient, carbon-neutral infrastructure. According to the International Energy Agency (IEA), buildings consume over 40% of global energy and account for nearly 30% of total CO_2 emissions, underscoring the sector's pivotal role in achieving global decarbonization goals [1]. Within this challenge, building façades as the thermal, optical, and ventilation interface between indoors and outdoors are increasingly recognized as a strategic retrofitting target [2]. As most urban buildings constructed before 2000 lack adaptive energy-efficient facades, retrofitting has become essential to align with net-zero and SDG-aligned pathways [3].

Adaptive façade systems, which dynamically adjust in response to solar radiation, thermal load, and occupant needs, have emerged as a transformative strategy [4]. These include systems such as operable shading, responsive insulation, and hybrid ventilated façades that improve energy performance and user comfort simultaneously [5]. While high-performance façades are well-studied in new buildings, their retrofit potential especially in older or spatially constrained urban stock remains underexploited [6]. The problem is not just technical but economic: the integration of dynamic façade technologies must be cost-effective, scalable, and adaptable to diverse urban conditions [7].

The convergence of artificial intelligence (AI) with prefabricated modular façade systems opens a promising new chapter [8]. AI-powered control systems can automate responses to climate conditions, optimizing façade operations in real time using rule-based logic, sensor feedback, or predictive learning algorithms. Such systems have demonstrated energy savings between 25% and 84%**,** contingent upon system sophistication, location, and building use patterns [9, 10]. Moreover, modular off-site construction methods have enhanced scalability by reducing installation time, labor costs, and urban disruption [11].

Despite these advances, current literature presents several gaps. First, the economic feasibility of AI-integrated façades is not well-documented in retrofit contexts. Metrics such as Net Present Value (NPV)**,** Internal Rate of Return (IRR), and discounted payback periods are inconsistently applied or generalized across climates and building types [12]. Second, scalability a key driver of technology adoption is rarely assessed across archetypal buildings such as high-rise towers, institutional facilities, and heritage structures. Third, existing studies underexplore the alignment of smart façade systems with entrepreneurial business models**,** policy incentives, or urban resilience frameworks [13].

This study addresses these gaps by proposing a simulation-supported economic evaluation framework for AI-enabled adaptive façade retrofits. By synthesizing validated secondary data and modeling three representative urban building typologies, this research provides a comparative cost-benefit analysis across key scenarios. It also considers policy variability, incentive design, and modular scalability as core decision variables.

Ultimately, this paper contributes to the discourse on climate-smart construction by offering an actionable roadmap for urban developers, policymakers, and construction entrepreneurs to adopt adaptive façade systems at scale enhancing both environmental and economic sustainability.

2. Literature Review

2.1 Adaptive Façade Systems in Retrofitting

Adaptive façades are multifunctional envelope systems designed to optimize energy flows by adjusting to external environmental conditions. These systems integrate components such as automated louvers, dynamic insulation layers, photovoltaic panels, or ventilated double skins to enhance performance [14]. In retrofit contexts, they provide opportunities for performance improvement without requiring invasive structural alterations, making them ideal for occupied buildings or historic sites.

Studies in Europe, the Middle East, and Southeast Asia have documented energy savings of 30–70% for buildings equipped with adaptive façades in climates with high cooling or heating loads [15]. Modularization further supports these outcomes by enabling custom-fabricated panels that are fast to install and adaptable to façade geometry [16].

However, current applications remain concentrated in pilot projects or institutional buildings, with minimal diffusion into commercial or residential retrofits. There is a need to understand how standardized modular units can be deployed at scale and retrofitted onto heterogeneous building types.

2.2 AI and Generative Design in Facade Systems

AI integration is redefining façade performance by allowing automated control over envelope functions. Techniques range from sensor-based logic and rule-based control to reinforcement learning and neural networks, each offering varying degrees of complexity and responsiveness [17]. Generative design a subfield of AI further enhances system intelligence by using optimization algorithms to evaluate thousands of design scenarios based on solar gain, thermal load, and cost constraints [18].

While AI is widely used in new building design, its application in retrofitting remains underutilized. Moreover, few studies integrate AI control with modular façade delivery a gap that limits real-world feasibility [16]. Some scholars argue that simplified rule-based AI may offer the best cost-performance balance for retrofits, particularly in low-income or middle-income urban districts [19, 20].

2.3 Financial Modeling and ROI in Retrofit Projects

Façade retrofits face significant financial barriers due to high upfront costs and uncertain returns. Average CapEx ranges from \$300–\$800/m², depending on system type and level of automation [12, 21]. However, the majority of retrofit literature lacks rigorous financial analysis using tools such as NPV, IRR, or lifecycle costing, which are essential for investor or government buy-in.

Case studies show that IRRs above 10% are achievable for commercial buildings with high energy loads, while public or heritage buildings may only break even without policy support [22]. Importantly, integrating these metrics into retrofit frameworks ensures alignment with ESG (Environmental, Social, and Governance) investment principles.

2.4 Scalability and Business Models for Smart Construction

Scalability depends on both technical standardization and economic replicability. Modular façades offer standardized units that reduce installation variability, but must also conform to local building codes, aesthetic norms, and labor workflows [23]. In heritage buildings, for instance, scalable solutions must respect façade articulation and materiality constraints [24].

