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The role of aerogel-based insulation in sustainable renovation of cultural heritage within a circular economy framework

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ABSTRACT

Improving the energy performance of existing buildings while preserving their architectural value represents a major challenge in achieving European Union climate targets and advancing circular economy (CE) principles in the construction sector. This challenge is particularly pronounced in culturally protected buildings, where conventional insulation systems may compromise authenticity and material integrity. This study investigates the potential of aerogel-based thermal insulation materials, with a focus on silica aerogel plaster, as a non-invasive solution for sustainable renovation of heritage buildings.

A comparative evaluation of commercially available nanomaterial-based insulation systems was conducted based on thermal conductivity, environmental impact, required thickness, and compatibility with conservation criteria. Silica aerogel thermal plaster was identified as the most suitable solution for façade applications in protected structures. Its performance was assessed through dynamic energy simulation of the Macedonian Academy of Sciences and Arts building in Skopje, a representative example of post-earthquake modernist heritage architecture. Two scenarios were analyzed: the existing condition and an improved model incorporating aerogel façade insulation and upgraded envelope elements.

Simulation results indicate a 48.3% reduction in annual heating energy demand, a 10% reduction in cooling energy consumption, and a 15% decrease in overall electricity use. Total annual CO_2 emissions were reduced by 35%, accompanied by significant operational cost savings. The findings demonstrate that aerogel-based plaster enables substantial energy and environmental improvements while maintaining architectural authenticity and reversibility, thereby supporting both energy efficiency goals and circular economy principles in heritage renovation.

1 Introduction

In recent years, scientific and technological interest in the application of nanomaterials and biomaterials in energy-efficient construction has grown substantially, largely driven by the introduction of the “Nearly Zero-Energy Buildings” (NZEB) concept under the Energy Performance of Buildings Directive 2010/31/EU [1]. This directive requires that all new buildings achieve near-zero energy consumption by 2030, thereby significantly tightening energy efficiency (EE) standards. This shift has led to an increase in the required thickness of thermal insulation materials, introducing both economic and technical challenges, particularly the rising costs of high-performance insulation systems [2]. On the other hand, sustainability in construction extends beyond thermal performance. Reducing embodied energy in material production and transportation, minimizing environmental toxicity and waste, and promoting material longevity have become key priorities. These objectives align with circular economy (CE) principles, which emphasize resource efficiency, material durability, and extended building lifespans.

Considering that new buildings account for only about 1% of Europe’s annual building stock, existing structures offer the greatest opportunity for implementing CE strategies [3]. It has been shown that renovation, compared to new construction, is significantly more resource-efficient, consuming four to eight times fewer resources [4]. Nevertheless, a review of the literature indicates that one of the main challenges in retrofitting heritage buildings is preserving their architectural authenticity while enhancing EE and sustainability.

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This paper presents the use of advanced nanomaterials in construction, with a focus on their energy-saving performance in alignment with CE objectives and sustainability in culturally significant buildings. Particular emphasis is placed on nano-ceramic coatings and silica aerogel-based materials, which have demonstrated promising results. Among these, silica aerogel thermal plaster stands out as the most effective solution, offering high thermal performance, low embodied energy, and compatibility with heritage conservation requirements. To validate these findings, an energy simulation was conducted on a culturally protected building. The analysis considered two scenarios: the building's original condition and its condition after the application of aerogel-based thermal plaster to the façade. The comparison of results confirmed notable improvements in energy efficiency and sustainability, achieved without compromising the building's architectural integrity.

2 State of the art review of nanomaterials and aerogel-based thermal insulation plasters

Nanomaterials, particularly silica aerogels, vacuum insulation panels (VIPs), phase-change material composites, and nano-ceramic coatings, have emerged as cutting-edge solutions for enhancing energy efficiency in buildings due to their ultra-low thermal conductivity, multifunctionality, and adaptability to historic structures [5,6]. Their ability to deliver high thermal performance in thin layers makes them especially suitable for renovation projects where spatial constraints and conservation requirements limit the use of conventional insulation systems.

Aerogel-based plasters are particularly promising for façade applications, as they significantly reduce heat losses while preserving the architectural integrity and material authenticity of cultural heritage buildings. Early studies reported thermal conductivities of $\lambda = 0.025–0.027$ W/mK for mineral and organic binder plasters [7–9], while lime-based aerogel plasters achieved $\lambda = 0.014–0.016$ W/mK at high aerogel content and $\lambda \approx 0.05$ W/mK for mechanically optimized formulations [8,9]. More recent research confirms their long-term compatibility with historic façades, improved mechanical performance through fiber additives, and reliable in situ thermal behavior [10–14].

