

Article

Reliability Analysis and Economic Evaluation of Thermal Reflective Insulators

Davide Borelli , Alessandro Cavalletti, Paolo Cavalletti and Luca Antonio Tagliafico 

Department of Mechanical, Energy, Management and Transport Engineering, Division of Thermal Energy and Environmental Conditioning, University of Genoa, Via all'Opera Pia 15/A, 16145 Genoa, Italy

* Correspondence: davide.borelli@unige.it; Tel.: +39-010-33-52572

Abstract: High-performance thermal insulators allow a dramatic reduction in the thickness of coatings, thanks to their low thermal conductivity. This study provides an overview about thermal insulation materials, with regards to heat reflective insulators in particular. Then, the numerical investigation method adopted to compute the thermal resistance associated with reflective insulators is introduced. This method has been used in turn to check the accuracy of the declared, measured performance of different, heat-reflective materials on the market. Many manufacturers of reflective insulators were available to provide information and a good agreement between the declared and expected thermal resistance has been found. The choice of a non-experimental approach is meant to check the validity of an already performed test on a reflective insulator using a predictive approach instead of standard, additional testing. Then, the insulation of five typical walls at three different sites in Italy has been simulated, showing that most of heat-reflective materials cannot achieve the maximum required transmittance. Interstitial condensation is likely to occur in specific cases, also because of the aluminum layers inside. The economic analyses showed comparable costs for both heat reflective and traditional insulators, and their cost effectiveness needs to be evaluated case by case.

Keywords: thermal-reflective insulation; radiant barriers; interstitial condensation; cost effectiveness; transmittance numerical evaluation; reflective foils



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1. Introduction

The current political crisis has caused a steep increase in oil price, returning to costs comparable to the those in 1973 (the year of the Yom-Kippur war). Since then, European countries have been implementing concrete strategies and policies to improve their energy efficiency and reduce the energy dependence on fossil fuels [1]. For these reasons, the decrease in the energy-need in buildings, through the reduction in their thermal losses, represents one of the most cost-effective actions to cope with such an issue.

Insulation techniques can actually act either jointly or singularly on the three possible ways of heat transfer: conduction, convection, and radiation. More generally, the total equivalent resistance of a material (R_{tot}) can be estimated as the sum of the conductivity resistance for solid conduction (R_{solid}), gas conduction (R_{gas}), radiation (R_{rad}), and eventually convection R_{conv} (1):

$$R_{tot} = R_{solid} + R_{gas} + R_{rad} + R_{conv} \quad (1)$$

The higher each component, the higher the total resistance. Equation (1) frames all the possible strategies to reduce thermal losses. The parameter R_{solid} depends on the material thickness and on its thermal conductivity, defined as a measure of the ability of a substance to transfer heat by conduction. The measurement of this parameter can be carried out by means of either the guarded hot plate or the flow-meter methods [2,3].

A brief overview of the insulators available on the market and actually adopted in energy efficiency for buildings is presented.

Traditional thermal insulation materials (Table 1) try to reduce as far as possible the term associated to conduction [4–6]. A minimum limit value for this group of insulators can be found in the conductivity of motionless air (about 0.025 W/m K) [7].

Table 1. Types and average thermal performance of some traditional thermal insulation materials.

Insulation Type	Origin	Name	λ [W/mK]
Fibrous structure	Natural	Coconut fiber	0.050
	Natural	Sheep wool	0.037–0.064
	Synthetic	Rock wool	0.035–0.040
	Synthetic	Glass wool	0.032–0.067
Cellular structure	Natural	Expanded granulated cork	0.040–0.060
	Synthetic	EPS polystyrene	0.035–0.044
	Synthetic	XPS polystyrene	0.034–0.038
	Synthetic	XPS polystyrene + graphite	0.025–0.030
Porous structure	Natural	Pumice	0.110
	Natural	Vermiculite	0.077–0.082
	Synthetic	Cellular cement	0.070

The family of **Vacuum insulated panels (VIPs)**, belonging to innovative insulators, rely on a layer with a vacuum inside where heat can only propagate by means of radiation. This strategy can lead to very low equivalent conductivities (about 0.01 W/mK) with a weak point where every cut or perforation seriously damages the panel, at least doubling its conductivity [8]. Many works are available in the literature about the topic, starting from general reviews [9,10], and going more in detail with specific studies: e.g., influence of water inside the material [11], variation of thermal conductivity with different materials filling the VIP [12], and future development of VIPs [13]. Usually, the most relevant flaw in these insulators consists of the aluminum layers put inside of the VIPs (or similar materials) which almost block the passage of water vapor with a consequent risk of interstitial condensation.

Gas-filled panels (GFPs) represent another family of insulators exploiting a principle similar to the one for VIPs, where the void is replaced by gases with a conductivity lower than air. Regardless, the VIP panels still seem to be preferable to the GFP for durability reasons [14,15].