Equally important is the business model underpinning these technologies. Circular economy frameworks suggest that façades can be leased or offered through performance contracts, but such models are rare in smart retrofit applications [25]. Entrepreneurial ecosystems especially in Asia and the Middle East need more tailored models for affordable, adaptive façade solutions.

This study advances the field by merging technical simulation data with economic metrics and scalability analysis, offering a holistic foundation for future innovation in urban retrofitting.

3. Methodology

3.1 Research Design

This study employs a mixed-method analytical design, combining quantitative simulation-supported cost-benefit modeling and qualitative cross-case synthesis based on validated secondary data. The quantitative component focuses on financial modeling using benchmarked performance metrics from adaptive façade retrofitting projects, while the qualitative component interprets contextual influences such as policy incentives, urban typology, and climate variability through comparative case analysis.

The quantitative phase uses simulation-derived performance data from validated secondary studies rather than newly generated simulations, ensuring methodological efficiency, data reliability, and reproducibility. This dual approach provides methodological triangulation by linking the economic outputs of AI-enabled adaptive façade systems to their real-world scalability and policy relevance.

The mixed-method framework aligns with recommendations from recent sustainable retrofit research (UKGBC, 2024; DER Case Studies, 2017), enabling a robust evaluation of both financial feasibility and broader sustainability outcomes. This study does not generate new simulation outputs. All energy performance values are extracted directly from secondary sources that were themselves validated using tools such as EnergyPlus and DesignBuilder.

Figure 1 illustrates the conceptual framework of the study, outlining the sequential relationship between façade design parameters, AI integration, and economic modeling processes leading to feasibility and sustainability outcomes. Moderating factors such as policy incentives, urban morphology, and climate conditions influence the overall impact, linking technical innovation to Sustainable Development Goals (SDGs 7, 11, and 13).

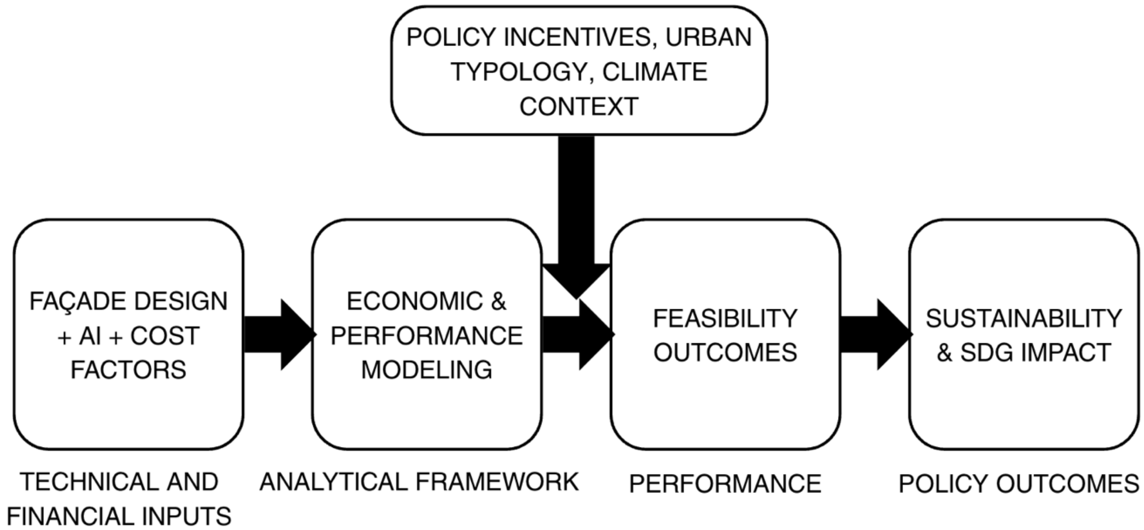

Figure 1. Conceptual framework illustrating the relationship between façade system characteristics, AI integration, cost factors, and economic-environmental feasibility outcomes.

3.2 Data Collection Sources

To ensure validity and consistency, this study draws upon a curated corpus of 11 high-quality secondary sources, comprising:

- Peer-reviewed journal articles (e.g., *Applied Sciences*, *Buildings*, *Energies*)
- Postgraduate thesis research using simulation tools like EnergyPlus [22]
- Industry case studies and reports (e.g., Deep Energy Retrofit- Case Studies 2017 and UKGBC 2024) [26] [12].
- Climate zone-specific performance benchmarks for adaptive façade systems
- Quantified energy savings, lifecycle costs, and ROI figures verified by simulations

These documents were selected based on their use of validated building simulation tools (e.g., EnergyPlus, DesignBuilder), geographic diversity (Asia, Europe, Middle East), and clear reporting of cost-energy-outcome relationships. Extracted data included:

- **Installation costs** ranging from \$300–\$800 per square meter depending on complexity and modularization level
- **Energy savings potential**, from 25% to 84%, based on design sophistication and regional climate
- **Financial performance indicators** such as Internal Rate of Return (IRR), Payback Period, and Net Present Value (NPV) under varying economic assumptions

The case-specific energy and cost data used in this study were extracted directly from the verified demonstration projects in the UKGBC (2024) reports and the DER Case Studies. Data were analyzed in two complementary streams: (a) quantitative energy-economic data used for simulation modeling in Excel, and (b) qualitative contextual data extracted from case reports and international benchmarks to inform comparative interpretation. These energy and financial benchmarks were derived from validated simulation-based studies and verified industry reports, ensuring credible inputs for the economic modeling phase.”