Beyond energy efficiency, current developments increasingly emphasize sustainable renovation within a circular economy framework, focusing on bio-based or recycled aerogel precursors, low-energy manufacturing processes, and composite systems that minimize environmental impact while maintaining high performance [15–19]. Consequently, aerogel-based materials represent a state-of-the-art solution for energy-efficient, environmentally responsible, and culturally sensitive building renovation, supporting the preservation of architectural heritage while meeting contemporary sustainability goals.

3 Methodology

3.1 Criteria for selecting nanomaterials

In recent years, a variety of commercially available nanomaterials have been developed and deployed to improve energy efficiency in buildings, such as:

- **Graphite-enhanced expanded polystyrene**: a material with incorporated graphite nanoparticles or carbon particles within a polystyrene matrix, which significantly enhances its thermal insulation properties [20].
- **Nano-ceramic thermal coatings**: advanced thin-film coating materials applicable to a range of surfaces, providing both reflective and insulating properties and contributing to overall thermal performance [21].
- **Vacuum Insulation Panels (VIPs)**: materials that provide outstanding thermal insulation in ultra-thin configurations, making them ideal for applications where spatial constraints are critical.
- **Phase Change Materials (PCMs)**: materials comprising paraffin nanoparticles and salt hydrates encapsulated in polymer shells, which regulate indoor temperatures by undergoing phase transitions in response to thermal fluctuations. These materials enable precise and passive thermal regulation, achieving high capsule densities—up to three million per square centimeter—due to particle diameters ranging from 2 to 20 nm [22].
- **Aerogel-based insulation systems**: materials suitable for both transparent and opaque building elements, offering exceptional thermal performance at minimal thicknesses [23].

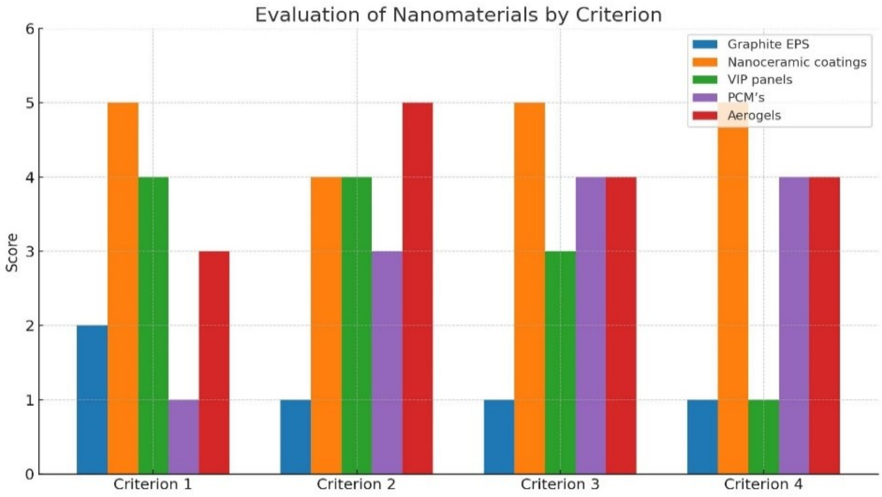

Figure 1. Evaluation of nanomaterials according to different criteria

For the purposes of this study, the performance of the five listed nanomaterial categories for façade applications was evaluated according to four criteria:

1. Thermal conductivity
2. Environmental impact (toxicity, pollution, and embodied energy)
3. Material thickness
4. Compatibility with cultural heritage conservation

The results obtained from the analysis, shown in Figure 1, reveal that aerogel-based products and nano-ceramic coatings consistently outperform other materials across all assessment parameters. These solutions demonstrate low environmental toxicity, reduced embodied energy, and minimal pollution during production. Moreover, they provide superior thermal insulation with minimal thickness. Crucially, their integration has a negligible impact on the architectural authenticity of façades, making them particularly suitable for the sustainable renovation of historically and culturally protected structures.

3.2 Criteria for selecting aerogel products

Due to their exceptional thermal performance, even at minimal thicknesses, and significantly lower embodied energy compared to conventional insulation systems and other nanomaterial-based solutions, silica aerogel-based products have emerged as some of the most advanced and promising insulation materials currently available in the building industry [23].

Silica aerogels exhibit remarkable physical and thermal characteristics, including an extremely low density of approximately 1.9 kg/m³, porosity of up to 99.8%, and a specific surface area ranging from 400 to 1000 m²/g. Pure silica aerogels demonstrate exceptionally low thermal conductivity ($\lambda \approx 0.014$ W/mK), while commercial variants typically range between 0.01 and 0.02 W/mK [24]. Their high porosity also makes them highly effective for acoustic insulation, with typical pore sizes ranging from 1 to 100 nanometers. Furthermore, the presence of silanol groups in their structure can be modified to induce hydrophobic behavior, enhancing durability in humid environments.

Silica aerogel insulation materials are commercially available in various configurations, including panels, blankets, plasters, lightweight concrete, granules, and transparent films, offering diverse solutions tailored to different architectural requirements.