On the other hand, **aerogel materials** belong to a group where the improved conductivity is reached by the replacement of the liquid part of a gel with gases during a supercritical drying process. Aerogels lower the limit conductivity for traditional insulators (0.015 W/mK against 0.025 W/mK for motionless air) [16] thanks to the so-called Knudsen effect, which is a reduction in thermal conductivity in gases when the size of the containing cavity is almost equal to the mean free path [17]. A further improvement in the performance of aerogels can be reached with carbon black, which suppresses the radiative transfer as well [18].

Nanotechnology-based materials try to exploit the same Knudsen effect adopted in aerogels with a dramatic decrease in the size of the pores and therefore in conductivity. Such technology could overcome the issue of excessively high vapor resistance highlighted for VIPs and any perforation would not decrease its performance. The Knudsen effect in very small pores (order of magnitude of nanometers) can be associated to the fact that gas molecules are more likely to hit the walls of the pores instead of other molecules. In this context, the sizes of the pores (compared to the mean free path of the gas molecules) determine the reduction in conductivity. In actual fact, an excessive decrease in the cavities size might cause a relevant increase in the radiation heat transfer, since they tend to be lower than the wavelength of infrared radiations (about three orders of magnitude, 10 nm as reference pore size against 10 μ m for infrared radiations) [19,20]. The contribution of radiation heat transfer against the conduction/convection ones still has to be exhaustively estimated and tested [20]. Regardless, if the conductive/convective mechanisms still remain dominant, the conductivity of the nanotechnology-based insulator can reach very

low values (about 0.004 W/mK) with the consequent use of very thin layers to insulate buildings. This group is composed by mortars, resins, plasters, and paints containing nanoparticles, usually hollow glass or ceramic microspheres of variable size (between 20 and 120 μm of diameter), which are bonded by a mixture of synthetic rubber and other polymers granting the mechanical properties, flexibility, and water resistance as well. Their effective composition is under industrial secrecy and therefore different explanations are provided by the different manufacturers, leaving room for discussion about the reliability of the insulating mechanism and on the accuracy of the models available in the literature [21–24]. Moreover, the technical information about conductivity for nanotechnology materials is, most of the time, contradictory, and very different values can be found on the market, differing even of two orders of magnitude, e.g., from 0.001 W/mK [21] up to 0.14 W/mK [22]. No CE marking, neither compulsory nor voluntary, is available for nanotechnology-based materials since there is neither a harmonized standard nor a manufacturer's voluntary adoption of ETA (European Technical Assessment). The performance needs to be tested in authorized laboratories within one of the member countries of the European community [25] to adopt the declared conductivity reported in the technical sheet. Moreover, the evaluation has to be conducted following a statistical approach (i.e., a single test is not sufficient), following the methodology reported in UNI ISO 10456 [26].

Ultimately, **heat-reflective materials** can be found: The thermal insulation system is made of one or more low-emissivity reflective surfaces, in contact with one or more cavities filled with air. They work with a range of wavelengths between about 5 μm and 50 μm (infra-red field) because the radiation heat exchange occurs between bodies at room temperature. The reference standard for materials exploiting the contribution of either reflective or low-emissivity surfaces in contact with an air cavity can be found in [27]. One of the most effective applications of reflective materials can be found in [28], where the simple application of a reflective panel between a radiator and the perimetral wall (common pattern in residential applications) leads to an energy saving of 3.50% in the worst insulation conditions. Several studies were developed in the past regarding heat reflective insulators and were mainly divided into two groups: numerical approaches, with the aim to be implemented into simulation software [29–42], and experimental approaches to characterize their properties [43–49]. A research review about heat-reflective materials [50] estimates that about 59% of the studies were concerned with experimental approaches (either field measurement or indoor test rigs) whereas only 41% regarded numerical simulations (e.g., building performance or CFD).

To the best of the authors' knowledge, no relevant study about the reliability of the declared performance of reflective material has been conducted. In addition, most of scientific literature does not account for the compatibility of the heat-reflective materials with the required thermal resistance. The economic aspects are lacking as well, neglecting the cost effectiveness of these materials compared to other traditional insulating solutions. The present study aims to cover these topics, by means of the following steps:

- Firstly, the thermal resistance of the insulator has been computed by means of the theoretical approach contained in the UNI EN ISO 6946:2018 standard [51]. The results have been compared with the values reported in the declared transmittance data of different heat reflecting materials available on the market. A substantial good agreement with most of materials has been found. The names of the different brands considered are kept anonymous. The numerical approach has been intentionally chosen instead of experimental tests in order to test the reliability of the measured values declared by the producers by means of a predictive numerical approach.
- The most effective position for heat reflective insulators when considering cavity, brick and stone walls has been investigated. Indeed, the thermal resistance of such insulators is influenced by their position in a multilayer wall.
- Then, the insulation of the main and most common walls in Italy with heat-reflective materials has been examined. In particular, cavity, stone, and brick walls were considered, assuming three different locations in Italy (Genoa—climatic zone D, Milan—

climatic zone B, and Naples—climatic zone C). The limits set by the Italian laws in terms of transmittance and interstitial condensation have been checked.