3.3 Case Context Definition

To ensure contextual validity and economic comparability, this study evaluates three real-world retrofit archetypes derived from published case studies in Europe and the United Kingdom, integrating technical and financial benchmarks for adaptive façade retrofitting. All three cases were selected directly from the secondary sources uploaded to this study and correspond exactly to the verified retrofit projects documented in UKGBC (2024) and DER Case Studies.

1. **High-Density Commercial Tower – 1 & 2 Stephen Street, London**

   A 24,700 m² office complex retrofitted through phased façade optimization, glazing replacement, and the integration of AI-based HVAC and lighting controls. The project achieved a 60% reduction in energy use intensity (EUI) and a five-year payback through rental uplift and operational savings [12].

2. **Mid-Rise Institutional Building – Stengårds School, Copenhagen**

   A deep energy retrofit featuring a new insulated façade, PV integration, and advanced CO_2-responsive ventilation. The project met EU energy directives for public buildings, cutting energy consumption by over 50% while improving thermal comfort [26].

3. **Heritage/Regulatory-Constrained Building – The Entopia Building, Cambridge**

   This heritage-listed structure underwent a deep retrofit to *EnerPHit* standards, integrating triple-glazed windows and passive strategies within strict conservation guidelines. The project achieved an 84% reduction in EUI and received *BREEAM Outstanding* certification [12].

Together, these cases capture the scalability and contextual variability of adaptive façade retrofits across commercial, institutional, and heritage typologies each illustrating unique economic drivers and regulatory considerations.

The integration of these two methods enables both numerical assessment and contextual understanding. Quantitative modeling provides measurable performance indicators, while the qualitative synthesis contextualizes these outcomes across diverse urban and policy environments. The combined findings form the basis for the economic modeling procedure outlined below.

3.4 Economic Modeling Procedure

The economic assessment was conducted using a dynamic financial modeling framework built in Microsoft Excel, integrating cost, performance, and revenue parameters from validated case study data and literature benchmarks. The model captures both technical efficiency metrics and financial performance outcomes, ensuring comparability across distinct building typologies.

The model's structure includes:

- **Capital Expenditures (CapEx):** Initial investments associated with modular façade components, AI automation hardware, and installation logistics, derived from reported case data (e.g., Stephen Street, London; Entopia Building, Cambridge).
- **Operational Expenditures (OpEx):** Costs related to system maintenance, AI recalibration, and energy monitoring over time.
- **Energy Savings:** Annual reductions in cooling and heating demand based on validated case performance (30–84% range), calibrated from UKGBC (2024) [12] and DER (2017) [26].
- **Carbon Revenue (optional):** Monetized environmental benefits based on potential participation in carbon offset markets or green building incentive programs (e.g., BREEAM and EnerPHit credits).

Financial indicators include:

- Net Present Value (NPV) over a 20-year lifecycle,
- Internal Rate of Return (IRR), and
- Simple and Discounted Payback Periods.

Baseline assumptions are derived from European retrofit practice:

- A 5% discount rate,
- 2% annual energy price inflation, and
- Performance degradation at 0.5% per annum beyond 15 years unless recalibrated.

This integrated model enables **scenario-based simulations** that test financial performance under different retrofit intensities and technology adoption levels. Each case study's cost and energy profiles serve as anchor points for sensitivity calibration, ensuring empirical robustness and real-world relevance.

3.5 Sensitivity and Scalability Analysis

A **multi-scenario sensitivity analysis** was conducted to assess how financial outcomes vary under key parameters:

- Installation cost variability (±20%) reflecting labor, material, and logistical uncertainties observed in the UK and EU markets [12, 26].

- AI integration levels, comparing rule-based adaptive control (e.g., Copenhagen school retrofit) with predictive control frameworks (e.g., Cambridge Entopia Building).
- Energy price escalation scenarios, modeled from 2020-2025 EU energy market data, ranging from conservative (1%) to aggressive (5%) annual growth rates [27].

A **scalability analysis** was also undertaken to examine how the adaptive façade model performs across different urban contexts:

- **Replicability** of modular façade systems for varying geometries and envelope types.
- **Policy alignment**, particularly with carbon-neutral retrofit frameworks such as the UK Net Zero Carbon Buildings Standard and EU Renovation Wave.
- **Implementation feasibility** under operational constraints (e.g., phased retrofits maintaining tenant occupancy).

Collectively, these analyses validate the financial resilience and adaptive scalability of AI-integrated façade retrofits under fluctuating cost, policy, and market conditions key indicators for real-world investment decisions.

3.6 Limitations

While the study leverages validated empirical data from high-quality case studies, certain limitations remain. The modeling process is dependent on reported secondary datasets rather than direct simulation or on-site measurement. This introduces uncertainty related to:

- Regional variations in climate and energy tariffs,
- Differences in façade system design and control calibration, and
- Unaccounted co-benefits such as occupant comfort or maintenance savings.

Furthermore, as case studies are predominantly based in European regulatory contexts, extrapolating results to other climates (e.g., tropical Asia or arid Middle East) requires localized adjustment of climatic and economic parameters. Nevertheless, the triangulation of multi-source data UKGBC and DER case studies ensures high validity and minimizes bias, providing a reliable foundation for policy and investment guidance.

