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# High-performance materials and technological solutions to improve the thermal performance of historic buildings

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**Abstract.** The aim of the paper is to outline the state-of-the-art in the field of historic buildings' energy retrofit through high-performance materials or innovative solutions. The research question is to understand if the latter can be positively applied to historic building in terms of compatibility and can contribute to create tailor-made solutions, avoiding or mitigating critical issues from the preservation point of view. This required the evaluation of many publications including papers, handbooks, booklets, and guidance as well as research reports. The literature review was then summarized in two research fields for each building element: retrofit solutions and high-performance materials and solutions applied to historic buildings. The technical properties of these highly efficient materials and their possible uses in heritage buildings are shown through the comparison and the data analysis of some case studies. Starting from a general reasoning on retrofit solutions and the interactions between the various building components within a whole building energy retrofit project, the paper assesses how high-performance materials are or are not widespread, which kind of data is available and what is still missing.

**Keywords** – High-performance materials; Historic buildings; Energy retrofit; Thermal performance improvement; Literature review.

## 1. Introduction

The literature focused on improving the energy efficiency of built cultural heritage has increased in the last years, becoming an important topic within the scientific community. Considering that approximately 30% of the European building stock consists of historic buildings [1], any energy management and performance improvement may lead to a significant reduction in the global energy consumption and greenhouse gas emission. However, it is considered that historic buildings are not energy-efficient and this mindset leads to radical changes to upgrade them. Actually, the energy performance of most historic buildings can be improved, but it is essential to find alternative and compatible energy retrofit approaches that harmonize energy efficiency needs, sustainability and conservation principles. The best way to find the right compromise between the issues involved is to adopt a “Whole Building Approach” which integrates reflections on building conditions and context with measures on the envelope and services, also taking into account the way people live and use the building itself [2]. In particular, among the energy retrofit interventions on the envelope, there are some solutions involving the addition to the existing components of high-performance materials, such as aerogel, vacuum insulation panels (VIPs), vacuum insulation glazing (VIG) and so on. So far, the application conditions and compatibility of these materials and their potential in the enhancement of indoor microclimatic conditions in heritage buildings have not yet been evaluated from a quantitative and qualitative point of view. Hence, the aim of the paper is to understand what data is available to assess not only durability, effectiveness and compatibility of these materials, but also whether they, given their reduced thickness and excellent properties, can

favour the conservation of historic buildings or, at least, reduce the criticalities that create a barrier to their application.

## **2. Literature review methodology**

A literature review was carried out with the aim of outlining an overview of the research status on energy retrofit solutions and the integration of high-performance materials in historic buildings. For this purpose, many publications were selected through three electronic databases of peer-reviewed literature (Scopus, Web of Science and Google Scholar). Here, a set of keywords were combined in different way in order to obtain as many publications as possible: both terms related to the energy retrofit of historic buildings (Retrofit, Historic\* Building) and high-performance materials (Innovative material OR High-performance material) were entered. After analysing all these documents, only papers related to the retrofitting of historic buildings were picked: 125 references were therefore examined in full. To these should be added guidance instruments such as handbooks, guidance, booklets and so on published on the websites of public body as well as non-profit organizations. A total of 124 examples, published in Europe and America, were examined. Finally, there are many Research Institutes and Centres that have developed long-term research programs and projects which significantly contributed to the production of study reports. In addition to the previous documents, other 37 references were taken into consideration, for a total of 286 publications. The literature review process is here summarized in the following two paragraphs. The first is dedicated to the retrofit solutions for the four building components, also investigating the relationships between them as part of a whole building energy retrofit project, the second to the technical properties of highly efficient materials and their possible uses in historic buildings, explored through case studies.

## **3. Retrofit solutions**

Planning retrofit interventions is a complex process of choosing between many possible solutions. Different historic construction techniques, conservation conditions and usage types of buildings, locations and boundary conditions (local climate, orientation and exposure) do not allow to identify one-size-fits-all solution that can be applied indiscriminately to all historic buildings. It is therefore necessary to adopt a tailor-made approach able to implement solutions case-by-case according to the specific needs of each building. In particular, improving the thermal performance of the historic building envelope (walls, windows, roofs and floors) requires finding the right balance between heritage conservation, energy efficiency requirements, sustainability, indoor comfort, health and well-being of people and so on. The selection of well-calibrated solutions, deemed suitable for historic buildings, is a challenge and, in order to tackle it, several solutions have been recognised in the literature: as a matter of fact, the 286 publications analysed provided a picture of energy retrofit options.

