THE IMPACT OF TEXTILE SHADING SYSTEMS IN FAÇADE RETROFITTING: EVALUATING THE OPERATIONAL PHASE IN THE LCA

STRUCTURAL MEMBRANES 2025

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Key words: Textile Façade Retrofit, Solar Shading Systems, Life Cycle Assessment (LCA), Operational Energy, Energy Efficiency, Building Sustainability

1   INTRODUCTION

The existing building stock, currently responsible for approximately 40% of global energy consumption and CO_2 emissions[1], requires functional improvements, including the enhancement of façade energy performance, in order to reduce the overall environmental impact of buildings[2]. In line with the decarbonization of the construction sector, façade retrofitting represents one of the most effective strategies, as it simultaneously addresses both the functionality and the aesthetics of existing buildings[3,4].

The use of textile materials in façades offers distinctive advantages over traditional systems[5], making them particularly suitable for retrofitting processes: thanks to their intrinsic lightness and reduced thickness, architectural textiles allow for more flexible and less invasive applications, reducing structural loads and minimizing alterations to existing elements[6,7]. Their potential use as solar-shading systems further amplifies these benefits, improving indoor comfort during the summer cooling period[8]. Therefore, adopting such materials for façade retrofitting represents an innovative opportunity to enhance the environmental sustainability of buildings, with potential benefits also in terms of energy savings and CO_2 emission reduction[9].

In order to assess the actual environmental contribution of such interventions, it is crucial to adopt a Life Cycle Assessment (LCA) approach, quantifying and comparing the environmental impacts associated with all phases—from the production of the additional materials required for retrofitting to the end of the building's life cycle—while paying particular attention to the operational stage[10]. However, accurately quantifying the overall environmental impacts remains challenging, especially with regard to the contribution of the operational phase (B6) to the life cycle. This stage is often overlooked in favour of assessing only the production phase of retrofitting materials, largely due to the greater emphasis placed on the aesthetic value of the intervention[11]. This tendency limits the understanding of real benefits, relegating the potential contribution of the operational phase to a marginal role.

In this context, the present study aims to thoroughly investigate the potential of textile materials in façade energy retrofitting, assessing not only the benefits in terms of energy efficiency and emission reduction, but also the importance of an integrated approach that considers the entire life cycle of interventions. Through a critical analysis of existing methodologies and innovative practices, the study seeks to make a significant contribution to academic and professional discourse on sustainability in the construction sector.

Specifically, the research focuses on evaluating how addressing the often-neglected operational phase within life cycle assessments can influence the overall appraisal of façade retrofitting solutions. By examining the environmental and economic implications associated with the production, installation, and use of textile materials, the study aims to develop a more comprehensive framework for assessing the sustainability of these interventions throughout their life cycle. The objective is to demonstrate how this integrated approach can serve as a model for future LCA studies in the construction sector.

Despite their potential, architectural textile materials remain underexplored for façade retrofitting, particularly regarding their contribution to energy efficiency. Building upon the advantages previously outlined, this study further investigates their practical application and performance as retrofitting solutions. When employed as solar shading systems, these materials further enhance indoor comfort during warmer seasons and contribute to reducing operational energy demand[8].

To accurately quantify the environmental contribution of these interventions, the research adopts the previously introduced Life Cycle Assessment (LCA) framework, covering all phases from material production and installation to end-of-life, with particular focus on the operational phase (B6) identified as a key yet frequently overlooked stage[10],[11]. This study applies such an approach to a case study of façade retrofitting using textile materials, comparing scenarios that exclude and include operational impacts, thereby providing a holistic understanding of environmental performance over the building's life cycle.

2 METHODOLOGY

This study aims to analyze the environmental impact of introducing solar-shading systems through the application of tensile textile materials across the entire existing façade. The analysis considers both the production and installation phases of the components, as well as the operational phase of the building, highlighting the different environmental implications resulting from these design choices. The study adopts the LCA approach in accordance with ISO 14040 and 14044 standards[12],[13] and EN 15804[14], applied to a case study of façade retrofitting carried out using textile materials.