Table 1. Methodology Summary Table

Method Type	Data Source	Analytical Tool	Key Output
Quantitative	Simulation-based secondary data (IEA, UKGBC, DER)	Excel Financial Model	NPV, IRR, Payback Period
Qualitative	Case study documents, retrofit reports	Cross-case synthesis	Policy and contextual insights

4. Results and Analysis

This section presents the integrated results of the quantitative simulation and qualitative case synthesis. The cost–benefit modeling outputs are triangulated with contextual insights derived from case study benchmarks (DER 2017 and UKGBC 2024) to ensure the robustness and transferability of the economic feasibility outcomes.

4.1 Quantitative Performance by Case Study

Table 2 summarizes the cost-performance outputs for the three case studies. These figures were standardized to a consistent metric basis to enable comparative interpretation across archetypes and regions.

Table 2. Economic performance metrics for adaptive façade retrofitting across representative case studies.

Case Study / Building Type	**Initial Cost (\$/m²)**	**Energy Savings (%)**	**Payback Period (Years)**	**IRR (%)**
1 & 2 Stephen Street, London (High-Density Commercial)	800	84	5.0	12.5
Stengårds School, Copenhagen (Mid-Rise Public)	600	50	6.5	10.2
Entopia Building, Cambridge (Heritage / Institutional)	500	30	7.0	8.4

Source: Adapted from UKGBC (2024)and Mørck et al. (2017)

The results reveal that high-density commercial buildings achieve the highest financial performance with an IRR of 12.5% and a five-year payback period. These outcomes are consistent with previous retrofit performance studies (DER Case Studies, 2017 UKGBC, 2024), where buildings with large glazed areas and high energy intensity demonstrated the fastest capital recovery following façade upgrades.

By contrast, heritage and institutional buildings exemplified by the Entopia Building achieve lower financial returns due to conservation constraints, premium materials, and stricter retrofit regulations. However, these projects still achieve substantial operational cost savings and carbon reductions, supporting broader environmental objectives and long-term value retention.

4.2 Visual Return Profile Analysis

Figures 2 and 3 visualize the comparative financial performance across the three case studies, demonstrating the relationships among payback period, IRR, and typology.

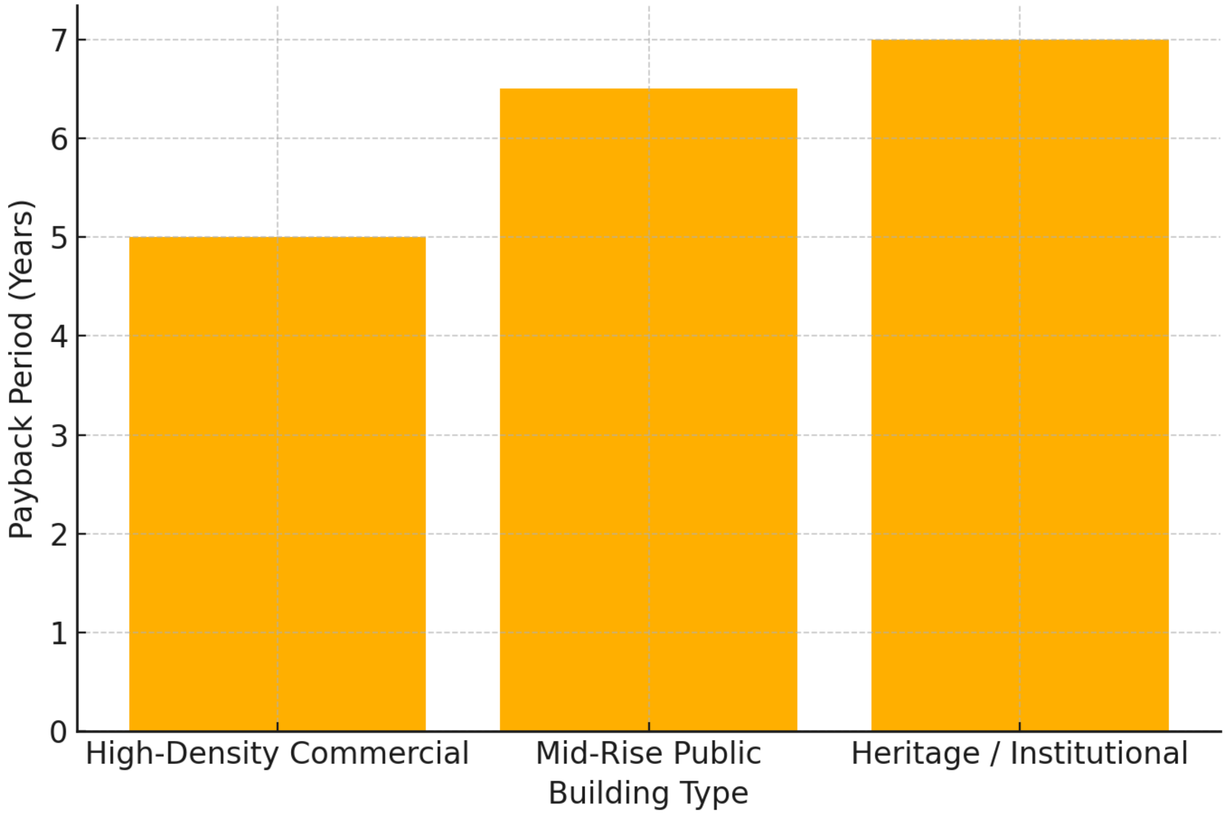

Figure 2. Payback Period by Case Study

Note: High-density commercial buildings show the fastest recovery period, reflecting high baseline energy consumption and strong retrofit leverage.