- A simplified economic analysis is proposed to identify the insulating material which grants a required performance (in terms of thermal transmittance) at the lowest possible price. Clearly, the conclusions on this topic do depend on the market price fluctuations of thermal insulation materials, which have been experiencing a steep increase since the “Superbonus” [52] tax incentives came into force. In fact, it is preliminary estimated that an increase in the prices for building insulation of about 35% has occurred in the past couple of years. Although the analyses refer to a period former to 2020, the results still provide interesting conclusions because the increase in the prices has affected almost homogeneously the group of heat reflective thermal insulation materials.

2. Materials and Methods

This section proposes a first recall on the numerical method used to assess the thermal resistance of reflective insulators. Then, the walls used in the simulations are presented, recalling also for the mandatory energetic efficiency Italian limits (i.e., total thermal resistance of walls according to the different Italian climatic zones).

2.1. Thermal Resistance in Cavity Walls—Reflective Insulators

The thermal resistance associated to a cavity filled with air can be carried out by means of the approach reported in the UNI EN ISO 6946:2018 standard [51] and previous numerical studies [2,3,26,27,50,53] which can be applied both to air voids (i.e., the width/length are comparable to the thickness) and to air layers (i.e., the width/length are more than 10 times the thickness along the heat flow direction). In particular, the adopted approach applies to unventilated airspaces with length and width which both exceed 10 times the thickness. Even airspaces with openings which allow no airflow through the layer and do not have an extended area (500 mm² per meter of length for vertical air layers or 500 mm² per square meter of surface area for horizontal air layers) can be considered as unventilated. Assuming that the heat exchange between two opposite emitting surfaces with an interposed air layer depends on the mean surface temperature, the thermal resistance can be expressed as:

$$R_g = 1/(h_a + h_r) \quad (2)$$

where:

R_g is the thermal resistance of the air cavity, [m²K/W];

h_a is the convective heat transfer coefficient, [W/m²K];

h_r is the radiative coefficient, [W/m²K].

In turn, h_a can be determined according to the direction of the heat flow and the temperature difference (Tables 2 and 3). Indeed, the convective heat transfer is assumed to be either constant or function of the width of the air gap with low temperature differences (<5 K), then it depends on temperature as the difference increases (>5 K).

Table 2. Values for the convective heat transfer coefficient (h_a) according to the direction of the heat flow for temperature difference lower than 5 K [51].

Direction of the Heat Flow	h_a [W/m ² K] ¹
Horizontal	1.25
Upwards	1.95
Downwards	0.12d ^{0.44}

¹ if the values are lower than 0.025/d, where d is the thickness of the air gap in the direction of the heat flow, then 0.025/d is assumed.

Table 3. Values for the convective heat transfer coefficient (h_a) according to the direction of the heat flow for temperature difference higher than 5 K [51].

Direction of the Heat Flow	h_a [W/m ² K] ¹
Horizontal	$0.73 T^{1/3}$
Upwards	$1.14 T^{1/3}$
Downwards	$0.09 T^{0.187} d^{-0.44}$

¹ if the values are lower than $0.025/d$, where d is the thickness of the air gap in the direction of the heat flow, then $0.025/d$ is assumed.

On the other hand, the radiative coefficient (h_r) can be represented as:

$$h_r = E h_{r0} \quad (3)$$

with:

h_{r0} radiative coefficient for a black body surface [W/m²K], as reported in Equation (4);
 E surface-to-surface emittance, formulated in Equation (5).

The radiative coefficient for a black body surface has been expressed assuming unit values for the view factors, since the airspace is usually large and thin

$$h_{r0} = 4 \sigma T_m^3 \quad (4)$$

where:

σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m²K⁴);

T_m is the average temperature of the surface and of its surroundings, assumed to be at 282 K for the case study. Therefore, the radiative coefficient for the black body surface is 5.1 W/m²K.

Finally, the emittance is given by:

$$E = 1/(1/\varepsilon_1 + 1/\varepsilon_2 - 1) \quad (5)$$

where ε_1 and ε_2 are the hemispherical emissivities of the surfaces bounding the airspace. These values should account for the effects of deterioration and dust as well.

The so-estimated thermal resistance of a cavity can be accounted in the global transmittance for a multilayer wall by means of Equation (6):

$$U_{tot} = 1/(R_{si} + \sum S_j/\lambda_j + R_{gk} + R_{se}), \quad (6)$$

where:

R_{si} and R_{se} are the surface resistances determined according to the direction of the heat flow (m²K/W) [51];

s_j and λ_j represent respectively the thickness (m) and the conductivities (W/m K) of the j th layer;

R_{gk} is the thermal resistance of the k th cavity (m²K/W).

The values for the materials were taken from the UNI/TR 11552:2014 Italian standard [54].