On the other hand, aerogel-based products are considered sustainable and environmentally friendly due to their mineral nature, as well as their recyclability and reusability as insulation materials, aligning with circular economy (CE) principles. These materials offer versatile applications and can be tailored to meet specific CE requirements, owing to their relatively low embodied energy compared to conventional insulation materials [25,26]. Moreover, aerogels can be integrated into green building composites, providing unique properties and significant potential for sustainable construction [26,27].

Nevertheless, certain CE-related criteria—such as the applicability of aerogels on façades of cultural heritage buildings—are not universally satisfied by all aerogel types, which may limit their use in building renovation and adaptive reuse, key objectives of the CE framework.

To provide a comprehensive overview of current applications in the construction sector, as well as their potential to enhance energy efficiency (EE), support circular economy (CE) practices, and contribute to the preservation of architectural heritage through non-invasive renovation techniques, various types of silica aerogel-based nanomaterials were examined. Several commercially available aerogel-based products were analyzed in terms of their application methods in cultural heritage buildings. Their technical properties, along with their roles and impacts in the restoration and renovation of cultural heritage, were evaluated according to four key criteria: authenticity, integrity, reversibility, and compatibility (Table 1).

Table 1. Evaluation of aerogel-based products according to their Impact on cultural heritage

Type of aerogel product	Authenticity	Integrity	Reversibility	Compatibility
Aerogel blanket	Adaptable to uneven surfaces and suitable for applications where space and proportions must remain fixed, such as around windows and doors	Removal and replacement of original materials, as well as the use of anchoring points, should be minimized	Reversibility is essential; it can be added to existing façades, and visual distinction from original materials is beneficial	Must be compatible with historic materials and techniques; note that exterior rendering may reduce vapour permeability, therefore scientific validation of compatibility is required
Panel / board	The authentic appearance must be preserved and not obscured; interior application is permissible only if no protected elements are present	Boards may be installed using adhesive fixation without mechanical anchors	Application must be reversible; it may be added to existing façades, and visual distinction from original materials is desirable	Must be compatible with historic materials and techniques; note that exterior rendering may reduce vapour permeability, therefore scientific validation of compatibility is required
Plaster / render	Suitable as a mouldable material for uneven surfaces and detailed architectural features, allowing replication of the original appearance	Can be applied as an additional layer over existing plaster without compromising structural integrity	Reversible; it can be removed to expose original layers using a trowel, with a stiff brush for residue removal; its softness is an advantage	Must be compatible with historic materials and techniques; note that exterior rendering may reduce vapour permeability, therefore scientific validation of compatibility is required

Granular form	Filling of unexposed cavities with granules does not affect authenticity	Addition of granules does not affect the structural integrity of the building	Reversible; material can be removed to restore the previous state	May reduce adhesion of adjacent materials; increased hydrophobicity should be considered
Translucent panel	Provides diffused daylight while remaining visually distinguishable from original glazing; also improves acoustic performance	Existing translucent panels can be replaced without compromising integrity, although additional framing may be required	Reversible; panels can be removed and replaced to restore the original condition	Generally compatible with existing glazing systems; panels may fit within existing frames; glass and polycarbonate outer layers are considered compatible

Based on the analysis presented in Table 1, it can be concluded that aerogel-based thermal insulation plasters emerge as the most suitable materials for the renovation and preservation of historic buildings. Aerogel-based thermal plasters or renders demonstrate significant potential for application in existing buildings, particularly in cultural heritage contexts, due to their soft texture and adaptability to varied surfaces [26,27].

In accordance with preservation criteria for historic structures, aerogel plasters exert minimal impact on authenticity, provided that they are chemically compatible with the original materials and can be removed without causing damage or requiring invasive fixings [28].

The application of aerogel plasters not only enhances a building's energy efficiency and sustainability but also provides protection against climatic effects, thereby extending its lifespan. Owing to their composition and application methods, these plasters are available in various textures and colors, enabling them to closely replicate existing materials. This makes differentiation challenging while preserving the original fabric (Figure 2).

3.3 Case Study: Energy Performance Simulation

3.3.1 Description of the selected case study building

Buildings constructed after the 1963 Skopje earthquake represent more than 60% of today's building stock in Skopje and, at the same time, constitute an important part of the city's modernist cultural heritage. Most of these buildings have significant architectural, cultural, and historical value, not only for Skopje but also within the broader context of the global heritage of the Modern Movement.

However, these buildings were constructed without adequate thermal insulation, in accordance with the standards of their time, when energy efficiency and circularity were not considered key factors in building design. As a result, they are now major energy consumers, characterized by poor thermal comfort, high energy demand for heating and cooling, and substantial CO_2 emissions. In addition, they experience accelerated material degradation and increased maintenance costs, making them far from sustainable [29].