Given that the preservation of the historic buildings' values may impose constraints on certain interventions, the solutions identified were grouped into three levels of increasing impact on the heritage, in the perspective of a step-by-step approach to energy efficiency improvement. The first level concerns low-impact interventions, i.e. conservative options potentially applicable to any building, such as repairing deteriorated element, recovering shutters and adding curtains to windows, lining interior walls with hangings, insulating the ceiling, adding rugs or carpets to ground floors and so on. The second regards medium-impact interventions: in this case the sustainability of the intervention depends on the characteristics of the building and the climatic zone in which it is located. It includes strategies like installing secondary glazing or replacing glass units in windows, applying thermal insulating plaster to walls, insulating pitched or flat roofs and existing ground floors etc. The third level has the greatest impact and, therefore, needs careful reflection because it is aimed at achieving high performances while taking little account of the values of the historic buildings. This last level consists of replacing windows, roofs, tiles and existing floors with new components and insulating walls inside or outside.

Furthermore, the literature review allows to discuss some general findings for each building component. With regard to windows (93 documents), they are commonly considered the weakest element of the envelope and, therefore, the first to be replaced in the name of a significant energy saving which is actually minimal compared to the interventions on other building parts [3]. Unfortunately, window replacement is a widespread practice, also promoted by tax incentives, and has caused the loss

of a large number of traditional windows [4]. Moreover, from the environmental point of view, the replacement of the original windows by new ones leads to a 7-fold increase in CO<sub>2</sub> emissions into the atmosphere, due to the whole production cycle of the new building components and to the disposal of those removed [5]. Contrary to what one may think, more “sustainable” solutions are possible: there are several strategies that can be applied to enhance windows thermal performance without having to replace them (adding window films, storm windows etc.). In the case of walls (89 documents) the common measures do not fully meet the conservation requirements because they lead to the loss of historic finishes, hence new solutions, maybe seasonal or removable, are needed. On the subject of roof (73 documents), all identified retrofit solutions focus on ceiling or roof level depending on whether the attic is inhabited or not. From a conservative point of view the best solutions are those that intervene below the roof level because they have a low impact. However, if it is necessary to intervene above the rafters, it would be better to favour some roof measures that recall traditional practices such as the one well-known in Palermo of covering the original tiles with light paint [6]. Finally, the research on the floor is scarce compared to the other elements (31 documents). In general, there is a tendency to replace them by taking the opportunity to install underfloor heating systems.

Currently, there are some high-performance materials that can be used to optimise the energy performance of historic buildings. For instance, the Italian MiBACT Guideline includes a collection of sheets on types of intervention and available materials in which high-performance ones play a leading role: vacuum insulation panels, cool materials, phase change materials and insulating glazing with aerogel are just some examples of the systems considered [7]. However, in the section dedicated to the case studies, these types of materials are not mentioned. On the contrary, the literature review highlighted some interesting projects integrating them into their retrofit interventions.

### *3.1. Understanding the complex interactions among building components in a whole retrofit project*

The retrofit solutions presented in the previous section cannot be selected and installed uncritically, but as part of an energy efficiency project that considers the whole building and the impact of each measure on it [8]. For example, solid wall insulation, whether internal or external, should not be considered as a stand-alone measure, but should be planned, designed and implemented taking into account interactions with other building components to avoid unintended consequences (moisture, poor air quality, discomfort, etc.). Thus, it is not possible to install this measure successfully without considering the details of the junctions between external walls and floors, ceilings, roofs and windows: working on connections is essential to avoid the creation of thermal bridges which lead to air infiltrations and moisture-related problems such as mould growth and condensation risk [6]. The window-wall connection, in particular, is a weak point for both insulation types. In this case, the problem is not only to ensure the correct resolution of the thermal bridges but also, in a conservative prospective, to preserve the original windows. Although there are some guidelines suggesting their conservation by showing different connection scenarios between the internal/external insulation and the existing window [9], the variety of window types and positions in relation to the wall thickness require ad hoc solutions that are difficult to standardise. All of this, together with the high thickness of the conventional insulation materials (which makes the connection with the existing windows not so practical) and a lack of recognition of the windows historic value, leads to their widespread replacement. This is just an example of how a single retrofit measure can lead to a series of problems in the design process that even cause the loss of historical material consistency.