2.2. Type Walls Adopted in the Simulations and Computation of the Global Transmittance

The carried-out simulations apply the reflective insulation to different kinds of walls which represent some of the most common construction typologies in the Italian building stock. Eight configurations have been evaluated, including brick, cavity, and stone walls. The results for all the simulations can be found in Appendix A, whereas three relevant cases are analyzed in detail as follows:

- cavity walls (Figure 1a): typical of the post-war buildings with reinforced concrete structure. Usually, two layers of bricks (respectively 8 and 12 cm) are separated by an air cavity which can be from 4 cm up to 16–18 cm wide. The contribution of the air

cavity to the global thermal performance of the wall shows a very weak dependence on the thickness. Indeed, the thermal resistance of unventilated air cavities at least 25 mm wide, with high emissivity surfaces, are associated to constant thermal resistances [51]. The total transmittance associated to such walls (without reflective insulation) is usually between 1 and 1.2 W/m²K. The reflective insulator shall be simulated within the air cavity in the most effective position (i.e., either in the middle of the air cavity or on one of the two faces between bricks). The average temperature of the cavity surfaces is assumed to be at 10 °C, representative of a winter steady-state condition common in Italian climatic zones from A to E;

- brick walls with a low insulation layer (built between 1976 and 1990) (Figure 1b): the wall is entirely made of bricks and an insufficient external insulation was applied for instance to avoid interferences; for instance, the reduction in the width of the balconies. The global initial transmittance of the wall is assumed to be 0.39 W/m²K;
- stone walls (Figure 1c): such typology is common, especially in historical buildings, which are in turn subjected to architectural constraints and therefore a classical external coating is not feasible. The global transmittance of these walls depends on the total thickness, and an average of 2.33 W/m²K could be considered representative of this kind of walls.

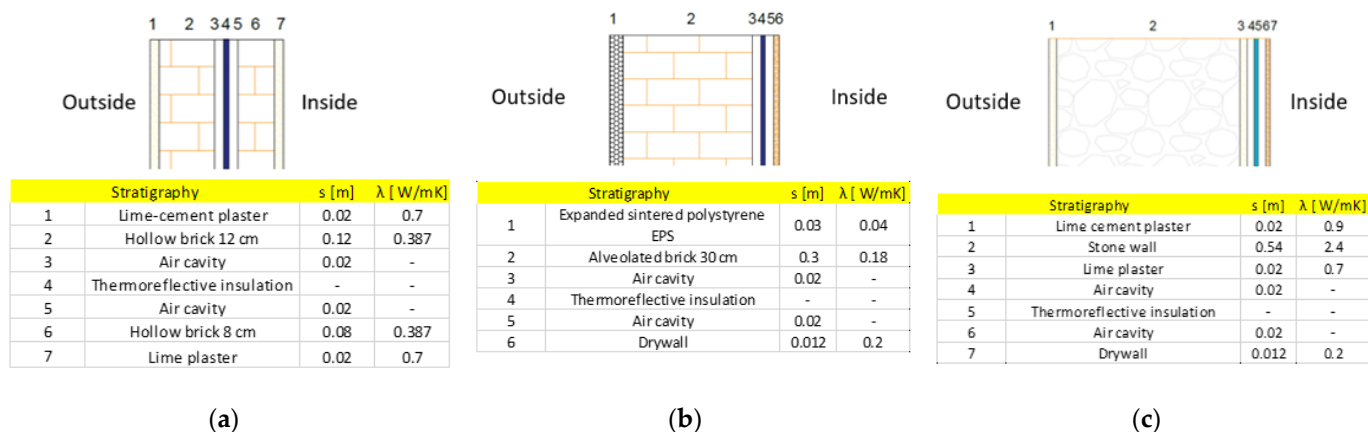


Figure 1. Kinds of walls investigated in the present work to simulate the contribution of the reflective insulator with the assumed conductivities for the different layers. (a) Cavity wall; (b) Brick wall; (c) Stone wall.

2.3. Maximum Legislative Limits for the Total Transmittance

The simulations were performed assuming three different climatic zones among the Italian zones: E (e.g., Milan), C (e.g., Naples) and D (e.g., Genoa). The other climatic zones were preliminary neglected because they are associated to a smaller part of the Italian territory. Table 4 recalls the legislative limits according to the different climatic zones.

Table 4. Reference value for thermal transmittance of vertical opaque structures, to the exterior, and unheated spaces or against the ground [55].

Climatic Zone	U _{ref} [W/m ² K]
A-B	0.43
C	0.34
D	0.29
E	0.26
F	0.24

2.4. Economic Analysis—Cost Effectiveness

The “cost-effectiveness analysis” allows the comparison of several alternatives according to their cost and a measured (not economic) useful effect (e.g., thermal transmittance for

the present study) [56]. The cost-effectiveness index for the i -th alternative can be expressed by means of Equation (7):

$$CE_i = C_i / E_i, \quad (7)$$

where:

C_i is the cost of the i th alternative [$\text{€}/\text{m}^2$], for our case the cost of both the materials and the installation.

E_i is the related benefit, i.e., the thermal resistance for the present study [$\text{m}^2\text{K}/\text{W}$].

As a consequence, the unit measure for the cost effectiveness (CE) depends on the related benefit. In this case CE can be measured in [$\text{€W}/\text{Km}^4$].