Figure 2. Visual comparison of façades in case of original materials and aerogel plaster application: (a) Renaissance building façade; (b) natural concrete façade

Furthermore, these buildings are equipped with outdated heating systems connected to the municipal district heating network, which relies heavily on fossil fuels and contributes significantly to air pollution in Skopje—one of the city's most pressing environmental challenges.

It can be concluded that these types of buildings are highly exposed to climate-related degradation, and that circular economy (CE) practices are difficult to implement under their current conditions. Therefore, there is an urgent need for their modernization and proper renovation, incorporating contemporary systems and equipment, as well as effective thermal insulation and sustainable, circular materials. At the same time, their architectural authenticity must not be compromised during the renovation process.

For this study, the building of the Macedonian Academy of Sciences and Arts was selected as a representative example of the post-earthquake period and its characteristic typology (Figure 3). The building serves as a multifunctional public facility with administrative and educational functions and represents significant architectural heritage. It has a total net area of 8,298 m² and a heated volume of 29,770 m³, supplied by the city's central district heating system. Constructed entirely from exposed concrete, the structure lacks thermal insulation and includes a large glazed façade, with a total window area of 2,236 m² (Figure 3a).

To evaluate the building's energy performance, a 3D model was developed based on the original project documentation (Figure 3b). Condition assessments were carried out through on-site inspections, complemented by interviews with building occupants.

The key challenge in terms of sustainability, energy efficiency, and maintenance of the building of the Macedonian Academy of Sciences and Arts, as a protected example of Skopje's modernist architectural heritage, is the preservation of its original appearance during renovation. Therefore, an energy performance simulation was conducted for two building conditions: the existing state and an improved scenario incorporating thermal insulation materials applied to the building envelope.

3.3.2 Energy Performance Simulation Methods

An energy performance analysis of the building was conducted using the EnergyPlus simulation engine. A detailed model of the building, internally divided into 257 thermal zones, was developed using DesignBuilder. In addition to the thermal zoning, the baseline model incorporated all relevant information obtained from the project documentation and on-site assessments, including detailed geometry, HVAC systems, and material specifications.

The second building model was derived from the baseline model by adding insulation to the walls, roof, and windows. To preserve the building's original appearance, 10 cm of extruded polystyrene (XPS) was applied only to non-visible elements, such as the basement slab and roof. The windows and glass doors were upgraded to energy-efficient, aluminum-framed triple glazing. The selection of aerogel-based thermal plaster (FIXIT 222) as the primary insulation material was based on its advantages over conventional insulation materials, particularly for cultural heritage applications, including low thickness, environmental sustainability, and the ability to replicate the texture and visual characteristics of exposed concrete.

Due to its compatibility with historic materials and minimal visual impact, 6 cm of aerogel plaster was applied to façade walls where the preservation of authenticity is critical. The analyses were performed with respect to energy efficiency, environmental impact, and heritage conservation for both models, the baseline and the improved one. The results obtained were compared and discussed in terms of key performance indicators, including heating and electricity consumption, operational costs, and CO_2 emissions.

4 Results

The simulations demonstrated significant reductions in the U-values of all envelope assemblies (walls, ground floor, roof, windows, and doors). Notably, substantial improvement was observed in the façade walls where aerogel plaster was applied across all façade wall assembly types. Optimizing the U-values of the façade walls was critical, as they represent the largest fraction of the building envelope, while the aerogel insulation is limited to a 6 cm layer and the walls must maintain their original architectural appearance. Table 2 presents a comparison between the baseline condition, with U-values prior to renovation, and the improved scenario, with U-values after renovation, clearly illustrating the reductions achieved across all assemblies.

The results obtained for average monthly heating energy consumption in kWh of the baseline and improved model are compared in Figure 4. The simulation results indicate that required thermal energy for heating of the building in the current state during the winter months established it as huge energy consumer.

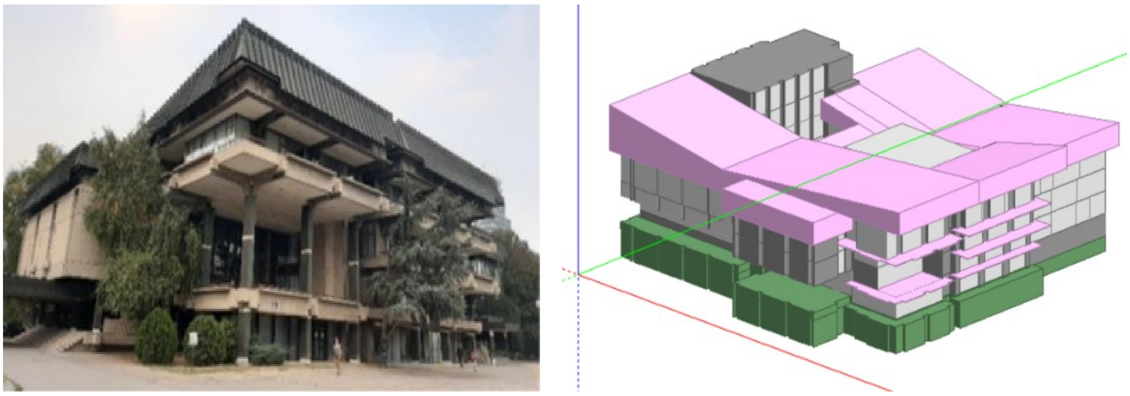
(a) (b)