With the aim of providing comprehensive, well-considered and building-friendly energy efficiency interventions, it would be interesting to investigate if the application of high-performance materials in retrofit solutions can lead to particular benefits in solving problems at building junctions. Some authors, for instance, have pointed out that the window-wall connections can be optimised by applying a thin layer of a materials with high thermal resistance to insulate the interior side of the wall, such as aerogel: its low thickness makes it possible to work around the windows (turning the insulation over the windowsills and reveals) limiting the narrowing of the opening compartment and allowing the original window to be kept in place [6, 10]. Currently there are few studies exploring the potential and criticality of these materials in the connection details between building components [11]. As a matter of fact, most of the literature tends to focus on assessing the performance of individual retrofit measures.

#### 4. High-performance materials and solutions applied to historic buildings: limits and possibilities

Conventional insulation materials (e.g. glass wool, EPS etc.) are widely used in the construction field and commercially available, therefore, their characteristics are well-established and well-known, as well as their performance in cultural heritage applications. On the contrary, high-performance materials are object of numerous ongoing studies and their potential or limits in balancing conservation, energy and sustainability needs are still to be studied. The literature review shows that only 48 documents out of 286 concern the use of retrofit solutions with highly efficient materials: among them, most are dedicated to walls (31), while the others are divided between windows (8), roofs (8) and floors (1). These documents deal with in-situ experiments, software simulations, in-lab tests and, above all, with real cases subject to energy efficiency improvements, so they are particular interesting for highlighting the property and the problems of those materials. Table 1 summarise the most studied parameters. One of the most relevant problems in any analysis considering real case studies is that we are never in the position to understand which analyses and reasoning led to the final choice and which possible alternative solutions were considered and rejected.

**Table 1.** Data before and after the refurbishment works.

Intervention and site	Before refurbishment		After refurbishment		U-value reduction (%)	Product $\lambda$ (W/mK)	Product price (€/m <sup>2</sup> )
	Description	U-value (W/m <sup>2</sup> K)	Description	U-value (W/m <sup>2</sup> K)			
<b>(a) Windows</b>							
Archibald, Edinburgh (Scotland) [12]	Single glazing units	4.4 (tot. window U-value)	Pilkington Spacia VIG (6.2 mm)	1.9 (tot. window U-value)	57%	/	From 220 to 385 <sup>a</sup> [13]
Hermitage Museum, Amsterdam (Netherlands) [14]	Single glazing units (4 mm)	ca. 5	Pilkington Spacia VIG (6.2 mm)	1.4 (centre-of-pane U-value)	72%		From 220 to 385 <sup>a</sup> [13]
Alte Börse, Zürich (Switzerland) [15]	Skylight	> 2.00	OKAGEL aerogel glazings	0.6	70%	0.018	/
Tenement flat, Edinburgh (Scotland) [16]	Timber window shutters	2.2	Aerogel blankets (10 mm) fitted to shutters	0.4	82%	/	/
<b>(b) Walls</b>							
Landshövdingehus (County governor's house), Gothenburg (Sweden) [11]	Brick (362 mm) and wood (102 mm) walls	1.1	VIPs (20 mm) and glass wool panels (30 mm), EXT.	0.4	63%	VIPs 0.007 Glass wool 0.04	/
Mühle Sissach, Sissach (Switzerland) [17]	Stone walls (700 mm)	1.1	FIXIT 222 aerogel render (50 mm), EXT.	0.4	63%	0.028 [15]	100 / 190 <sup>b</sup> [15]
Müli Oberhallau, Oberhallau (Switzerland) [15]	Stone walls (900 mm)	1.7	SPACELOFT aerogel blankets (20 mm), EXT.	0.48	72%	0.015 [15]	180 <sup>b</sup> [15]
MFH Fichtenstrasse, Zürich (Switzerland) [18]	Stone walls (ca. 500 mm)	1.9	EPS (20 mm), INT. SPACELOFT aerogel blankets (20 mm), EXT.	0.4	79%	EPS 0.038 Aerogel blanket 0.015 [15]	Aerogel blanket 180 <sup>b</sup> [15]
Residential building, Rothesay (Scotland) [19]	Masonry rubble walls (500 mm)	1.3	Aerogel blankets (10 mm), INT.	0.6	54%	ca. 0.015 [15]	/