As regards to the costs for heat-reflective materials, most of them were declared by the producers, except for material 1, where the manufacturer did not reply to the question and therefore was excluded from this part of the study. On the other hand, the cost of installation, when not declared, was estimated basing on the regional price list carried out by Regione Liguria. The installation cost obtained by means of the regional price list leads to values comparable to the declared ones.

The cost-effectiveness approach was carried out twice: at first, it was applied to the heat-reflective materials under study, and then it was applied for a comparison among different thermal insulation materials.

3. Results

The present section presents the main results obtained following the approach illustrated above.

Firstly, the thermal resistance is computed following the numerical approach illustrated before, comparing the results with the declared, tested performance of the heat-reflective materials on the market.

Secondly, the most effective position of the reflective insulator in multilayer walls (especially cavity walls) is investigated to justify the chosen stratigraphy adopted in the following simulations. This issue is not trivial because the best, ideal position may not be always feasible or the same for different, existing walls.

In conclusion, the reflective insulators formerly verified are applied to the chosen walls to enquire their convenience from the point of view of both thermal performance and cost effectiveness.

3.1. Comparison between Declared and Computed Thermal Resistance for Heat Reflective Insulators

Table 5 presents the main results about the calculation performed to compute the expected total thermal resistance for each of the eight, heat reflective insulators considered, according to the numerical approach illustrated above. The materials are kept anonymous, but the samples here examined represent quite a complete range of heat-reflective materials available on the market.

Table 5. Calculated thermal transmittance for eight heat reflective thermal insulation materials—main results.

Mat. N.	ε_1 [-]	ε_2 [-]	E [-]	h_r [W/m ² K]	Air Cavity Thermal Resistance [W/m ² K]	Core Thermal Resistance [W/m ² K]	Total Thermal Resistance [W/m ² K]
1	0.06	0.9	0.060	0.304	0.644	0.285	1.572
2	0.05	0.9	0.050	0.254	0.665	2.761	4.091
3	0.05	0.9	0.050	0.254	0.665	0.968	2.298
4	0.02	0.9	0.020	0.102	0.740	1.521	3.000
5	0.05	0.9	0.050	0.254	0.665	0.200	1.530
6	0.05	0.9	0.050	0.254	0.665	0.420	1.750
7	0.04	0.9	0.040	0.203	0.688	0.417	1.793
8	0.12	0.9	0.118	0.604	0.539	1.252	2.331

The total thermal transmittance referred to in Table 5 is associated to a horizontal heat flow of two air gaps 20 mm thick each, divided by the reflective insulation (Figure 2). The information required (i.e., emissivity, conductivity, and thickness) was taken from the data sheets of the materials to ensure the comparability of the results whereas the convective heat transfer coefficient has been assumed according to Table 2.

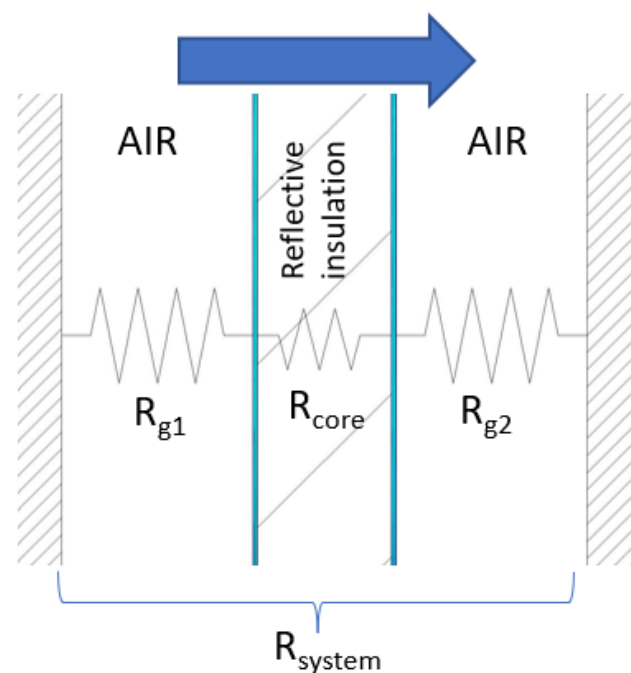


Figure 2. Scheme of the system of thermal resistances considered to compare the calculated results with the declared ones. The resistances associated to the air gaps (R_{g1} and R_{g2}) also consider the reflective contribution. R_{core} represents instead the conductive thermal resistance associated to the core material itself.

Then, a comparison between the computed and measured thermal resistances declared by the producers is provided in Table 6.

In general, predicted and declared values are in good agreement, with a variation below 5%. Only one case differs (about 13%—material 8) and the manufacturer, when informed about this result, admitted that the value needed to be certified again.

Table 6. Comparison between declared and calculated thermal resistance for eight heat-reflective materials available on the market. The trademarks are kept anonymous.