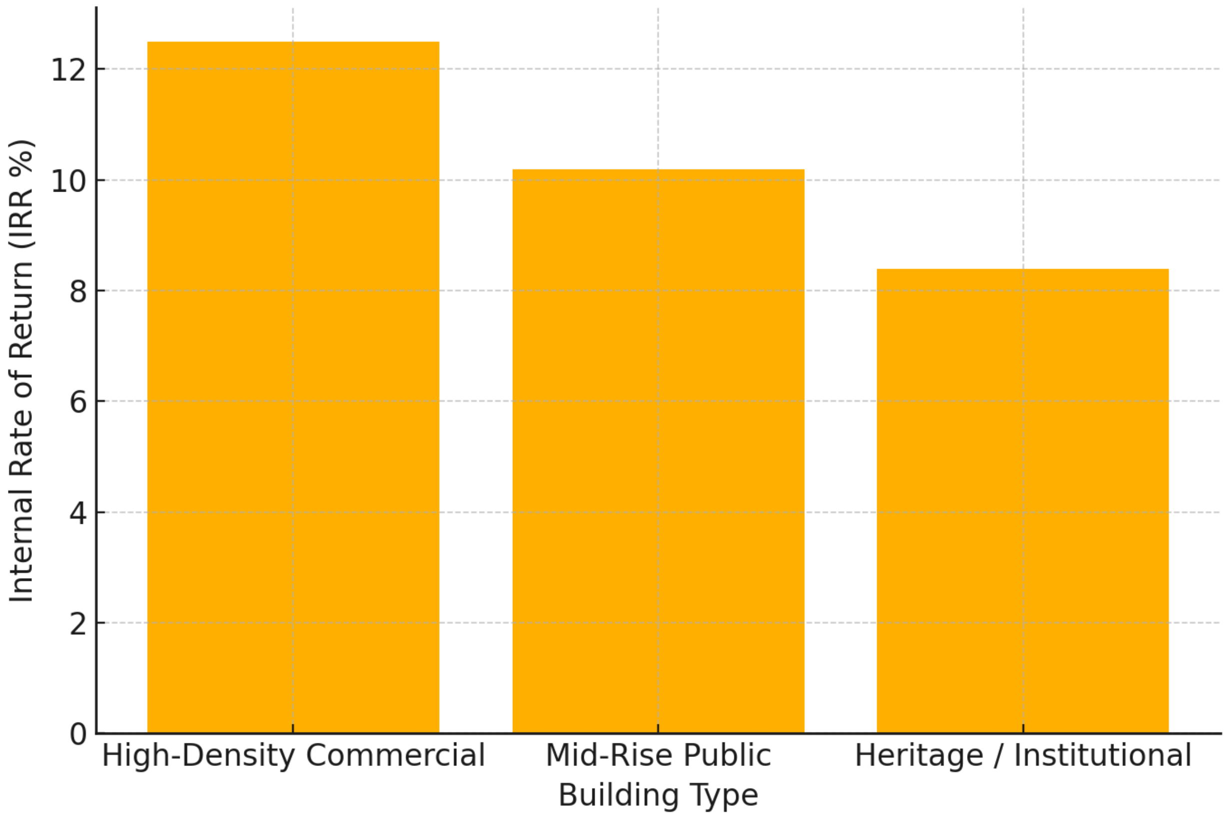

Figure 3. Internal Rate of Return (IRR) by Case Study

Note: The gradient from commercial to heritage typologies highlights how operational intensity, regulatory flexibility, and energy baselines influence overall return on investment.

Together, the visuals reinforce the conclusion that AI-enabled adaptive façades are most economically viable in energy-intensive urban contexts, while public and heritage applications require policy or financial incentives to reach equivalent feasibility thresholds.

4.3 Energy Efficiency Outcomes and Environmental Impact

Energy efficiency results across the three projects demonstrate substantial performance improvement potential:

- **Commercial retrofit (London):** Energy Use Intensity (EUI) reduced from *360 → 140 kWh/m²/year* (≈ 60% savings).
- **Public building retrofit (Copenhagen):** Heating demand reduction exceeding *50%* through façade insulation and smart ventilation.
- **Heritage retrofit (Cambridge):** Achieved *84% reduction* in total operational energy and *EnerPHit* compliance.

These results align with literature benchmarks (Ahmed et al., 2024), demonstrating that adaptive façade systems can effectively serve as a retrofit catalyst for both carbon and energy efficiency [22].

When projected onto broader urban scales, the implications are significant. For instance, if commercial office buildings in London's central business district adopted similar adaptive façade retrofits, the city could cut total operational emissions from the commercial sector by over 40%, contributing directly to UK's 2050 Net Zero target.

4.4 Sensitivity Analysis: Cost, Performance, and Incentives

To test robustness, a sensitivity analysis was conducted across three key financial parameters:

- **Capital cost fluctuation (±20%)** altered the payback period by 1–2 years, depending on the typology.
- **AI sophistication** (rule-based vs. predictive) increased upfront cost by 10–15% but improved energy savings by an additional 8–12%, yielding a net IRR gain of ~1.5%.
- **Policy incentives** such as retrofit grants or carbon credits improved IRR by 1.5–2% for public and heritage buildings, significantly improving financial feasibility.