Wee Causeway, Culross (Scotland) [20]	Sandstone rubble walls	1.6	Aerogel blankets (10 mm), INT.	0.9	44%	ca. 0.015 [15]	/
Manoir de Cormondrèche, Cormondrèche (Switzerland) [21]	Stone walls (600-700 mm)	1.4	Heck AERO aerogel boards (20 mm), EXT.	0.4	71%	0.019 [15]	190 <sup>b</sup> [15]
Ryesgade 30 A-B, Copenhagen (Denmark) [22]	Brick walls (from 360 mm to 720 mm)	1.4	AEROROCK aerogel-stone wool boards (40 mm), INT.	0.4	71%	0.019	/
Multifamily house, Biel (Switzerland) [15]	Cavity walls	1.1	CABOT aerogel granulates blown into cavity (90mm)	0.17	84%	0.019	120 <sup>b</sup> [15]
<b>(c) Roofs</b>							
Duncairn Centre for Culture and Arts, Belfast (Northern Ireland) [15]	Timber pitched roof	ca. 1	SPACELOFT aerogel blankets (20 mm), above the rafters	ca. 0.56	44%	0.015	180 <sup>b</sup> [15]
Kirkton of Coull farmhouse, Aberdeenshire (Scotland) [23]	Timber pitched roof	0.49	Aerogel boards (11 mm), underside of the ceiling	0.32	35%	/	/
<b>(d) Floors</b>							
Kildonan, South Uist (Scotland) [24]	Thin concrete screed (40 mm)	3.9	Aerogel boards (30 mm) laid onto the floor	0.8	79%	/	/

<sup>a</sup> The price quoted in the document is 200-350 £/m<sup>2</sup>, but it was converted in €/m<sup>2</sup> to make it comparable.

<sup>b</sup> Prices for U=0,5 W/m<sup>2</sup>K.

The high-performance materials tested in the case studies are: aerogel, VIPs and VIG.

Aerogel is a highly porous material with a very low thermal conductivity (from 0.015 W/mK to 0.028 W/mK), strong hydrophobicity, low water vapour diffusion resistance and good fire ratings [15]. These physical properties make it well suited as thermal insulation in buildings. 13 case studies out of 16 regard the use of aerogel in historic buildings: 8 focus on walls, 2 on roofs, 1 on floors and 1 on windows. With regard to the opaque envelope, the most popular aerogel product types are blankets, boards, renders and granules. The effectiveness of their application varies according to the thickness, composition and thermal conductivity of the product, as well as the construction characteristics of the building. Aerogel blankets consist of a fibre fleece into which aerogel is embedded [15]. Four case studies used this type in walls: with an insulation thickness of 10 mm the U-value decrease between 44 [20] and 54% [19], while with a thickness of 20 mm from 72 [15] to 79% [18]. In the only case where a 20 mm aerogel blanket was applied to a timber pitched roof, a U-value reduction of 44% occurred [15]. The difference with the data found in walls with the same thickness of insulation is obviously due to the different stratigraphy of the building components. Another widespread product are aerogel boards created by gluing numerous layers of blankets or by binding aerogel granulate into boards [15]. Regarding walls, its application to two case studies led to a 71% reduction in the U-value, from 1.4 W/m<sup>2</sup>K to 0.4 W/m<sup>2</sup>K, even though in one case the insulation thickness double the other (40 and 20 mm) [21,22]. Finally, where aerogel boards were applied to a historic floor (30 mm) [24] and a roof (11 mm) [23] the U-value decreased by 79% and 35% respectively. A last well-liked aerogel type is the render made by joining aerogel granulate with inorganic binders [15]. In the only case found in literature, the application of a 50 mm layer of aerogel render on an external façade led to a decrease in wall thermal transmittance of 63% [17]. Another intervention is blowing aerogel granules into the cavity of a double wall construction:

