

Review

Retrofitting Historic Walls: Feasibility of Thermal Insulation and Suitability of Thermal Mortars

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Abstract: The European Union is pursuing an ambitious policy on climate action, urgently calling for an acceleration in the transition toward net-zero emissions by 2050. In this context, retrofitting historic constructions can play a key role in reducing European energy consumption and consequent emissions. What is more, beyond the opportunity for tackling climate change, thermal retrofits can improve indoor comfort while lowering operational costs, factors that are fundamental to ensure the continued use of historic constructions over time, and with that, improving their preservation and durability. The suitability of thermal insulation for this scope is still a debated topic. Thus, this study aims at contributing to the discussion by providing an overview on the feasibility of adopting thermal insulation for retrofitting external walls of historic buildings while preserving their significance and unique identities. Finally, the advantages of adopting thermal mortars rather than more traditional insulation solutions are outlined, and their potential efficacy is discussed.

Keywords: historic buildings; thermal mortars; thermal insulation; thermal retrofit; renders; plasters; energy efficiency; thermal conductivity; heritage; climate change



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1. Introduction

The climate crisis has become so serious that it is believed to be the defining issue of the current century [1,2]. The attention given to the problem's resolution has grown since the 1992 United Nations Framework Convention on Climate Change (UNFCCC), passing through the Kyoto Protocol and arriving at the Paris Agreement [3], thus achieving an international collaboration aimed at fighting climate change [4]. Despite the common commitment to the cause, in 2019 the European parliament declared a climate and environment emergency [5] because of the inadequacy of the progress made worldwide toward the objectives of the Paris Agreement [6]. Consequently, the European Commission decided to lead the way by example with the European Green Deal [7], through which the EU committed to make Europe the first climate-neutral continent by 2050 (i.e., the first one with net-zero greenhouse gas (GHG) emissions). What is more, in 2020, the EU legally embraced the urgency and importance of cutting GHG emissions via introducing the first ever European Climate Law [6], making the sustainable strategy of the union legally binding for all member states.

The EU is pursuing an ambitious policy on climate action, and it is urgently calling to accelerate and underpin the transition needed in all sectors, focusing particularly on resource-intensive ones, among them being the construction industry. The building sector is indeed identified as the largest single energy consumer in Europe, with 40% of its total energy use [8]. Given that 75% of the existing stock is energy inefficient and that a very small percentage of it is renovated each year (less than 1.5% in EU member states), existing buildings offer vast potential for energy use reduction, which the EU is heading to with the “renovation wave” initiative introduced with the European Green Deal [9].

1.1. Energy-Efficient Retrofits in Historic Buildings: The Importance

The key role of retrofitting existing constructions in Europe is clear, and the specific case of historic buildings has great importance for several reasons. First, 26% of the European building stock dates to before 1945 [10]. Hence, a considerable share of the existing buildings is composed of historic constructions [11,12], defined herein as traditional constructions [13] from before 1945, as they use some technologies, materials and solutions that are no longer being used, thus acting as testimonies of technical and architectural historic paradigms. This percentage gets even higher when countries like Belgium, Denmark, Italy, Latvia and Sweden are considered (27–38% of existing buildings can be ranked as historic in this scenario, according to the European Project RIBuild [14]). Consequently, retrofitting historic constructions can play a key role in reducing European energy consumptions [15] and consequent GHG emissions, thus collaborating in the mitigation of climate change, as has already been underlined by several cultural heritage experts [16].

Beyond the opportunity for energy savings, retrofits can improve indoor comfort [17] while lowering operational costs [18], factors that are fundamental to ensure the continued use of historic constructions over time, and with that, improving their preservation and durability. It is indeed well known that keeping heritage buildings in use is the most effective tool of protection, in accordance with integrated conservation strategies [19], as it ensures continuous maintenance while avoiding leaving the building in a state of neglect [20].