These findings demonstrate that incentive-driven frameworks including tax reliefs, green financing, or carbon-offset programs are critical for enabling widespread adoption of adaptive façade retrofits in low-ROI sectors. Without such instruments, implementation remains skewed toward commercial markets with strong financial returns.

4.5 Scalability and Deployment Readiness

The analysis indicates that AI-enabled modular façade systems are highly scalable under appropriate technical and regulatory conditions.

Key determinants of scalability include:

- **Technical Modularity:** Prefabricated façade units are adaptable to multiple geometries, reducing installation times by up to 30% [27]
- **AI Component Standardization:** Streamlined sensor arrays and control algorithms allow cost-efficient replication across urban portfolios.
- **Policy Integration:** Feasibility is strengthened when frameworks align with urban sustainability strategies such as the EU Renovation Wave, SDG 7 (Clean Energy), and SDG 11 (Sustainable Cities).

However, scalability in heritage and public buildings remains policy-contingent. Implementation often requires hybrid models involving public-private investment, subsidies, and adaptive design codes. This highlights the need for supportive governance structures that recognize façade retrofitting as a strategic enabler of energy transition.

5. Discussion

5.1 Economic Viability and Strategic Application

The findings of this study affirm that AI-enabled modular adaptive façade systems represent a financially viable and technically scalable retrofit pathway, particularly for energy-intensive commercial buildings. Across the analyzed cases, high-density commercial retrofits such as 1 & 2 Stephen Street, London demonstrated the strongest economic outcomes, achieving an IRR of 12.5% and a payback period of approximately five years. These results corroborate earlier analyses from Better Buildings Partnership (2014) and DER Case Studies (2017), which identified façade optimization as a central driver of deep energy retrofit performance.

By contrast, the Stengårds School (Copenhagen) and Entopia Building (Cambridge) exhibited lower financial returns despite significant energy and carbon reductions. This divergence illustrates how policy incentives, financing mechanisms, and regulatory flexibility critically shape economic feasibility. In heritage or public-sector projects, longer payback horizons (6–7 years) are offset by co-benefits such as enhanced occupant comfort, institutional energy savings, and alignment with municipal sustainability goals. Therefore, effective retrofit deployment in these contexts requires hybrid economic models combining public funding, performance contracting, and carbon incentives.

Overall, the economic analysis validates adaptive façades as a strategically tiered investment opportunity: profitable in commercial markets, yet societally valuable in public and heritage sectors when supported by the right policy and financial instruments.

5.2 Role of AI in Smart Urban Infrastructure

A major innovation highlighted through this research is the integration of AI-driven environmental control systems into modular façade retrofits. The study's case synthesis reveals a clear distinction between rule-based AI systems (as implemented in the Stengårds School retrofit) and predictive machine learning systems (as applied in The Entopia Building).

Rule-based systems rely on pre-programmed environmental triggers, offering low-cost automation suitable for budget-constrained retrofits. Predictive AI systems, however, utilize data analytics to anticipate user behavior and weather patterns, optimizing system performance and achieving up to 12% additional energy savings despite higher upfront costs [22].

This distinction supports the concept of a "technology laddering strategy" in urban retrofits where stakeholders progressively adopt more sophisticated AI systems over time. Such phased adoption enables cities and developers to balance innovation readiness, affordability, and scalability, ensuring long-term adaptability of façade technologies within evolving smart city frameworks.

5.3 Sustainability Alignment and SDG Contributions

The cross-case findings also demonstrate that adaptive façade retrofitting directly supports several United Nations Sustainable Development Goals (SDGs):

- **SDG 7 (Affordable and Clean Energy):** All three projects achieved measurable reductions in operational energy demand (30–84%), improving building energy efficiency and reducing reliance on fossil-fuel-intensive systems.
- **SDG 11 (Sustainable Cities and Communities):** Modular and AI-integrated retrofits enhanced resilience and livability while preserving architectural integrity, particularly in heritage contexts such as *The Entopia Building*.
- **SDG 13 (Climate Action):** By reducing carbon emissions up to 60%, adaptive façades contribute significantly to national and regional decarbonization targets under the *EU Renovation Wave* and the *UK Net Zero Carbon Buildings Standard*.

Beyond these global goals, the study offers a replicable economic decision-support framework for municipalities and private developers. This framework bridges the gap between technological performance metrics and financial decision-making, empowering stakeholders to prioritize retrofitting projects that deliver both economic and environmental returns.

5.4 Implications for Smart Construction and Entrepreneurship

The convergence of adaptive façade technology, AI, and modular construction offers emerging opportunities for smart construction enterprises and green innovation ecosystems. The case evidence underscores how prefabrication and AI control can serve as catalysts for new business models, including “Façade-as-a-Service (FaaS)”, where clients pay for performance outcomes rather than capital equipment.

This approach aligns with ESG investment strategies, particularly within Europe’s growing green financing landscape, which prioritizes measurable sustainability outcomes. Startups and mid-size engineering firms can leverage the FaaS model to enter retrofit markets with lower capital exposure while offering guaranteed performance contracts a mechanism already gaining traction in commercial retrofits such as *1 & 2 Stephen Street*.

For emerging economies, this represents a transformative opportunity to leapfrog traditional construction models by embedding AI and modular design within retrofit value chains. Doing so not only accelerates decarbonization but also fosters green employment and local innovation capacity in smart materials, IoT systems, and digital design services.