Two methodological scenarios are compared: the first one considers only phases A1–A5 (production, transport, construction), B4–B5 (maintenance and replacement), and C1–C4 (end of life); the second also includes the operational phase of the building (B6), influenced by the integration of textile shading systems.

The LCA analyses were conducted using OneClickLCA software, whose datasets are based on the reference EPDs of the selected materials. The operational phase of the building was quantified through building modeling in SketchUp with the OpenStudio plugin and subsequent dynamic energy simulation using EnergyPlus. This allowed the quantification and comparison, across the reference scenarios, of the variations in building energy consumption required to maintain the same indoor comfort conditions.

The case study used as reference for the analyses is the Sedus Stoll AG Innovation and Development Center [Fig. 1] designed by Ludloff + Ludloff Architekten in Dogern, Germany between 2007 and 2010. For the evaluation, its characteristic trapezoidal architectural form was preserved, while simplifying the roof geometry and considering only the above-ground surface, corresponding to 2100 m², as the functional unit for the analyses. The building envelope is characterized by a tensile structure enveloping the main structure, except for the windows, which are equipped with movable blinds. This envelope configuration reflects the as-built condition of the case study and corresponds to the following "Wrapping + Shade" (W+S) scenario, which was used as the reference model for comparison with alternative configurations.

Figure 2: the main façade of the Sedus Stoll AG Innovation and Development Center by Ludloff + Ludloff Architekten in Dogern

Accordingly, three energy and architectural scenarios were compared to assess the impact of different shading solutions on the thermal performance of the building:

- "Bare" configuration: building without any shading elements i.e. non retrofitted [Fig. 3];
- "Wrapping" (W) configuration: building entirely wrapped with self-supporting fixed shading surfaces, spaced 50 cm from the façades [Fig. 4];
- "Wrapping + Shade" (W+S) configuration: building wrapped with self-supporting fixed shading surfaces, spaced 50 cm from the façades. These surfaces are perforated in correspondence with the windows, with additional movable external shading elements (like blinds) installed 20 cm away from the southwest- and southeast-facing windows [Fig. 5].
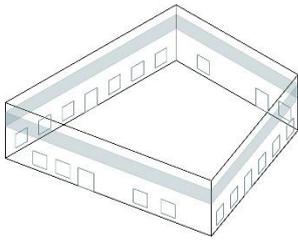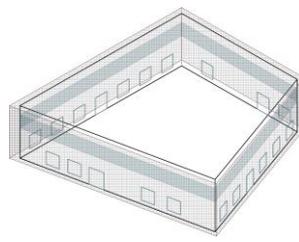
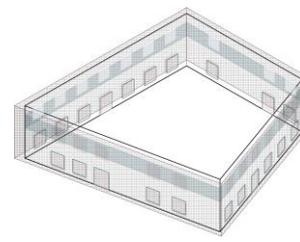**Figure 3:** "Bare"   **Figure 4:** "Wrapping"   **Figure 5:** "Wrapping+Shade"

A service life of 50 years was considered. The "Bare" configuration was proposed as the reference scenario against which to calculate the additional impact of façade retrofitting in the alternative scenarios. The specifications and quantities related to the case study in its "Wrapping + Shade" configuration were derived from the detailed documentation provided in [15], which reports the original project and served as the main source for the data used in this analysis, while for the simplified "Wrapping" configuration the movable shading elements and their supporting substructure were excluded, and a continuous fixed shading layer enveloping the façades was considered instead. In this case, the amounts of aluminum profiles and anchoring elements were reduced, considering that, in the absence of perforations in the textile membrane, the substructure requires lower dimensional requirements. Therefore, these quantities were parametrically defined according to this alternative design scenario.