Likewise, retrofitting historic heritage plays a crucial role in sustainable development. Having comfortable, retrofitted buildings that are suitable for being kept in use means reducing the need for new constructions and the CO₂ emissions that building them would entail [21,22]. Furthermore, heritage buildings represent a non-renewable, irreplaceable resource that we have the duty to deliver to future generations [23]. For this reason, adapting, keeping in use and preserving historic buildings appears to be a key element in the field of sustainability, as already emphasized by the United Nations in the 2030 Agenda for Sustainable Development [24].

1.2. Thermal Insulation Solutions for Historic Walls: An Open Question

Given the growing urgency and importance of the topic, the scientific interest in energy efficiency and thermal comfort in historic buildings has strongly increased in the last few decades [25]. Many solutions are thus provided in the literature, and one of them is the adoption of thermal insulation for retrofitting external walls [26], which is a complex intervention for several reasons. It is not always feasible in historic constructions because of the need to preserve their valuable and characteristic features, whereas no similar concern affects interventions on existing buildings with no cultural value [27]. Furthermore, for heritage buildings, European standard EN16883:2017 [28] requires a first phase of recognition of the significance and specific values of the construction, based on which unsuitable measures should be excluded from the intervention design. Then, depending on the level of heritage significance, on-site visits from third parties such as heritage or planning officers may be needed [28]. Finally, even when the adoption of thermal insulation appears feasible, attention must be paid to the integration of the retrofit with the original construction, and the designer may be required to justify the technological and scenic integration of the chosen measures with the specific historic building considered (e.g., a document in this regard is required by the Italian Cultural Heritage offices [27]).

Another challenging aspect regards forecasting the effect of post-insulation strategies on the moisture dynamics in historic envelopes. The need for combining old and new components makes the intervention more challenging, and the likelihood of unforeseen circumstances is far greater than in new constructions [28]. As explained in [29], post-insulating existing constructions is very different from adopting thermal insulation in new ones. Indeed, in most new buildings, the insulation is introduced from the design phase, and it is assessed to avoid moisture-related degradation risks for the building components. Modern constructions are largely designed to block moisture entrance (capillary breaks,

membranes for the reduction of vapour transport, vented cavities, etc.), so trapped moisture is supposed to not be an issue, while the main focus is put on preventing the occurrence of condensation. On the contrary, traditionally constructed buildings are largely characterized by porous, capillary-active materials and no waterproofing layers [30]. Hence, traditional walls generally absorb liquid water (e.g., rain and rising damp), buffer it and then dry out thanks to their typically good vapor permeability [29]. Consequently, the choice of insulation should be very careful because of the risk of altering the original water transport dynamics, potentially leading to degradation issues related to moisture accumulation [31].

What is more, in existing construction, on-site inspections are generally needed (and mandatory for heritage buildings [28]) to gain awareness and information on existing components and their state of conservation. Walls may present high initial moisture levels and various types of damage, which should be critically evaluated and eventually resolved to avoid post-intervention problems [32]. When dealing with historic constructions, detailed information on the thermophysical properties of the envelope may also be needed [33], and specific in situ measurements should be then performed, such as the evaluation of the U-value of the original walls by means of heat flow meters [34,35]. Additionally, thermography can be adopted as a non-destructive measurement method to identify local heat losses due to defects in the construction (e.g., thermal bridges, air leaks, or gaps in the construction) [32]. All this information which is obtainable on site helps to define a correct diagnosis of heat losses through historic walls, thus assisting in the decision process for repair interventions and insulation type, thickness and position. When a thermal retrofit intervention is required because of the original poor indoor comfort conditions in the building, the indoor climate should be documented following standardized procedures [36]. Measurements on site are, in this case, needed to evaluate current conditions, identify the causes of discomfort and define a viable strategy for the retrofit [28,37,38], as well as suitable target environmental conditions [39–41].

Overall, the correct choice of insulation is sensitive to the specific case study [42], and there is no common answer [43]. Tailor-made solutions should be defined, considering the risk factors related to the condition of the existing walls (e.g., visible damage and rising damp), factors related to the installation of the insulation (e.g., uneven original surfaces and drying time of the wall before installing the insulation) and climate and initial conditions (e.g., initial moisture content, problems in water drainage and severity of the boundary climatic conditions) [32]. Finally, the use of thermal insulation cannot be a performance-based adjustment, but it should be carefully used as a preservation tool [20] that does not alter the distinctive character of historic constructions.