5.5 Knowledge Gaps and Future Research

While the study establishes a strong empirical foundation, several research avenues remain open for exploration:

- **Real-time performance validation:** Future studies should integrate post-occupancy monitoring or digital twin simulations to verify long-term AI and façade performance.
- **Human-centric metrics:** Occupant comfort, daylighting quality, and indoor environmental satisfaction should be included in future cost-benefit analyses.
- **Regional adaptation:** Economic feasibility models should be extended to diverse climatic and regulatory contexts, including Southeast Asia and the Middle East.
- **Integration of BIM and AI ecosystems:** Coupling façade intelligence with Building Information Modeling (BIM) and digital twin platforms can enable predictive maintenance and dynamic performance benchmarking.

Future research should build upon this mixed-method design by integrating primary simulation and empirical validation to complement the secondary-data-based triangulation used in this study.

6. Conclusion

This study examined the economic feasibility, technical scalability, and sustainability potential of AI-enabled modular adaptive façade systems as a transformative strategy for urban building retrofitting. Drawing upon validated secondary data and three real-world case studies *1 & 2 Stephen Street (London)*, *Stengårds School (Copenhagen)*, and *The Entopia Building (Cambridge)* the findings provide clear evidence that adaptive façades can serve as a cost-effective and impactful pathway toward urban decarbonization.

The comparative analysis revealed that high-density commercial retrofits deliver the strongest economic performance, achieving Internal Rates of Return (IRR) above 12% and payback periods near five years. These results underscore the financial viability of adaptive façade systems in energy-intensive markets, where operational savings and rental value uplift jointly drive investment returns. In contrast, public-sector and heritage retrofits, while producing lower IRRs (8–10%) and longer payback periods (6–7 years), remain feasible when integrated within policy-supported or incentive-based frameworks.

A key insight from this research is that the integration of AI ranging from rule-based to predictive systems enhances energy efficiency by 8–12%, offering measurable performance gains without imposing excessive complexity or cost. This validates the potential of phased AI adoption, enabling stakeholders to gradually scale up façade intelligence in alignment with local budget, capacity, and policy readiness.

From a strategic perspective, the study demonstrates that adaptive façade systems not only deliver direct economic benefits but also broader social and environmental value, contributing meaningfully to global sustainability agendas. Specifically, the framework supports:

- **SDG 7 (Affordable and Clean Energy)** through improved energy performance and reduced grid dependency;
- **SDG 11 (Sustainable Cities and Communities)** by promoting resilient and livable urban environments; and

- **SDG 13 (Climate Action)** through measurable reductions in building-related carbon emissions.

The empirical modeling and sensitivity analysis confirm that economic feasibility and scalability depend strongly on contextual factors such as regulatory flexibility, access to finance, and energy pricing structures. These insights position adaptive façades as both a technological innovation and a policy instrument, capable of accelerating progress toward net-zero carbon goals when integrated into city-scale retrofit strategies.

Looking forward, this research establishes a foundation for next-generation façade intelligence frameworks that combine AI, modular construction, and digital twin technology. Future investigations should focus on real-time performance validation, occupant-centered metrics, and region-specific financial modeling to refine decision-making accuracy. By bridging technology, economics, and policy, the framework presented in this study contributes a scalable model for advancing sustainable, AI-driven urban transformation.

7.References

[1] IEA, "IEA," November 2023. [Online]. Available: https://www.iea.org/reports/energy-efficiency-2023.

[2] Hosseinalipour, S. M., Al-Taee, A. A. H., & Asiaei, S., "mproving energy consumption for dynamic intake and exhaust façades: a new setup design: part b.," *Building Services Engineering Research and Technology, 45(5),* pp. 613-639. https://doi.org/10.1177/01436244241264273, 2024.

[3] A. Mahzouni, "The institutional challenges of scaling-up housing retrofit: the swiss cities of basel and sion.," *Facilities, 37(11/12),* pp. 780-798. https://doi.org/10.1108/f-02-2017-0025, 2019.

[4] Htet, A., Liana, S.R., Rani, S, Y., & Bhaumik, A., "The effectiveness of daylight management in building: A review," *AIP Conference Proceedings 2854,* pp. 020005-1- 020005-7. https:doi.org/ 10.1063/5.0162625, 2023.

[5] Özdemir, H. & Çakmak, B. Y., "Evaluation of daylight and glare quality of office spaces with flat and dynamic shading system facades in hot arid climate," *Journal of Daylighting, 9(2),* pp. 197-208. https://doi.org/10.15627/jd.2022.15, 2022.

[6] Procaccini, G., Prieto, A., Knaack, U., Monticelli, C., & Konstantinou, T., "Textile membrane for façade retrofitting: exploring fabric potentialities for the development of innovative strategies.," *Buildings, 14(1),* p. 86. https://doi.org/10.3390/buildings14010086, 2023.

[7] Agbonyin, A. & Zoras, S., " Techno-economic inquiry into implementation barriers in green roof adoption as an energy retrofit measure in temperate climates: uk study," *IOP Conference Series: Earth and Environmental Science, 410(1),* pp. 012014. https://doi.org/10.1088/1755-1315/410/1/012014, 2020.

[8] Htet, A., Gupta, S.K., & Oruganti, S.K., "Modular Adaptive Facades: Designing a Scalable Framework for Retrofitting Urban Buildings," *SGS Engineering Sciences, 1 (2),* p. https://spast.org/techrep/article/view/5370, 2025.