In both alternatives evaluated, the primary substructure considered is made of aluminum with steel fastening elements. The variation in quantities, compared in Table 1, depends on the greater amounts required for the construction and fastening of the "Wrapping + Shade" configuration, which involves larger quantities of framing for building fixed vertical elements and openings near the windows, closed with external shading devices.

Table 1: Data e quantities of the materials used for the LCA analysis

Material	Unit weight	Service life	End of life	Qty – Bare Conf.	Qty – W Conf.	Qty – W+S Conf.
Reinforced concrete	2400 kg/m³	Equivalent to building lifespan	Crushing	94.89 m³	94.89 m³	94.89 m³
Rock wool insulation	39 kg/m³	Equivalent to building lifespan	Landfill	47.44 m³	47.44 m³	47.44 m³
Gypsum board	800 kg/m²	Equivalent to building lifespan	Recycling	474.45 m²	474.45 m²	474.45 m²
Rock wool insulation	39 kg/m³	Equivalent to building lifespan	Landfill	18.98 m³	18.98 m³	18.98 m³
Wood fiber panel	625 kg/m³	Equivalent to building lifespan	Landfill	20.87 m³	20.87 m³	20.87 m³
Cellulose insulation	50 kg/m³	Equivalent to building lifespan	Landfill	123.36 m³	123.36 m³	123.36 m³

Aluminum profiles	1.58 kg/m²	Equivalent to building lifespan	Recycling	–	1515.31 kg	588.42 kg
Fastening elements	0.033 kg/unit	Equivalent to building lifespan	Recycling	–	20738 units	8053 units
PTFE	2200 kg/m³	30 years	Incineration	–	1670 kg	1670 kg

For the purposes of the energy simulation, the materials used in the construction of the reference existing building were faithfully reproduced, with different wall stratifications between the first and second floors, and windows consisting of double glazing with 3 mm panels separated by argon gas. Table 2 summarizes the thermal transmittance (U-value) of opaque elements and the solar factor (g-value) of the windows for the three façade configurations. The U-values of walls, slabs, and the roof are largely consistent across configurations, as the wrapping primarily affects the exterior appearance and shading rather than the thermal resistance of the envelope. For transparent elements, the solar factor g remains 0.33 for the Bare and Wrapping configurations, while it decreases to 0.28 in the Wrapping + Shade configuration due to the addition of the external textile shading. These values were used in EnergyPlus to simulate the building's thermal behavior and the impact of shading strategies on energy demand. The characteristics of the existing building made it possible to conduct the analyses in EnergyPlus using the WindowMaterial:Shade model for window shadings and the Detached Shading Surface model for opaque façade shadings. It should be noted that the available simulation models allowed consideration of solar shading effects of the textile envelope, but possible modifications to convection phenomena in the air gap between the textile façade and the building envelope were not taken into account.

Table 2: U-values of opaque elements and g-values of windows for the three façade configurations

Building element	Bare	Wrapping	Wrapping + Shade
Wall F1 – Exterior	U = 0.95 W/m²K	U = 0.95 W/m²K	U = 0.95 W/m²K
Wall F2 – Exterior	U = 0.90	U = 0.90	U = 0.90
Ground slab	U = 0.35	U = 0.35	U = 0.35
Interior slab	U = 0.40	U = 0.40	U = 0.40
Roof – Exterior	U = 0.25	U = 0.25	U = 0.25
Window – Double glazing	U = 2.7 W/m²K, g = 0.33	U = 2.7, g = 0.33	U = 2.7, g = 0.28 (with shade)

For the sake of simplicity, the building was divided in two thermal zones corresponding to the two floors, each with a floor area of 2100 m². Internal loads and systems operation were set as follows:

- Occupants: 35 people per zone, present from 9:00 to 13:00 and 14:00 to 18:00 on weekdays. Metabolic heat gains were modeled using an activity schedule ranging from 70 W/person during off-hours to 150 W/person during working hours (9:00–18:00), with 30% of the metabolic energy considered as radiant heat.