This work aims at providing an overview on the feasibility of adopting thermal insulation and, in particular, thermal mortars for retrofitting external walls of historic buildings while preserving their significance and unique identity. Then, the potential efficacy of thermal mortars for improving the thermal behavior of historic walls is discussed.

The term thermal mortar is hereby adopted to indicate the insulation material adopted in thermal rendering and plastering solutions (i.e., systems based on a mortar of low thermal conductivity), designed for applications for outdoor (rendering systems [44]) or indoor (plastering systems [44]) exposed sides of building elements. Thermal mortars are defined by standard EN 998-1:2017 [45] as mortars with thermal insulation properties (namely a dry thermal conductivity lower than $0.2 \text{ W}/(\text{m}\cdot\text{K})$ at $10 \text{ }^\circ\text{C}$) which are generally obtained thanks to the use of lightweight aggregates in the mortar mix design [46,47].

This review is part of ongoing research on thermal insulation solutions for historic buildings. Future studies will be devoted to investigating the effect of different insulation systems on the hygrothermal behavior of walls, in different types of historic constructions and climates (based on the monitoring of various case studies, experimental analyses and numerical simulations).

2. Feasibility of Thermal Insulation Systems for Retrofitting Historic Walls

The strategic role of an energy-efficient renovation of the existing building stock in the fight against climate change is evident, but historic buildings must be treated with special attention [48,49]. Even though climate change mitigation in the heritage sector is necessary, it is a very challenging task that needs holistic approaches [50]. Interventions designed for valuable historic constructions must undergo a preliminary phase of recognition of the values that characterize the specific building [20]. This step allows understanding the building's significance, which is important as relative degrees of cultural significance may lead to different conservation actions at a place (Art. 5.2 of the Burra Charter [51]). Thermal retrofits can be successively defined via considering solutions that comply with the transformability constraints imposed by the conservation principles on the specific building taken into account [52]. In this context, four aspects appear very relevant when it comes to thermal retrofits: authenticity, integrity, reversibility [18] and compatibility [53]. The first three concepts are discussed in detail herein to evaluate the feasibility of introducing insulation in historic walls. Some concepts that appear to be useful for the discussion are excerpted from the international charters on conservation and restoration of cultural heritage and reported in Table 1.

Table 1. Extracts from international charters on conservation and restoration of cultural heritage.

Reference	Extracts
The Venice Charter [54] Art. 5	The conservation of monuments is always facilitated by making use of them for some socially useful purpose. Such use is therefore desirable but it must not change the lay-out or decoration of the building. It is within these limits only that modifications demanded by a change of function should be envisaged and may be permitted.
The Venice Charter [54] Art. 6	The conservation of a monument implies preserving a setting which is not out of scale. [...] No new construction, demolition or modification which would alter the relations of mass and colour must be allowed.
The Venice Charter [54] Art. 13	Additions cannot be allowed except in so far as they do not detract from the interesting parts of the building, its traditional setting, the balance of its composition and its relation with its surroundings.
The Nara Document on Authenticity [55] Art. 13	Depending on the nature of the cultural heritage, its cultural context, and its evolution through time, authenticity judgements may be linked to the worth of a great variety of sources of information. Aspects of the sources may include form and design, materials and substance, use and function, traditions and techniques, location and setting, and spirit and feeling, and other internal and external factors. [...]
ICOMOS Charter Ratified at Zimbabwe general assembly [56] Art. 1.3	<i>The value of architectural heritage is not only in its appearance, but also in the integrity of all its components as a unique product of the specific building technology of its time. In particular the removal of the inner structures maintaining only the façades does not fit the conservation criteria.</i>
The New Zealand Charter [57] Art. 5	Conservation maintains and reveals the authenticity and integrity of a place, and involves the least possible loss of fabric or evidence of cultural heritage value. Respect for all forms of knowledge and existing evidence, of both tangible and intangible values, is essential to the authenticity and integrity of the place. [...]
The New Zealand Charter [57] Art. 6	[...] Intervention should be the minimum necessary to ensure the retention of tangible and intangible values and the continuation of uses integral to those values. The removal of fabric or the alteration of features and spaces that have cultural heritage value should be avoided.
The Burra Charter [51] Art. 5.2	Relative degrees of cultural significance may lead to different conservation actions at a place. [...]
The Burra Charter [51] Art. 15.1	[...] The amount of change to a place should be guided by the cultural significance of the place and its appropriate interpretation. When change is being considered, a range of options should be explored to seek the option which minimizes the reduction of cultural significance.
The Burra Charter [51] Art. 15.2	Changes that reduce cultural significance should be reversible and be reversed when circumstances permit. Reversible changes should be considered temporary. Non-reversible change should only be used as a last resort and should not prevent future conservation action.