in the case examined, insulating 90 mm of cavity led to a reduction in the wall U-value by as much as 84% [15]. Generally speaking, the data collected indicates a significant decrease in U-values in all the building components and a consequent improvement in their thermal performance. Furthermore, aerogel can achieve the same insulation properties of conventional materials with about half the thickness [15]. Its reduced dimensions not only save precious space inside or outside the structure, but also allow to preserve the original windows and maintain distinguishable protruding decorative elements, without altering the proportions of the building, the alignment with adjacent buildings or the arrangement of topside waters gathering and disposal systems. In order to achieve a reasonable compromise between conservation and energy retrofitting, renders are considered the most suitable aerogel types [25]: they do not require anchoring points to the structure; they can be applied to uneven historic surfaces, maintaining their light and shadow effects; they can be easily removed down to original layers with a low impact on the building integrity. However, all aerogel product types, even if considered “reversible”, overlap the existing layers of the wall and this leads to the loss of historic finishes, that is often an unacceptable condition in most ancient buildings. Although further investigations are needed in the assessment of physical compatibility of aerogel with historical materials and techniques, they could provide opportunities for historic buildings.

The situation is different in the transparent envelope, where there are two viable solutions: working on the glazing systems or on shading systems like shutters. In the review, the only real application example of panels filled with aerogel in a listed building is the Alte Börse in Zürich [15], where the existing skylight was substituted with translucent elements with a U-value reduction of 70%. The aerogel panels show significant insulation properties, but they are characterised by a translucent aspect that alters the view to the outside (causing a hazily deformation of optical images) and the perception of the building. Moreover, their use led to the loss of historical glazing which is an irreversible change. In addition to that, there are few examples in historical context that may attest its compatibility: the use of aerogel in windows components is still too experimental to find widespread application in this field. More interesting is the case study of Edinburgh flat [16] where traditional shutters were upgraded using a 10 mm aerogel quilt. Here, starting from a U-value of 2.2 W/m<sup>2</sup>K the shutters reached a value down to 0.4 W/m<sup>2</sup>K, with an 82% improvement. Nevertheless, this type of intervention cannot be applied to all types of shutters: they must have enough internal space to house the insulation, so if they consist of a single piece of wood, alternative tailor-made solutions are required.

All these case studies show significant thermal improvements which, however, are still burdened with high costs of the material. This is one of the most evident barriers to the diffusion of aerogel outside its established niche markets: its price is about 10-15 times higher than other conventional materials, for the same insulation requirements, and this is mainly due to the overly expensive production process and raw materials [15]. Studies are currently underway with the purpose of optimising aerogel production process and this will probably lead to noticeably lower price in the near future [26].

Vacuum insulation panels (VIPs) and vacuum insulation glazing (VIG) are also tested in some case studies, for example VIPs (20 mm) in the walls of a listed building in Sweden [11]. VIPs have a very low thermal conductivity (0.007 W/mK), but they are fragile and if a panel is damaged a loss of vacuum occurs and the overall thermal resistance of the wall decrease considerably [27]. For this reason, in the case analysed, a protection layer of 30 mm glass wool boards was applied over the entire VIPs surface. The same conventional material was used in the insulation around the windows: the VIPs cannot be adapted on building site so, to cope with the irregularities of the historic wall, glass wool was used to fill the space between the VIPs and windows. However, the influence of the protective layer is significant: if the walls were insulated with a continuous layer of VIPs, the U-value would be about 0.22 W/m<sup>2</sup>K but, taking into account the thermal bridges that glass wool creates in the façade, the actual wall U-value is 0.4 W/m<sup>2</sup>K [11], i.e. an increase in thermal transmittance of about 82%. Comparing this case study with the project characterised by the aerogel render, a consideration emerges: although the thermal conductivity of VIPs is four times lower than that of aerogel render, in both cases the U-value was reduced by 63%, from 1.1 W/m<sup>2</sup>K to 0.4 W/m<sup>2</sup>K. It is therefore quite clear that glass wool severely limits the performance of VIPs and so there is no advantage in using them under these circumstances. The drawbacks highlighted, along with high costs and poor data about their lifetime expectancy, are some of the major reasons why VIPs are not so common in the historical context.