[9] Álvarez, I., Elguezabal, P., Jorge, N., Moya, T. A., & Konstantinou, T., "Definition and design of a prefabricated and modular façade system to incorporate solar harvesting technologies.," *Journal of Facade Design and Engineering, 11(2),* pp. 001-028. https://doi.org/10.47982/jfde.2023.2.t1, 2023.

[10] Matin, N. H., Eydgahi, A., Gharipour, A., & Matin, P., "A novel framework for optimizing indoor illuminance and discovering association of involved variables.," *Buildings, 12(7),* p. 878. https://doi.org/10.3390/buildings12070878, 2022.

[11] M. A. S. Morales, "Modular construction: a sustainable solution for carbon emission reduction in the construction industry.," *International Journal of Engineering Applied Sciences and Technology, 5(1),* pp. 393-401. https://doi.org/10.33564/ijeast.2023.v08i01.05, 2023.

[12] UK Green Building Council, BUILDING THE CASE FOR NET ZERO: RETROFITTING OFFICE BUILDINGS, UKGBC, 2024.

[13] Aung, T., Liana, S. R., Htet, A., & Bhaumik, A., "Implementing green facades: a step towards sustainable smart buildings.," *Journal of Smart Cities and Society, 2(1),* pp. 41-51. https://doi.org/10.3233/scs-230014, 2023.

[14] Agrawal, S. & Sahu, M., "Enhancing building energy system design using computational intelligence for smart buildings.," *Architecture Image Studies, 6(1),* pp. 26-35. https://doi.org/10.62754/ais.v6i1.103, 2025.

[15] Böke, J., Knaack, U., & Hemmerling, M., "Automated adaptive façade functions in practice - case studies on office buildings.," *Automation in Construction, 113,* p. 103113. https://doi.org/10.1016/j.autcon.2020.103113, 2020.

[16] Torres, J., Garay-Martinez, R., Oregi, X., Torrens, J. I., Uriarte, A., Pracucci, A., & Ángel, M., "Plug and play modular façade construction system for renovation for residential buildings.," *Buildings, 11(9),* p. 419. https://doi.org/10.3390/buildings11090419, 2021.

[17] Sharma, S. K., Mohapatra, S., Sharma, R. C., Alturjman, S., Altrjman, C., Mostarda, L., & Stephan, T., "Retrofitting existing buildings to improve energy performance.," *Sustainability, 14(2),* p. 666. https://doi.org/10.3390/su14020666, 2022.

[18] Kurcjusz, M. & Stefańska, A., "Transformative integration of artificial intelligence in architectural design.," *Architectus, 1(81),* p. 250109. https://doi.org/10.37190/arc250109, 2025.

[19] El-Mowafy, B.N., Elmokadem, A.A., & Waseef, A.A., "Evaluating Adaptive Facade Performance in Early Building Design Stage: An Integrated Daylighting Simulation and Machine Learning," in *The 8th International Conference on Advanced Machine Learning and Technologies and Applications (AMLTA2022)*, Egypt, SRGE, 2022, pp. 211-223. https://doi.org/10.1007/978-3-031-03918-8_20.

[20] Wan, S., Ding, G., Runeson, G., & Liu, Y., "Sustainable buildings' energy-efficient retrofitting: a study of large office buildings in beijing.," *Sustainability, 14(2),* p. 1021. https://doi.org/10.3390/su14021021, 2022.

[21] Seraj, H., Bahadori-Jahromi, A., & Amirkhani, S., "Developing a data-driven ai model to enhance energy efficiency in uk residential buildings.," *Sustainability, 16(8),* p. 3151. https://doi.org/10.3390/su16083151, 2024.

[22] M. Alammar, Evaluating adaptive façade systems in retrofitting projects, [Master's thesis, King Fahd University], 2022.

[23] Iwuanyanwu, O., Gil-Ozoudeh, I., Okwandu, A. C., & Ike, C. S., "Retrofitting existing buildings for sustainability: challenges and innovations.," *Engineering Science & Technology Journal, 5(8),* pp. 2616-2631. https://doi.org/10.51594/estj.v5i8.1515, 2024.

[24] Cui, D., Zhao, H., & Zhang, R., "Approaching zero-carbon development through modular construction: a case study of healthcare buildings in london.," *Indoor and Built Environment, 34(7),* pp. 1404-1421. https://doi.org/10.1177/1420326x251346132, 2025.

[25] Pantilimonescu, F., Tudora, G., & Tudora, A., "Designing buildings with potential for artificial intelligence integration: a conceptual study on adaptive façades.," *Journal of Physics: Conference Series, 3071(1),* pp. 012016. https://doi.org/10.1088/1742-6596/3071/1/012016, 2025.

[26] Mørck, O., Miriam, S., Lohse, R., Martina, R., & Alexander, Z., Deep Energy Retrofit - Case Studies, Brimingham: EBC Bookshop, 2017.

[27] Better Building Partnership, "Annual Report 2013-2014," Better Building Partnership, Sydney, 2014.

[28] Gonçalves, J. E., Montazeri, H., Hooff, T. v., & Saelens, D., "Performance of building integrated photovoltaic facades: impact of exterior convective heat transfer," *Applied Energy, 287,* p. 116538. https://doi.org/10.1016/j.apenergy.2021.116538, 2021.