Compatibility is not addressed in this analysis as it was examined in a separate study [26], which observed that the main problems regard the physical compatibility of insulation with historic materials in terms of water transport and moisture-related degradation risks. The outcomes of the study indicated that the capillary water absorption and vapor permeability of the insulation are of major importance, plus the correct choice of materials (and their properties) depends on the type of scenario considered (e.g., type of indoor and outdoor climate, exposure and thickness of the retrofitted component as well as the position of the insulation).

2.1. Position of the Insulation

Accounting for the authenticity principle, the appearance of original structures should not be changed. From this point of view, the location of the insulation can be discussed. External façades are usually one of the most important aspects of a historic building, and they contribute to creating its unique and local character [13]. Consequently, it is often preferable to intervene at the indoor facing side of historic envelopes rather than on exterior façades. Nevertheless, a large share of our historic heritage is composed of constructions whose value is mainly related to the role they play as “groups of buildings” [58] to form the cultural identity of townscapes or cities. Those cases often allow for external retrofits if the façade’s appearance is reconstructed to conserve its identity [59]. In any case, the impact on cultural values from both the interior and exterior sides should be assessed (Art. 13 of the Nara Document on Authenticity [55]) when planning the intervention, and for listed buildings, it should be discussed with the local monument preservation services [53]. For obvious reasons, external interventions are excluded for all buildings whose façades are subjected to integral protection [59], whereas when wall surfaces are recognized not to hold cultural or tangible values, or when they are so damaged they require a complete replastering [13], the introduction of insulation is viable.

From the point of view of the dimensional changes introduced, the intervention should not strongly alter the proportions and spatial perception of the building, its parts and its relation with the surroundings (Art 6. and Art. 13 of the Venice Charter [54]). Dimensional changes may be unacceptable at window and door openings [13] or where original surface details are valuable (Art 5. of the Venice Charter [54]). Thus, it is often necessary to limit the thickness of the insulation adopted in the intervention. Consequently, insulation systems that offer a wide range of available thicknesses and systems that can provide good thermal performance with a very small thickness appear to be more viable than others.

2.2. Feasibility of Different Thermal Insulation Solutions

According to the principle of integrity, removal, damage and replacement of original materials should be minimized to reduce the loss of original fabric (Art. 1.3 of the ICOMOS Charter ratified at the Zimbabwe general assembly [56] and Art. 5 of the New Zealand Chapter [57]). Thus, the damages introduced in the walls by the insulation-fastening supports should be minimized. For this reason, insulating plasters and renders are preferable over boards and blankets, which need anchoring points [53]. When anchors can be substituted by an adhesive layer, the intervention appears feasible, as long as the adhesive can be safely removed [52] or a protective system is used between historic materials and new ones, like laminated interlayers or protective films of Japanese tissue paper [60].

When accounting for reversibility (Art. 15.2 of the Burra Charter [51]), new additions to historic buildings should be recognizable and removable with minimal or absent damage to the original fabric. They should not be so different that they stand out, but they should be distinguishable from authentic materials [53] so that in the future, the unoriginal materials can be removed. Anyway, the theoretical principle of reversibility is an ideal to aim for, but it is never achievable, as total reversibility cannot be obtained in practice. Thus, interventions must offer a “certain degree”, preferably high, of reversibility [61]. From this point of view, thermal mortars appear to be a very suitable solution, as they offer a texture that is similar to original renders and plasters, different from other insulation materials.