Material Number	Calculated Thermal Resistance [$\text{m}^2\text{K}/\text{W}$]	Declared Measured Thermal Resistance [$\text{m}^2\text{K}/\text{W}$]	Variation [%]
1	1.57	1.61	2
2	4.09	4.05	−1
3	2.30	2.28	−1
4	3.00	3.00	0
5	1.53	1.52	−1
6	1.75	1.68	−4
7	1.79	1.86	4
8	2.33	2.64	13

3.2. Best Position of the Heat Reflective, Insulating Layer

The effectiveness of the reflective insulating layer changes according to its position inside a multilayer element. Although common insulators (acting mainly on conductivity) work better (or equally) when applied from the outside, heat-reflective materials need to be installed on the inner side of the wall for winter insulation because their effectiveness depends on the direction of the heat flow. Clearly, such a pattern might act negatively during summer, as it prevents the heat inside to flow through the wall instead of reflecting the heat coming from the outside. The risk of interstitial condensation recalled in the introductory section may be influenced in addition by the position of the insulator.

In the simulations carried out, the reflective materials have been assumed as applied on the inner side of the stone and brick walls by means of frames and pins in aluminum or wood. This pattern leads to two benefits: firstly, the insulator can work on both sides because it is not in direct touch with the wall. Secondly, the issue of interstitial condensation loses importance if the supporting frame is provided with openings on the top and on the bottom to allow ventilation. Unluckily, this feature is not very common in ordinary cavity walls. Among the examined types, the cavity wall deserves an additional remark, because the air gap between the two layers of bricks represents one of the most effective positions for the heat reflective material. This configuration avoids the increase in the total thickness of the wall, unlike the cases of solid multilayer walls (e.g., brick or stone walls). Figure 3 shows the effect of the different positions of the heat reflective layer (i.e., adherent to the layer of bricks; on the inner side of the wall; in the middle of the air cavity) on the total wall transmittance.

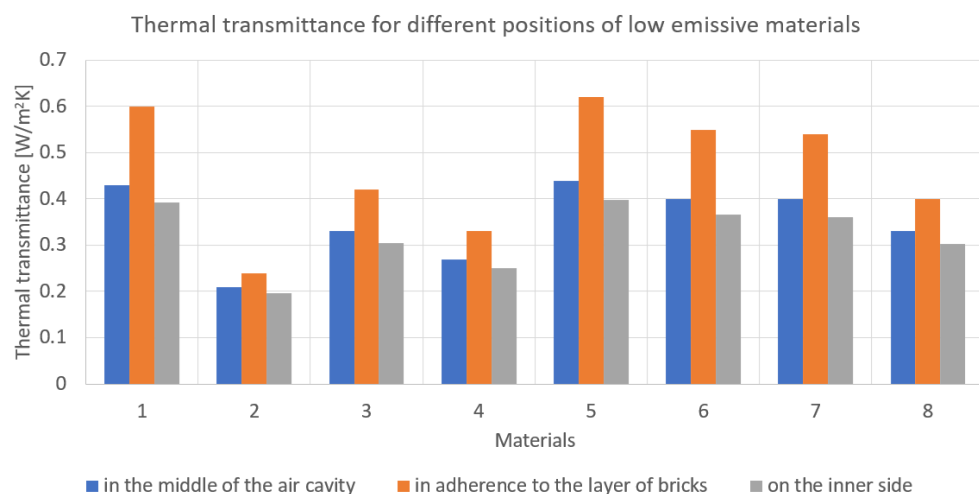
**Figure 3.** Variation of the thermal transmittances obtained for a cavity wall, positioning the heat reflective layer either in the middle of the air cavity (blue, no contact) or in the air cavity but in contact with the layer of the bricks (orange) or on the inner side of the wall (grey).

Figure 3 illustrates the obtained transmittance for a cavity wall applying singularly the seven heat-reflective materials considered (horizontal axis) in three different conditions: in the middle of the air cavity (blue columns), in adherence to the layer of bricks within the cavity (orange column), and on the inner side of the wall (grey columns). Clearly, the highest transmittance is always reached in the case of insulator inside the cavity but in contact with one of the two layers of bricks. This result is due to the loss of the heat reflective contribution of the insulator side in contact with the bricks.

On the other hand, the cases of insulation in the middle of the air cavity are quite similar to the ones with insulation on the inner side of the wall. The slight improvement in this last case (grey columns) is due to the additional thermal resistance provided by the additional drywall, necessary to protect the heat reflective insulating layer from shocks.

3.3. Application of the Heat Reflective Thermal Insulation Materials to the Case Study Walls

In this section, the eight heat-reflective materials previously compared with the numerical results are applied to the walls described in Section 2 (Materials and Methods). A comparison with the limits imposed by the law for three Italian climatic zones (i.e., maximum transmittance) is performed, with a brief recall to the issue of interstitial condensation.

- Cavity wall: Figures 4 and 5 show, respectively, the application in the middle of the air cavity and in touch with one of the layers of bricks. Only one of the eight heat-reflective materials leads to a total transmittance within the limit for the climatic zones associated to Genoa (i.e., D) and Milan (i.e., E). As far as the climatic zone C (Naples) is considered, just four materials are eligible to respect the threshold. Clearly, the case in Figure 5 with respect to Figure 4 slightly worsens due the installation of the insulator in touch with the layer of bricks (and the consequent partial loss of the reflective insulation on one side).