- Lighting: Active from 9:00 to 18:00 on weekdays, with a total electrical consumption of 950 W per zone.
- Equipment/Plug Loads: In use from 9:00 to 18:00 on weekdays, with a total electrical consumption of 9000 W per zone.
- Heating system: Operates on weekdays from 8:00 to 18:00 during the winter season (October 15 to April 15), maintaining a constant indoor setpoint temperature of 20°C.
- Cooling system: Operates on weekdays from 9:00 to 18:00 during the summer season (June 1 to September 30), maintaining a constant indoor setpoint temperature of 25°C

The analysis covered the entire year, using hourly weather data from a Typical Meteorological Year (TMY) file for Milan, Italy, which is based on local climate measurements and representative of average conditions. For both energy simulations with shading devices, a textile material with solar transmittance and solar reflectance equal to 28% and 37% respectively, was adopted. This choice was based on preliminary energy analyses comparing different transmittance scenarios (9%, 28%, and 40%), derived from technical datasheets of commercial textile materials. The results showed that a transmittance of 28% allows for adequate solar gains in winter conditions while at the same time limiting summer overheating.

The HVAC system was modelled in EnergyPlus as an ideal system, allowing the calculation of the building's thermal demands for heating and cooling. Subsequently, by assuming a heat pump with average seasonal performance coefficients of 3.0 in winter and 2.5 in summer, the annual electricity consumption for climatization was obtained.

The building's annual energy consumption was therefore calculated as 33,750.0 kWh for the "Bare" configuration, 23,091.0 kWh for the "Wrapping + Shade" configuration, and 23,923.6 kWh for the "Wrapping" configuration.

Table 3 reports the thermal demands (Qh and Qc) and the corresponding electrical consumptions (Eelh and Eelc) of the heat pump for the different façade configurations. As expected, the introduction of the wrapping layer increases the heating demand (due to reduced solar gains in winter) but significantly decreases the cooling demand. Overall, the annual electricity consumption for climatization (Eel) is reduced by 20–26% depending on the transmittance value of the wrapping layer, and up to 36% when the wrapping is combined with movable external shading.

Table 3: *Heating and cooling demands (Qh, Qc) and heat pump electricity use (Eelh, Eelc) for each façade configuration, with annual savings (ΔEel) relative to the Bare case.*

Configuration	Qh (kWh/m²)	Eelh (kWh/m²)	Qc (kWh/m²)	Eelc (kWh/m²)	Eel (kWh/m²)	ΔEel (%)
Bare	8.23–9.59	2.74–3.20	26.57–38.94	10.63–15.58	13.82–18.32	—
Wrapping t = 0.09	15.78–19.52	5.26–6.51	10.57–15.15	4.23–6.06	10.73–11.32	−22% to −38%
Wrapping t = 0.28	13.55–17.02	4.52–5.67	13.00–18.49	5.20–7.40	10.87–11.91	−21% to −35%

Wrapping t = 0.40	12.33–15.58	4.11–5.19	14.57–20.66	5.83–8.26	11.02–12.37	−20% to −32%
Wrapping + Shade t = 0.28	10.99–13.23	3.66–4.41	14.64–20.15	5.86–8.06	10.27–11.73	−26% to −36%

These results confirm the effectiveness of the façade wrapping in reducing overall energy use, particularly when combined with shading devices that further limit summer solar gains.

As illustrated in Figure 5, the results of the energy analyses were subsequently used to simulate the energy load of the operational phase (B6) within the LCA framework. This dual methodological approach was designed to compare the environmental impact of material production for the façade retrofit of the building with the environmental impact associated with the building's operational load, under a service life scenario of 50 years.

3 RESULTS

The final assessment presents a detailed comparison of LCA and LCC across the three scenarios, highlighting differences in environmental and economic performance.