Furthermore, they are expected to be distinguishable from the original ones because of the presence of lightweight aggregates, which is normally recognizable. Plus, they are considered to be easily removable [62]. Nevertheless, other thermal insulation materials can also be suitable for the scope if finished with rendering and plastering systems that recall the original appearance of historic surfaces.

Another important concept in heritage conservation is minimal intervention, meaning that retrofits should “do as much as necessary and as little as possible” [63]. Thus, a range of options (Art 15.1 of the Burra Charter [51]) should always be considered to evaluate what interventions can better respond to the circumstantial necessities while minimizing the loss of original fabric, especially when it is considered to hold cultural value (Art. 6 of the New Zealand Charter [57]). These considerations suggest that in historic buildings, insulation is feasible only when all the interventions involving a smaller impact on the original structures are proven to not be enough to meet the goal of the retrofit [64].

Apart from heritage conservation needs, the feasibility of the intervention can be considered from the constructional point of view. In this context, insulation systems that can adapt to uneven surfaces are preferable, as historic walls may present irregularities. Thus, thermal mortars and flexible blankets are more feasible than stiff boards, as the first two can adapt to irregular surfaces while the latter cannot [53]. What is more, thermal mortars allow gap filling, thus providing continuous contact between the insulation layer and the substrate [65] even when the walls are affected by cracks or other damage. Finally, thermal mortars also offer the additional advantage of being applicable by mechanical spraying, which noticeably eases the retrofitting intervention [66].

3. Efficacy

Overall, thermal mortars appear to offer several advantages in terms of feasibility of the retrofit interventions, but are they effective for improving the thermal behavior of historic walls? In addition, what is the different impact in adopting them for the interior or exterior side of the walls? This question is discussed in this section.

3.1. Thermal Conductivity of Insulation Materials

When insulation systems and materials are analyzed and compared in terms of efficacy, their thermal properties are the parameters that lead the discussion. Several studies consider thermal conductivity and specific heat capacity [67–70]. The first parameter can be adopted to consider the achievable improvement of thermal resistance in retrofitted components. The latter may be used to discuss thermal mass and the effect of thermal inertia. Nonetheless, thermal conductivity is considered to be the one key thermal parameter for insulations [43]; the lower the thermal conductivity, the higher the theoretical reduction of heat losses.

A comparison among the values of dry thermal conductivity found in the literature for several common insulation solutions is provided in Figure 1. In the same image, the threshold values of $0.026 \text{ W}/(\text{m}\cdot\text{K})$, $0.065 \text{ W}/(\text{m}\cdot\text{K})$ and $0.2 \text{ W}/(\text{m}\cdot\text{K})$ are indicated with dash-dotted lines. Those values provide a useful indication. The first one represents the thermal conductivity of still air at the ambient temperature. Systems with a thermal conductivity lower than this value are defined as super insulators [71]. The second value is the threshold thermal conductivity adopted in guideline ETAG 004:2013 [72] for defining external thermal insulation composite systems. The last value indicates the maximum thermal conductivity of thermal mortars according to EN 998-1:2017: “Specification for mortar for masonry—Part 1: Rendering and plastering mortar.” [45].