Figure 3. Building of the Macedonian Academy of Sciences and Arts: (a) current condition; (b) 3D model

Table 2. Comparison of U-values of building envelope assemblies before and after renovation

Envelope assemblies	**Baseline – U-values before renovation [W/m²K]**	**Scenario 1 – U-values after renovation [W/m²K]**
Facade wall assembly type 1	4.632	0.284
Facade wall assembly type 2	3.966	0.393
Facade wall assembly type 3	4.679	0.424
Facade wall assembly type 4	0.542	0.251
Ground floor assembly type 1	1.188	0.244
Ground floor assembly type 2	0.995	0.235
First floor assembly type 1	1.982	0.378
Roof assembly type 1	0.420	0.127
Roof assembly type 2	0.280	0.153
Windows and doors (type 1)	5.61	0.60
Windows and doors (type 2)	2.00	0.60

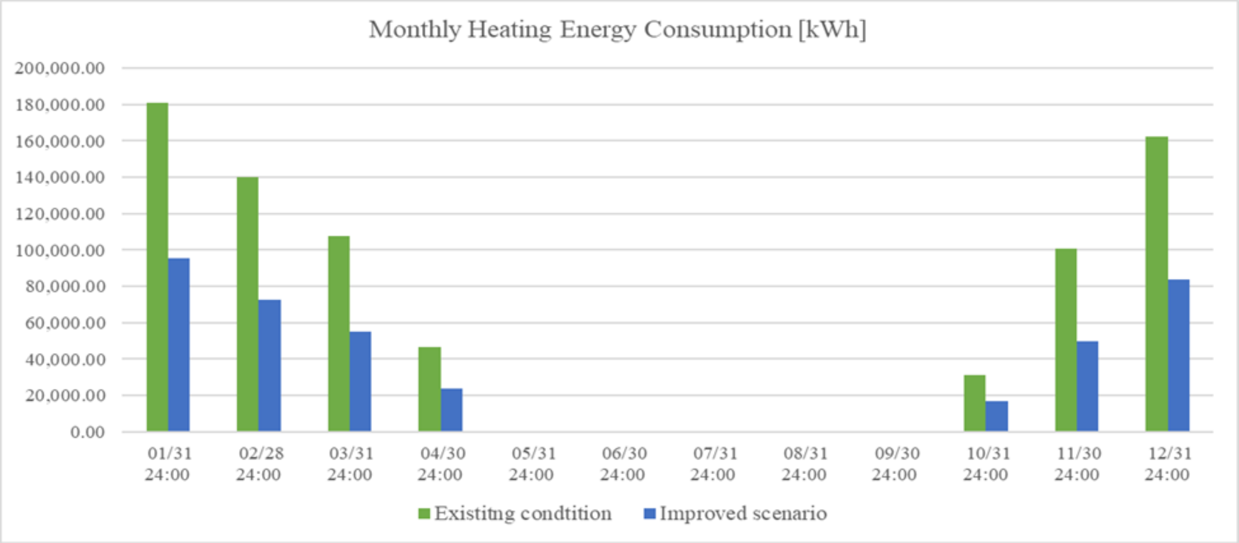

Figure 4. Monthly heating energy consumption of the baseline and improved building

From the results shown in Figure 4, it can be observed that the baseline model requires an average monthly heating energy of 64,107 kWh, corresponding to an annual heating energy consumption of 769,284 kWh, or 96.5 kWh/m². On the other hand, the improved building requires an average monthly heating energy of 33,112.6 kWh, corresponding to an annual heating energy consumption of 397,351.2 kWh, or 51.6 kWh/m².

It can be concluded that the application of aerogel plaster to the façade walls, along with conventional thermal insulation applied to non-visible building elements, leads to a significant reduction of 48.3% in heating energy consumption compared to the current state of the building.

The average monthly cooling energy consumption (kWh) of the baseline and improved models during the summer months is compared in Figure 5.

From the results shown in Figure 5, it can be observed that the baseline model requires an average monthly electricity consumption for cooling of 6,550 kWh, corresponding to an annual electricity consumption for cooling of 78,600 kWh, or 9 kWh/m². The improved building requires an average monthly electricity consumption for cooling of 6,020 kWh, corresponding to an annual electricity consumption of 72,240 kWh, resulting in a reduction of approximately 10% in cooling electricity demand.