3.1 The Impact of the Operational Phase in the LCA

In the chart shown in Figure 6, which excludes the operational phase of the building, it can be observed that the greatest impact is attributable to the material production phases (A1–A3) and their management throughout the life cycle, including transport, installation, and replacement. The GWP amounts to 64.68 kgCO₂e/m² for the Wrapping configuration and 70.37 kgCO₂e/m² for the Wrapping + Shade configuration, due to the larger amount of material required for the retrofit intervention. This highlights how strongly material choice influences the environmental impact of a retrofit project.
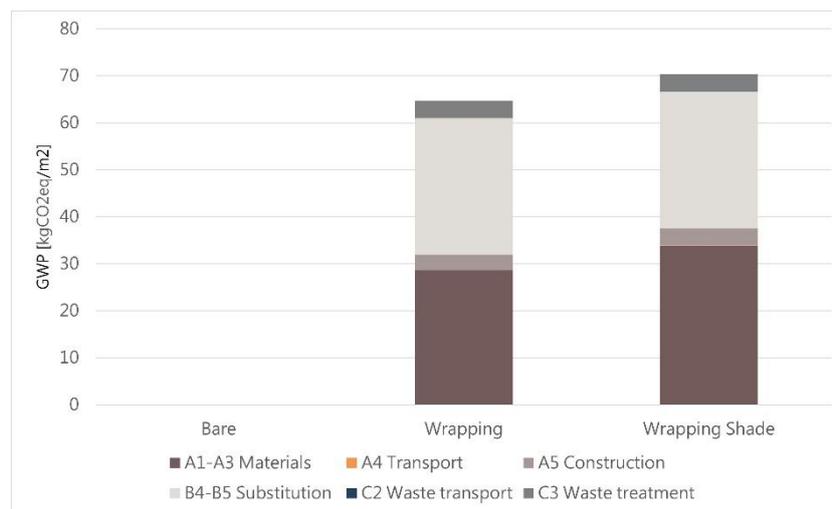
Figure 6. LCA analysis of the retrofit interventions excluding the operational phase (B6) – Unit: kgCO₂e/m²

The second chart [Fig. 7], which instead includes the operational phase (B6), shows a different perspective: considering a 50-year time horizon, the impact of the use phase becomes predominant, while the relative contribution of material-related phases decreases drastically. This result demonstrates that energy consumption during the building's use is the most significant environmental factor in the long term. Façade retrofitting, by improving the building's energy performance, allows for a drastic reduction of this impact, compensating for and outweighing the initial environmental burden associated with material production and installation.