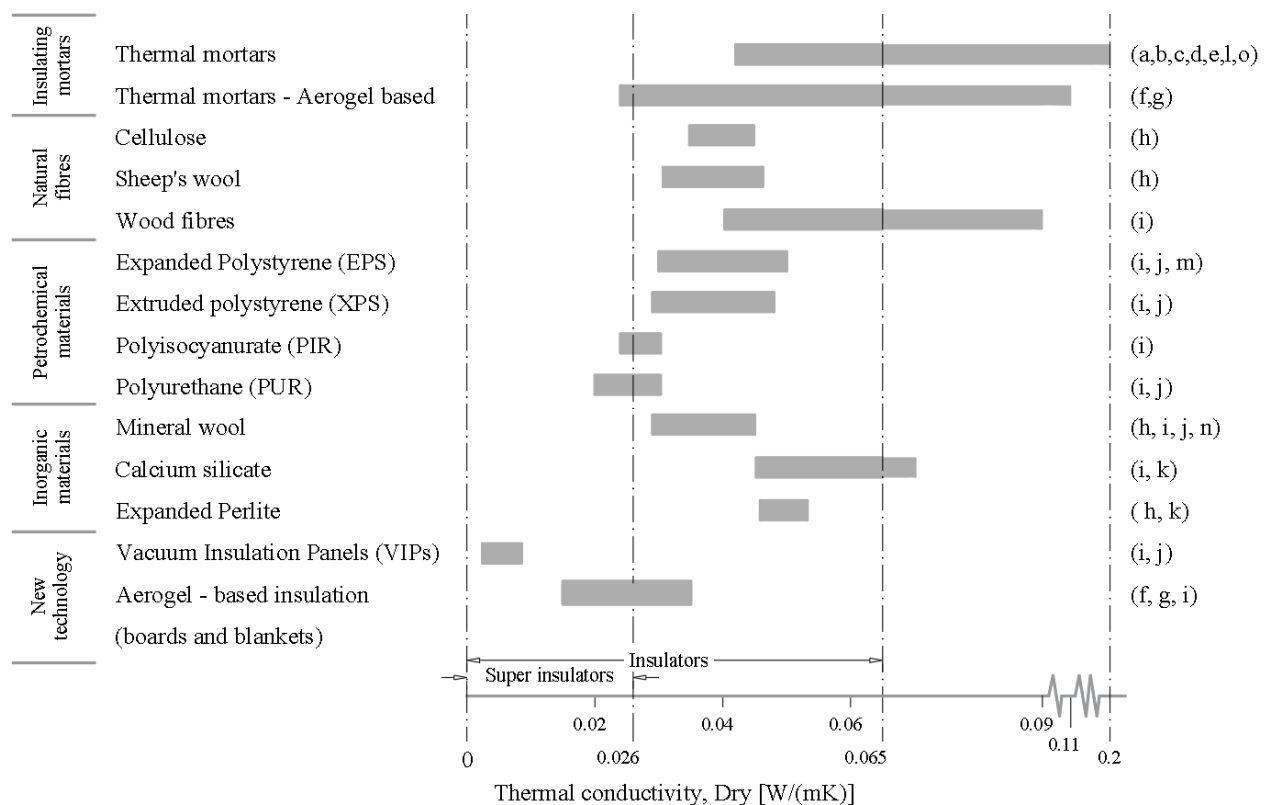


Figure 1. Comparison of thermal conductivity of common thermal insulation materials. References: (a) Walker and Pavia [67], (b) Govaerts et al. [59], (c) Maia, Ramos and Veiga [66], (d) EN 12524:2000 [73], (e) Gomes et al. [47], (f) Ganobjak, Brunner and Wernery [53], (g) Nosrati and Berardi [71], (h) Lekavicius et al. [74], (i) Blumberga et al. [43], (j) Cuce et al. [75], (k) Zhao et al. [68], (l) EN 998-1 [45], (m) Malanho, Veiga and Farinha [76], (n) Parracha et al. [77] and (o) Bouzit et al. [78].

The graphical comparison shows that thermal mortars can have much higher thermal conductivities than traditional insulations. For instance, Walker and Pavia [67] performed a field investigation on the thermal performance of insulation materials suitable for historic buildings and obtained a thermal conductivity of about 0.07 and 0.09 W/(m·K) for lime plasters containing cork and hemp, respectively. Govaerts et al. [59] tested a lime–perlite insulating render for heritage buildings and observed a dry thermal conductivity of around 0.10 W/(m·K). Bouzit et al. [78] considered gypsum plasters with EPS and detected dry thermal conductivities spanning 0.12–0.22 W/(m·K).