The relatively low percentage reduction in cooling energy consumption can be attributed to several factors. During the summer period, when the building typically experiences the highest cooling demand, a collective vacation period for building users results in reduced occupancy and overall building utilization.

Another contributing factor is that the cooling demand occurs only during the months of July and August, in contrast to the heating season, which extends over a significantly longer period of several months. A further reason is the high thermal mass of concrete, the primary construction material of the building. Due to this property, the building heats up more slowly and dissipates heat more effectively, thereby reducing the demand for cooling energy.

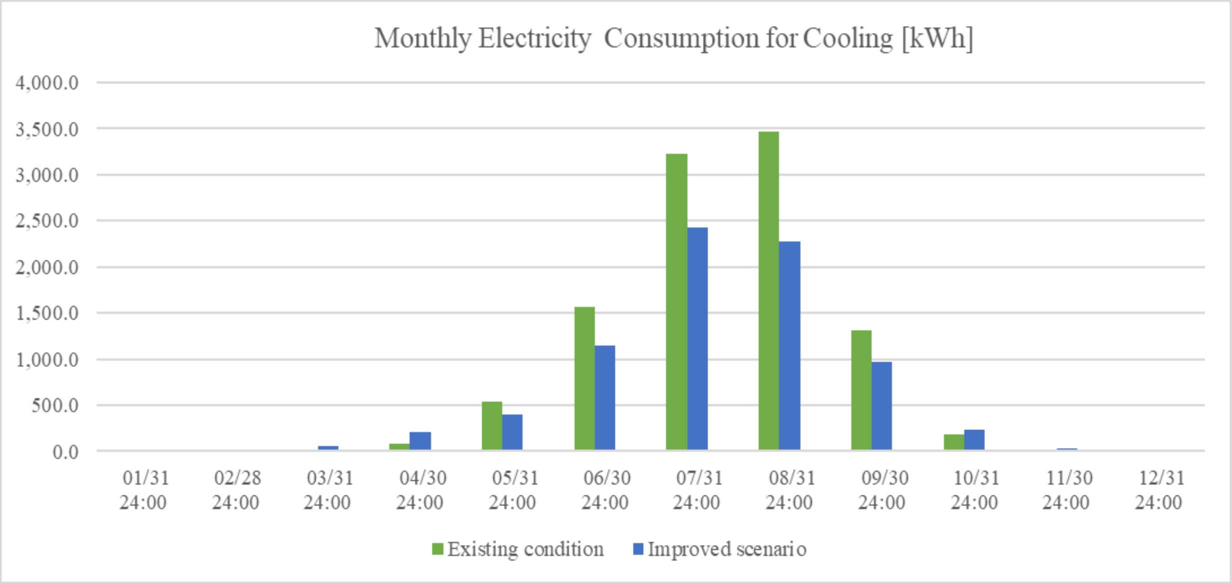

Figure 5. Monthly energy consumption for cooling of the baseline and improved building

Furthermore, the average monthly electricity consumption for lighting, operation of electrical equipment and appliances, as well as cooling and ventilation provided through a heat recovery system during the summer and supplementary air conditioning and electric heating during the winter months, is compared for the baseline and improved models in Figure 6.

From the results shown in Figure 6, it can be observed that the baseline model requires an average monthly electricity consumption of 41,335.5 kWh, corresponding to an annual electricity consumption of 496,026 kWh, or 62.2 kWh/m². The improved building requires an average monthly electricity consumption of 36,053 kWh, corresponding to an annual electricity consumption of 432,636 kWh, or 54 kWh/m², resulting in a reduction of approximately 15% in overall electricity consumption.

These results indicate that the installed systems for maintaining indoor conditions operate inefficiently due to inadequate thermal insulation, resulting in poor thermal performance of the building envelope.

The evaluation of total energy costs for consumed thermal and electrical energy during building operation, for both the baseline and improved models, is presented in Figure 7.