In fact, when including the operational phase of the building, while the GWP for the Bare configuration—driven solely by the building's use phase—amounts to 1013.42 kgCO₂e/m², the GWP decreases to 748.21 kgCO₂e/m² (-26%) for the Wrapping configuration and to 763.73 kgCO₂e/m² (-25%) for the Wrapping + Shade configuration.
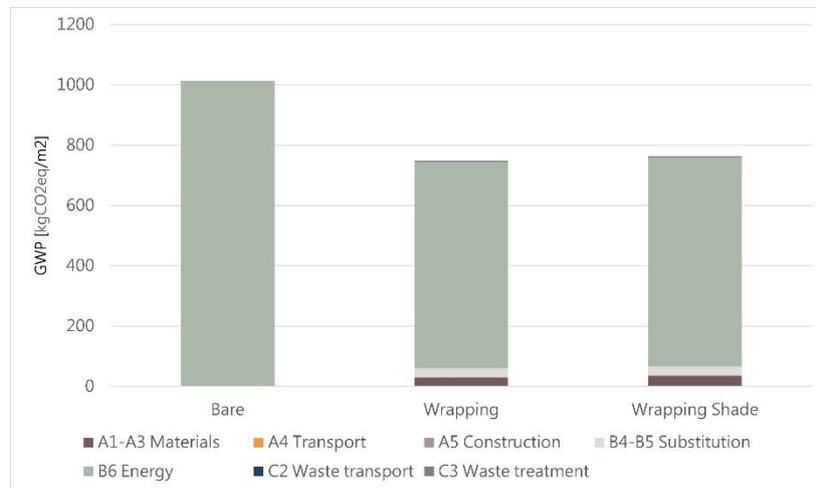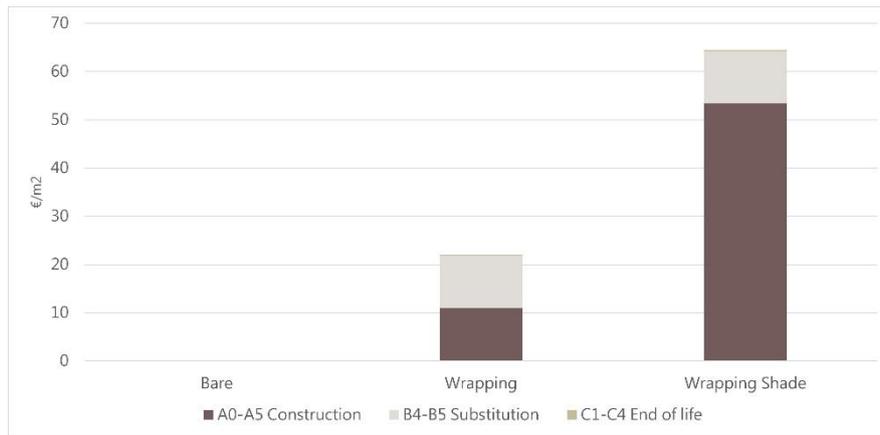

Figure 7. LCA analysis including the operational phase (B6) – Unit: kgCO₂e/m²

3.4 The Impact of the Operational Phase in the LCC

The life cycle cost (LCC) analysis of the three scenarios considered shows that the initial costs associated with the production, transport, and installation of materials represent a significant share in the short term but diminish considerably when assessed over a 50-year horizon.

In the chart excluding the building's operational phase [Fig. 8], the costs associated with material production and the periodic replacement of the cladding are predominant, highlighting the importance of selecting durable materials and cost-efficient installation technologies. The cost of the façade retrofit is 22 €/m² for the Wrapping configuration, while it rises to 64.50 €/m² for the Wrapping + Shade configuration, due to the additional substructure required to support the movable shading devices.

Figure 8. LCC analysis excluding the operational phase (B6) – Unit: €/m²

However, when including the costs related to the operational phase, it becomes evident that the initial investments are largely offset in the long term [Fig. 9], thanks to reduced energy consumption and improved thermal performance of the building envelope. Specifically, the "Wrapping" configuration achieves up to 25% reduction in life cycle costs compared to the Bare case, while the "Wrapping + Shade" option provides a 19% reduction. The slightly lower savings of the "Wrapping + Shade" configuration are due to the additional substructure required for the shading system, which increases upfront costs despite its higher environmental performance. This highlights that, while both retrofit solutions significantly improve energy efficiency, the "Wrapping" option may be more attractive from an economic standpoint, whereas "Wrapping + Shade" offers greater environmental benefits.