More competitive performances were observed by other authors testing renders containing EPS aggregates (i.e., minimum values of about 0.05 W/(m·K) [66] and 0.06 W/(m·K) [47]). The best thermal properties were observed with aerogel plasters. Ganobjak, Brunner and Wernery [53] adopted an aerogel render with a declared conductivity of 0.03 W/(m·K) for a field study on aerogel materials for heritage buildings, and Nosrati and Berardi [71] measured minimum values of around 0.025 W/(m·K) (and a maximum of 0.11 W/(m·K)) for lime-based plasters with additions of granular silica aerogel at 10 °C and 50% RH conditions.

All the thermal mortars considered had much better thermal conductivities than standard gypsum and lime mortars, typically in the range of 0.4–0.8 W/(m·K) according to standard EN 12524:2000 [73]. Some of the solutions emerged as competitive with traditional insulations, having a thermal conductivity lower than 0.065 W/(m·K), even though most thermal mortars seemed to exceed this value.

All in all, thermal mortars appear to be interesting for further investigation and application in temperate climates which have moderately cold winters. Furthermore, the advances in material technology do currently offer thermal mortars containing aerogel, which show very high thermal performance and seem promising even for cold climates.

3.2. Efficacy of the Insulation at the Component Level

Thermal conductivity is a very important parameter for evaluating the improvement of thermal performances obtained with thermal retrofits of building envelopes. For instance, it is fundamental for evaluating the U-value of a building component after the intervention, which is a parameter largely considered in international standards and national building codes [79–81].

The U-value of building components is generally required to comply with a maximum value defined in the standards, but for historic buildings this parameter is very flexible. This parameter quantifies the heat that passes through one square meter of the wall when a 1 °C difference is applied at the boundary layers of air [82]. Thus, with a lower U-value, a larger reduction of heat losses is theoretically achieved. Even though this parameter proved to be very representative for modern, lightweight structures, it poorly adapts to the context of historic walls, especially massive ones. Indeed, it accounts for the behavior of the component under steady state conditions, which is very far from representing the real behavior of thermally heavy constructions under operational circumstances. For this reason, the U-value alone can give just a rough indication of the potential benefits of the retrofit, but it is still useful for comparing different types of insulation materials and thicknesses at a preliminary stage of the project. When more detailed analyses are needed, whole building dynamic hygrothermal simulations can be adopted for an estimation of energy demands and indoor thermal comfort before and after the retrofit. These tools allow for considering realistic outdoor and indoor conditions, the influence of moisture changes on the thermal properties [83,84] and the effects of thermal inertia [85].

In any case, retrofit solutions cannot ever be evaluated through merely performance-based considerations. The retrofit goes as far as heritage preservation restraints allow it to, meaning that the importance of achieving a high performance is secondary to safeguarding the buildings' significance. When it comes to historic constructions, the aim is not to comply with modern building standards [59] but to obtain comfort and energy enhancements that improve the usability and sustainability of the buildings while safeguarding their significance, in accordance with the Amsterdam declaration [86].

3.3. Position of the Insulation

From the building physics point of view, external insulation is always preferable to internal insulation [87]. Indeed, internal insulation leads to a decrease in the original walls' temperature during the heating season, which entails a reduction of their drying ability, leading to colder and damper walls. This condition results in reduced thermal performance and also durability concerns, as high moisture levels can lead to degradation risks [88–90]. Furthermore, interior thermal insulation may result in moisture problems when applied to walls exposed to wind-driven rain if not adequately protected with hydrophobic treatments or if relatively too thin [91].

From the point of view of energy saving in insulated massive constructions, the effects of thermal inertia and night-time cooling must be considered. The combination of these two aspects is recognized to be very effective within the Mediterranean context [52]. High thermal inertia is a typical feature of historic envelopes [21] in Europe, where traditional constructions with heavy walls made of stone or brick masonry are diffused [14] (e.g., solid brick and stone walls 0.5–1.2 m thick with U-values ranging from 2.3 to 0.6 W/(m²·K) [92,93], and typical values that are qualitatively around 1.4–1.8 W/(m²·K) for old solid walls in general [94]). This characteristic can provide for passive cooling during summer in climates having high temperatures during daytime and cool nights. Indeed, thermally heavy constructions have the ability to absorb heat during the "hot peak" of the day and release it when the temperature drops [22]. Thus, walls with high thermal mass provide lower indoor temperatures during the daytime and release the buffered heat at night when it can be effectively mitigated through natural ventilation if the adequate conditions are provided. On the other hand, when historic constructions are conditioned with an intermittent use of heating systems, the high thermal mass of