Finally, as regards VIG, two case studies were found in the literature: the Archibald Place building in Edinburgh [12] and the Hermitage Museum in Amsterdam [14]. In both cases, the priority was to preserve the original window frames, replacing the 4 mm single-glazed unit with a glass characterised by a very low U-value and an extremely small thickness in order to fit the shallow frame rebate. As a matter of fact, VIG allow to achieve U-values of around 1.6 W/m<sup>2</sup>K with a 6.2 mm glazing thickness: their performance is comparable to that of a conventional double-glazed unit but taking up half the space [12]. Even though VIG are a valuable resource for the thermal performance improvement of historic windows, it is necessary to take into account some disadvantages related to the choice of these products: they employ metal pillars between glass panes, to prevent glass breakage (due to the pressure gradient), that are visible from a close distance and can induce thermal bridges; they can be produced only in limited sizes and their cost is still very high [12]. In the face of these limitations and with the aim of prioritising heritage conservation, other solutions are preferable such as the installation of a secondary glazing that allows to preserve the original windows adding a new high-performance layer. Nevertheless, VIG are a valuable resource for increasing energy efficiency in historic buildings, also fostered by the institutions involved in preservation.

An aspect of utmost importance, but neglected in almost all case studies, is the assessment of the environmental impact: the only exception is the Archibald Place building in Edinburgh [12], where the embodied energy of the VIG was calculated. Further studies on the sustainability of the intervention with high-performance materials are therefore needed.

In the spectrum of the materials available to satisfy the energy efficiency needs, there are also phase-change materials (PCMs) and cool materials, already mentioned in the Italian MiBACT Guideline [7] but not yet applied in historic case studies. Currently, they are subjects of some university experimental projects in existing context: valuable outcomes are provided by studies conducted on PCMs integrated in roof spaces [28] or on infrared reflective coatings for walls and roofs [29].

## 5. Conclusions

The interventions analysed (and the data obtained) together with the many present in the HiberAtlas online platform, developed within the IEA-SHC Task 59 and the Interreg Alpine Space ATLAS project [30], allow to make some general final considerations, keeping in mind the already expressed concept of "Whole Building Approach" and the necessary balance between conservation needs and performance improvement. The first reflection, inferred from the literature review, is that the study of the performance of single materials is more practiced than the analysis of the general behaviour of the building.

A second comment concerns research trends in retrofit solutions: on the one hand, there is a search of natural and local materials, perhaps in a logic of circular economy or revaluation of local production for market niches, and, on the other hand, the research focuses on "innovative" materials with the main purpose of minimising thickness. From a preservation point of view, for example, this allows to maintain other building elements (such as windows), also intervening on them with a multiplicity of solutions that can only be defined on a case-by-case basis. Anyway, there is a lack of LCA method for a sustainability assessment that are not only based on cost savings, payback or NPV. Other aspects such as acoustic comfort and CO<sub>2</sub> emissions over the whole life cycle of materials and components are seldom taken into account.

A third consideration regards the search for reversible elements, without any explanation on the reasons and advantages of the reversibility concept. If the problem of the building is real, the solution is unlikely to be removed, unless undesirable effects or errors occur. In a conservative logic, seasonal removable measures should rather be investigated. Reversibility and removability are therefore two different concepts and it is precisely in the long debate on preservation that the search for reversibility has now shifted towards retractability, i.e. avoid using products or components that leave no other possibility over time. If the research approach is understandably pushed on the more technical aspects, it is now recognised that other much less studied factors are deemed necessary for the success of the process. Only two are mentioned here (but others deserve attention): the involvement of users or asset managers and the teamwork between experts from different disciplines and conservation officers.

The aim of the paper is an overview and assessment of the range of possible solutions (there is no single way to act, but rather several alternatives) and a look at the problems and future prospects of the

integration of high-performance materials in the historical context. However, the more general objective is to examine possible different ways of intervening by overturning the common logic of considering the use of the best available technology today. In a delicate context such as the historical one, minimising the loss of historical material and preserving the built cultural heritage requires consideration of the most suitable technology among those available.

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