Considering the building's operational phase and a 50-year service life, with an electricity cost of 0.80 €/m² (including transport and supplier charges), the operational cost for the Bare configuration amounts to 519.45 €/m². This value decreases to 329.22 €/m² for the Wrapping configuration and to 419.88 €/m² for the Wrapping + Shade configuration.
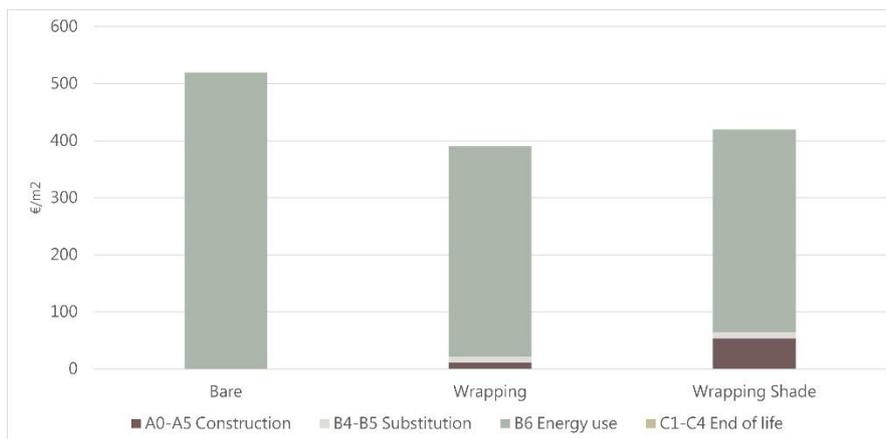
Figure 9. LCC analysis including the operational phase (B6) – Unit: €/m²

4   DISCUSSION

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Over a 50-year scenario, the analysis of the Case-Study building demonstrates that strategies incorporating shading elements perform significantly better in terms of $kgCO_2e$ than the configuration without shading, despite the higher initial emissions associated with material production for façade retrofit, their replacement over the life cycle, and the increase in winter energy demand. The main advantage is due to the substantial energy savings achieved through reduced summer cooling demand, with particularly significant savings for cooling that offset the increase in the building's winter energy consumption.

In particular, the Wrapping + Shade configuration, which combines two solar shading strategies, can prove especially advantageous for energy savings, despite the higher impact linked to the production of a greater quantity of material. If properly designed to maximize winter solar gains and reduce summer ones—for example, using dynamic shading devices—this configuration allows the optimization of the building's energy demand, significantly reducing operational costs compared to the Bare configuration. Moreover, when considering monthly consumption, the effectiveness of the shading system results in a favorable annual energy balance, with summer benefits compensating for winter performance drawbacks.

However, when considering cost implications over the same period, as illustrated in Figure 8, the additional substructure required for the Wrapping + Shade configuration significantly impacts overall expenses. Among the three options, the Wrapping configuration offers the most favorable economic advantages compared to the Bare configuration, achieving cost savings of up to 25%. In contrast, the Wrapping + Shade option, despite its environmental benefits, entails higher costs due to the increased need for substructure, reducing economic savings to 19%. The difference between environmental impact and costs can largely be attributed to the aluminum substructure used in the configurations.

Nevertheless, it is also worth noting that other qualitative aspects—such as the ability to maintain visual contact with the exterior—may influence the choice of retrofit solution. In cases where environmental and economic benefits are relatively similar, such factors can lead to a preference for one configuration over another, highlighting the importance of considering occupant comfort and experiential qualities alongside technical performance.

While the environmental burden of aluminum is mitigated by its recyclability at end-of-life—resulting in a reduction in $kgCO_2e$ — this environmental benefit does not directly translate into economic savings: the costs associated with aluminum remain a significant expenditure throughout the building's life cycle. This underscores the need to carefully consider material choices in order to balance environmental sustainability with economic feasibility.

5   CONCLUSIONS

In conclusion, this analysis provides an initial quantitative validation of façade solar shading solutions made with textile materials, widely adopted in architectural practice but so far never quantified in terms of energy and environmental impact. The study shows that, despite the higher upfront costs of certain strategies, the long-term benefits in terms of reduced energy consumption and CO_2 emissions justify their adoption. However, it also highlights the necessity of optimizing the design phase to maximize energy savings and, consequently, economic advantages.

In particular, the effective use of shading systems during the summer can significantly reduce cooling demand while improving indoor comfort and achieving considerable long-term economic savings. This demonstrates how energy efficiency interventions are essential not only to reduce environmental impact but also to optimize the overall costs of the building.

This research therefore highlights the critical role of careful planning and comprehensive LCA assessment in achieving retrofit solutions that are both sustainable and economically advantageous.

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