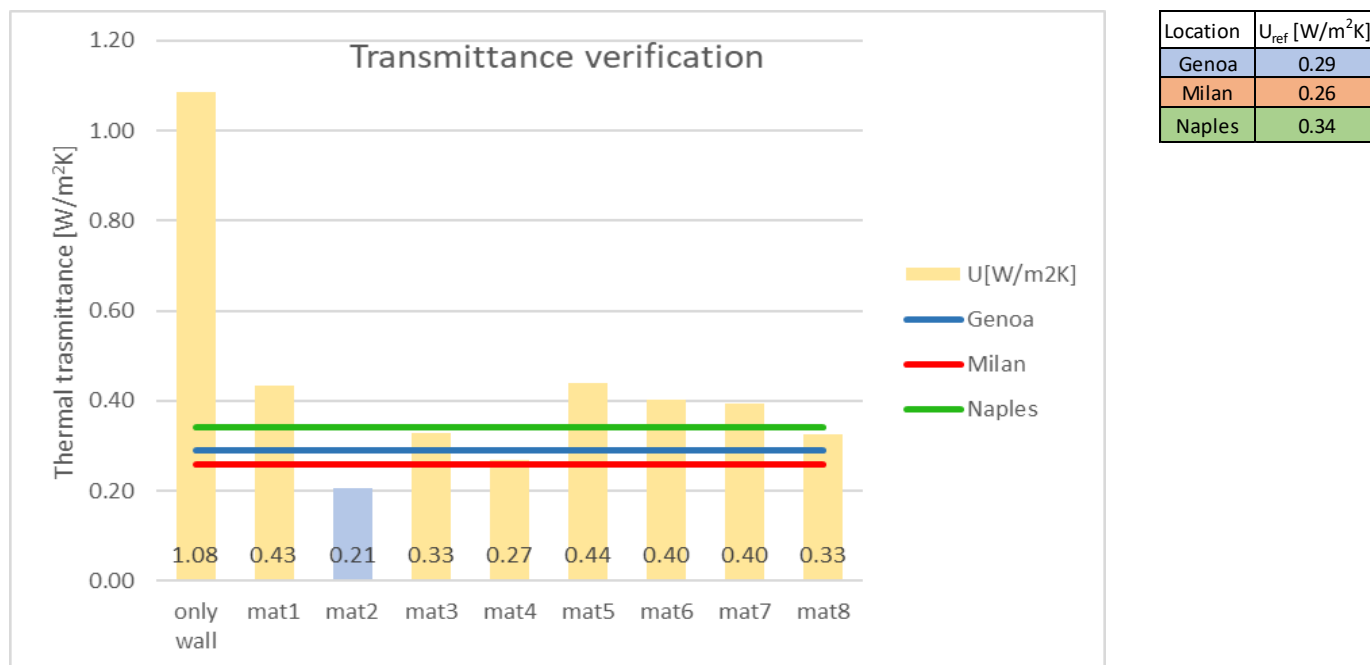


Figure 4. Thermal transmittance in cavity walls with different heat reflective insulating layers (application in the middle of the air cavity). The red, blue, and green lines represent the threshold for different cities.