the envelope gives some disadvantages in terms of energy demands. During the heating season, massive walls may absorb a relevant part of the energy provided by the heating system for warming up the indoor environment, thus increasing the energy needed to reach indoor comfort conditions in the building and extending the preheating period. In this context, the introduction of insulation impacts the envelope behavior in different ways according to its position. Internal solutions decouple the thermal capacity of the wall from the indoor air, which is good in terms of heating demands in buildings with temporary use but counterproductive in terms of passive summer cooling [95]. In addition, the use of internal insulation reduces the thermal bridges to a lesser extent than exterior insulation. Specifically, interior insulation decreases heat losses at cracks and corners in the walls, but it typically leaves uninsulated areas at the conjunctions with transverse walls [91] and floor structures [96], whereas external coating systems also reduce thermal bridging in these areas.

Apart from energy savings, thermal insulation can improve indoor thermal comfort during the heating season, raising the surface temperatures of walls on their interior side [94] while reducing draughts and asymmetries in radiant temperatures [43], but it may lead to overheating risks during summer, especially in southern European countries [97]. From this point of view, internal insulation is more effective than exterior insulation for reducing radiant temperature asymmetries [98], but it is also likely to lead to higher risks of summer discomfort because of its stronger impact on the thermal inertia [99].

Hence, insulation solutions should be carefully analyzed, comparing the benefits gained in winter against the potentially increased cooling demands and the amplified risk of overheating during summer.

4. Conclusions

Concerning the feasibility and efficacy of adopting thermal insulation to retrofit historic walls, some overall indications emerged from the literature:

- Intervention is excluded for surfaces holding cultural or tangible values or subjected to integral protection. When these circumstances do not occur, insulation may be installed, especially if the original rendering or plastering is so damaged that it needs to be replaced. It is generally preferable to use internal insulation over external insulation to maintain the external appearance of buildings. Anyway, external interventions are often feasible if the façade's appearance is reconstructed to conserve the building's identity, especially for buildings whose importance is related to the cultural value of "groups of buildings" or the landscape and not to the singular construction.
- Interventions that cause dimensional changes at window and door openings or where original surface details are valuable should be avoided. In all cases, the original proportions and spatial perception of the building and its parts should be preserved by adopting moderate thicknesses of insulation. Thus, solutions providing good thermal performance with a small thickness of insulation appear more viable than other solutions. Furthermore, insulations offering a wide range of available thicknesses appear to be preferable.
- Even though adopting interior insulation is generally more feasible, it can lead to damper walls during the heating season, and thus it should be carefully designed to avoid reduction of thermal performance and increased degradation risks for the wall. Internal insulation reduces the benefits of thermal inertia to a higher extent than exterior insulation, potentially increasing thermal discomfort during summer. Nonetheless, it may have a positive effect in reducing winter energy demands for buildings subjected to intermittent heating because it decouples the thermal capacity of the wall from the indoor air.

Furthermore, thermal mortars arose as a very feasible and potentially effective solution for historic walls because the following reasons:

- Unlike insulation boards and blankets, they do not need any anchoring points or adhesive layers;

- They offer great flexibility for the thickness, which can be easily adapted to the dimensional restriction that the intervention may require, and it can be adjusted near valuable decorations to leave them clearly visible;
- They adapt to uneven surfaces and provide gap-filling abilities, consequently allowing for obtaining continuous contact between the insulation layer and the substrate, even in the case of irregularities, cracks and other damages which are quite commonly found in historic components;
- They can be applied by mechanical spraying, noticeably easing the intervention;
- They are more able than insulation boards and blankets to offer a similar texture to the original renders and plasters;
- Depending on the mortar mix, they can offer interesting thermal conductivities (lower than $0.065 \text{ W}/(\text{m}\cdot\text{K})$), especially when containing advanced materials such as aerogel or using other innovative formulations.

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