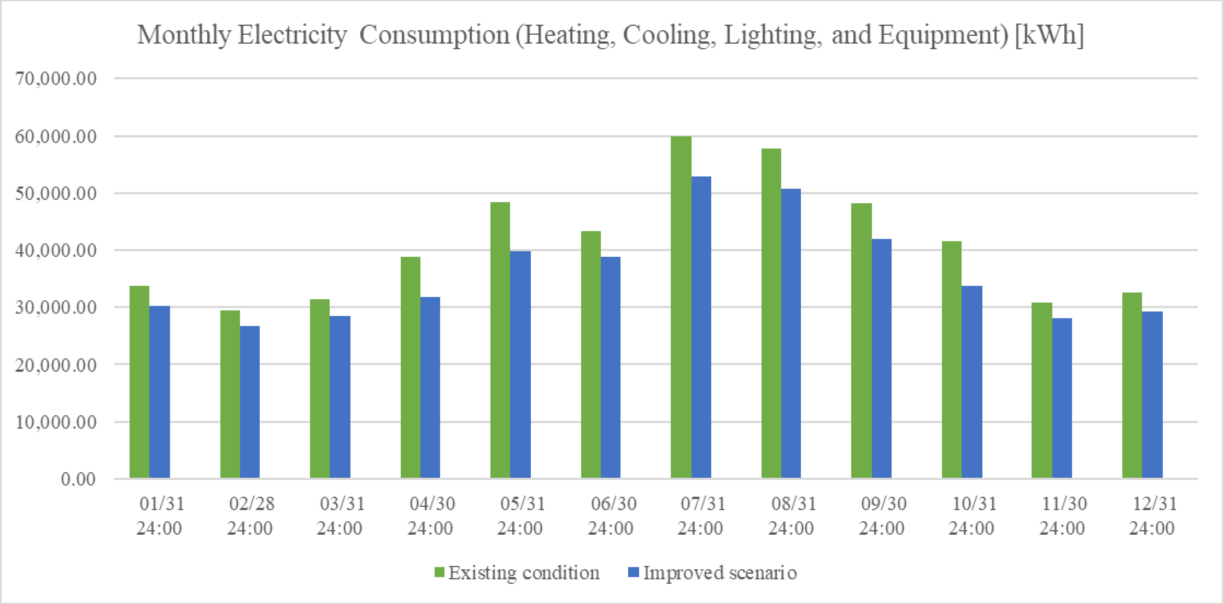

Figure 6. Overall monthly electricity consumption of the baseline and improved building

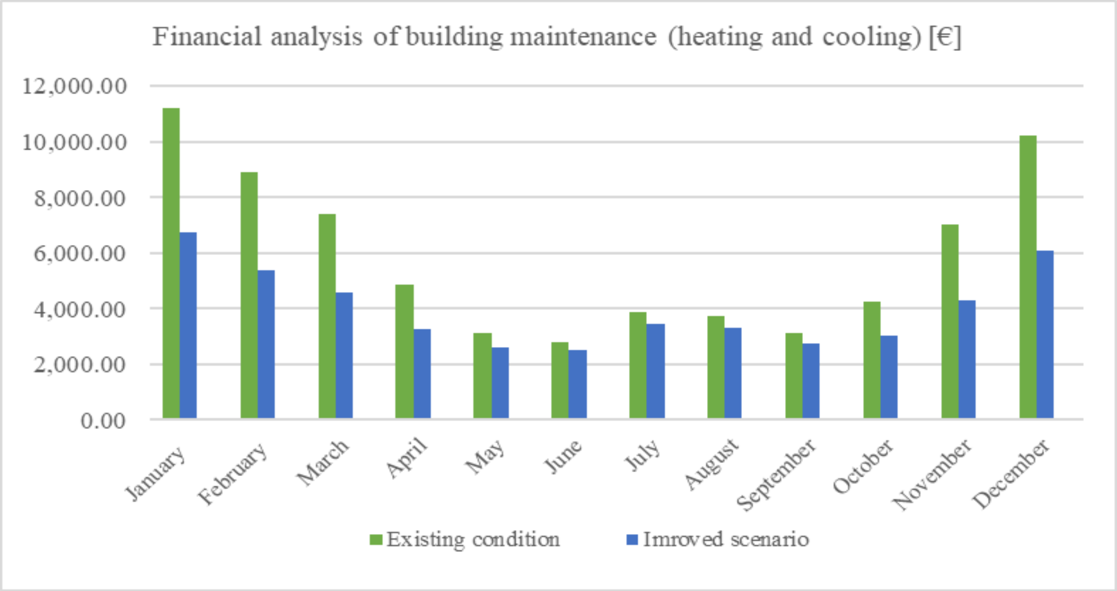

Figure 7. Overall monthly financial cost for maintenance of the baseline and improved building

From the results shown in Figure 7, it can be observed that maintaining thermal comfort in the building's current state leads to high financial costs throughout the year, particularly during the winter months. A reduction of approximately 40% in annual electricity costs for heating and cooling can be observed in the improved building compared to its current state.

The overall monthly CO_2 emissions generated during the operation of the building for both the baseline and improved models are compared in Figure 8. From the results presented in Figure 8, it can be concluded that the building of the Macedonian Academy of Sciences and Arts can be classified as a highly polluting building, considering its size and function.

From the results shown in Figure 8, it can be observed that the baseline model produces an average monthly CO_2 emissions of 61,727.7 kg, corresponding to annual CO_2 emissions of 740,732 kg, or 92.9 kg/m². The improved building produces an average monthly CO_2 emissions of 40,078.4 kg, corresponding to annual CO_2 emissions of 480,940.8 kg, or 60.3 kg/m², resulting in an overall reduction of approximately 35% in CO_2 emissions.

From the presented results, it can be concluded that CO_2 emissions are highest during the winter months, when the building's energy demand for heating reaches its peak.

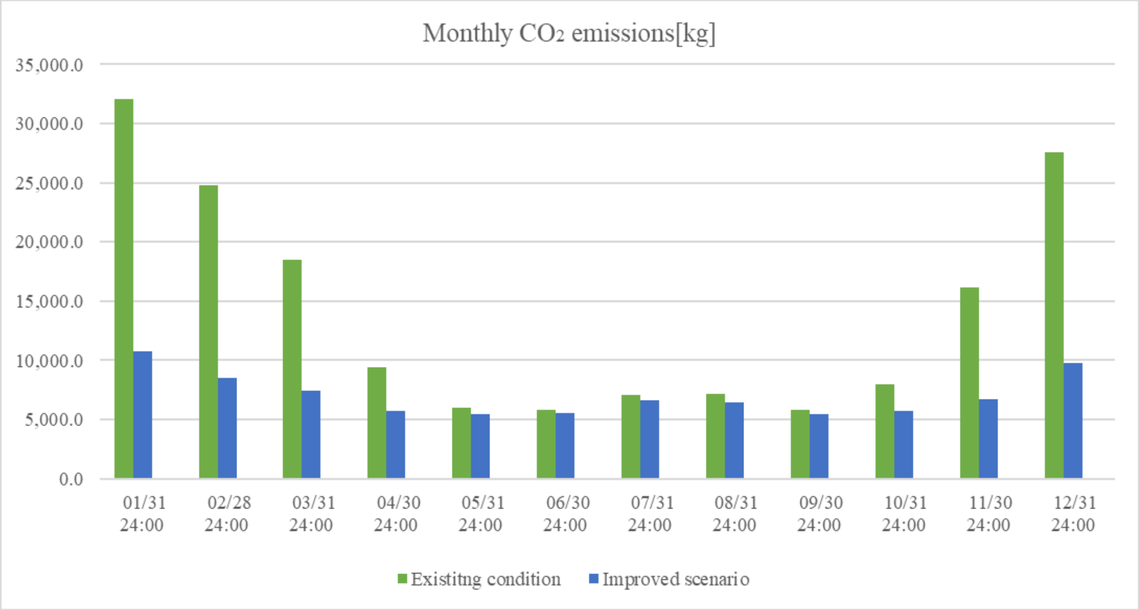

Figure 8. Overall monthly CO_2 emissions of the baseline and improved building

5 Conclusions

In order to achieve EU climate targets, improving the energy efficiency and sustainability of the building stock through the integration of circular economy (CE) practices is essential. The circular economy, particularly within the building sector, aims to reduce environmental pollution, extend building lifespans, minimize material waste, and promote the use of durable construction materials. Integrating CE principles into the renovation of existing buildings can significantly reduce material consumption, enhance energy performance and sustainability, and lower embodied emissions associated with building materials.

This paper presents the potential of various aerogel-based materials, emphasizing their superior thermal properties, low embodied energy, and versatility in application within the built environment. Aerogel-based materials are most often incorporated into new hollow walls or combined with concrete and other materials during product fabrication. However, such applications are typically limited to smaller architectural elements rather than being widely adopted as innovative solutions for improving the energy efficiency of existing structures, particularly where the preservation of authenticity and integrity is required.

The presented comparative analysis of aerogel-based materials for enhancing the sustainability of existing buildings indicates that aerogel thermal plaster is the most suitable solution for the renovation of buildings classified as cultural heritage, considering the conservation criteria of authenticity, integrity, reversibility, and compatibility. The results of the analysis show that the application of aerogel plaster to the building envelope leads to significant reductions in heating and electricity consumption, as well as lower CO_2 emissions and reduced operational costs compared to the current state.

Furthermore, the application of aerogel plaster contributes to building durability and environmental protection, in alignment with circular economy principles. Externally applied aerogel plaster can mitigate thermal bridges, protect the façade from climatic influences, and reduce material degradation and carbonation.

Therefore, it can be concluded that aerogel plaster represents an innovative and promising solution that integrates energy efficiency, circular economy principles, and the preservation of cultural heritage.

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CRediT authorship contribution statement

Liljana Dimevska Sofronievska: Data collection, Data analysis, Research, Methodology, Computer simulations, Validation, Writing - preparation of original text. Meri Cvetkovska: Methodology, Supervision, Validation, Writing-Review and Editing. Ana Trombeva Gavriloska: Methodology, Supervision, Writing-Review and Editing. Teodora Mihajlovska: Data collection, Data analysis, Writing - preparation of original text. Marija Grujic: Supervision, Validation, Writing-Review and Editing. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

This manuscript uses the following abbreviations:

CE – Circular Economy
EE – Energy Efficiency
NZEB - Nearly Zero-Energy Buildings
VIP - Vacuum Insulation Panel
PCM - Phase Change Material
XPS - Extruded Polystyrene

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