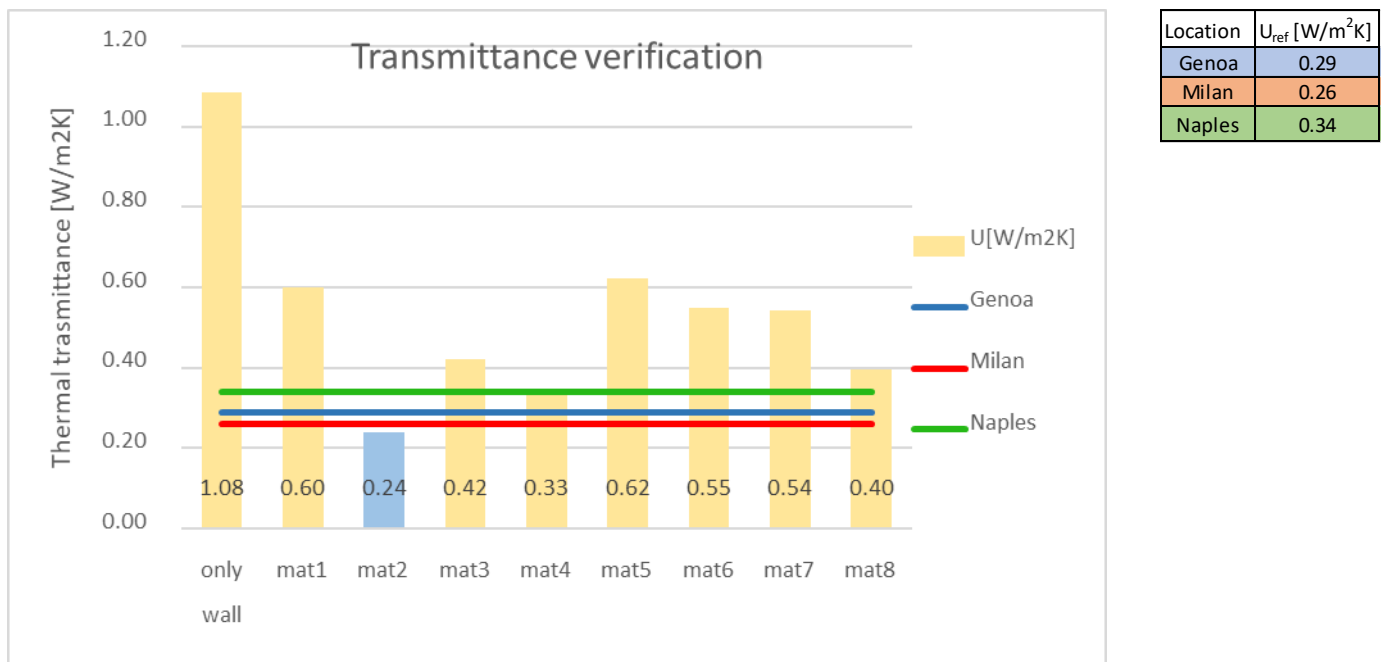


Figure 5. Thermal transmittance in cavity walls with different heat reflective insulating layers (in touch with one of the layers of bricks). The red, blue, and green lines represent the threshold for different cities.

- Brick wall: the contribution provided by means of the heat reflective insulator to the existing/reduced insulating coating allows the limits to be respected independently from the material (Figure 6).

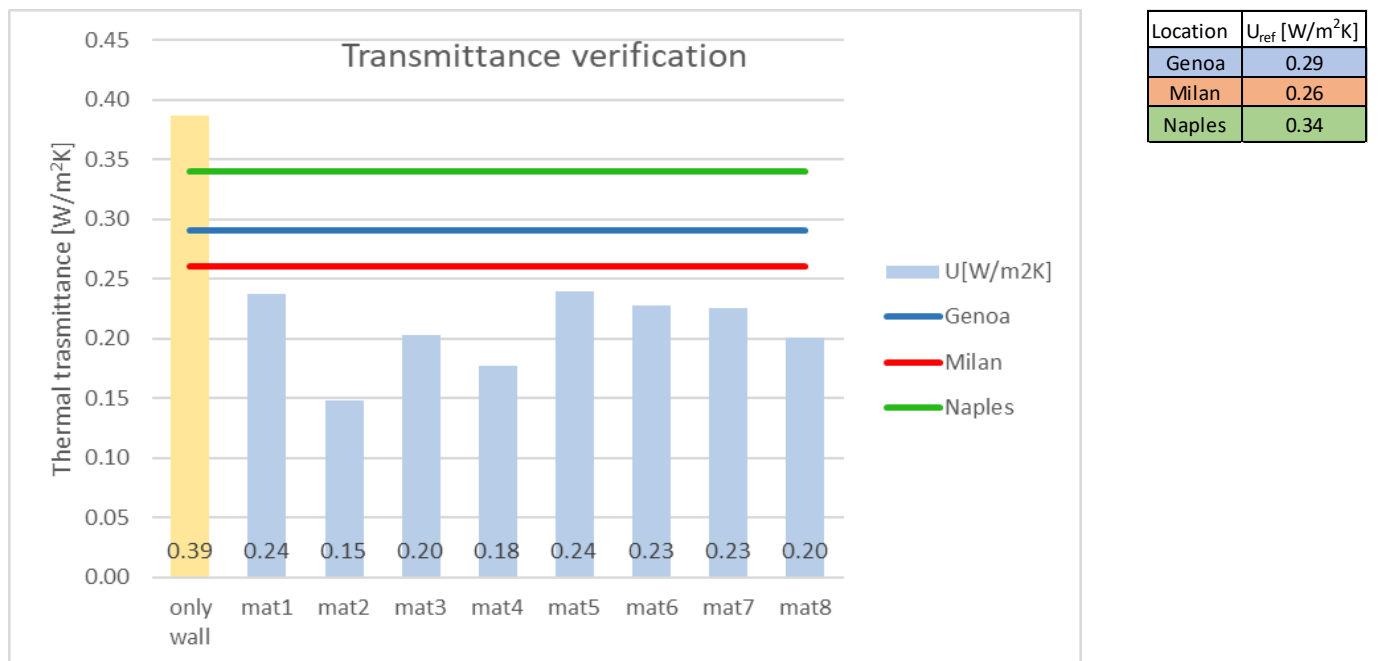


Figure 6. Thermal transmittance in brick walls with different heat reflective insulating layers. The red, blue, and green lines represent the threshold for different cities.

- Stone wall (Figure 7): only one material grants the limit transmittance for climatic zones D and E (Genova and Milan, respectively). On the other hand, only two reflective insulators grant the limits for climatic zone C (Naples).

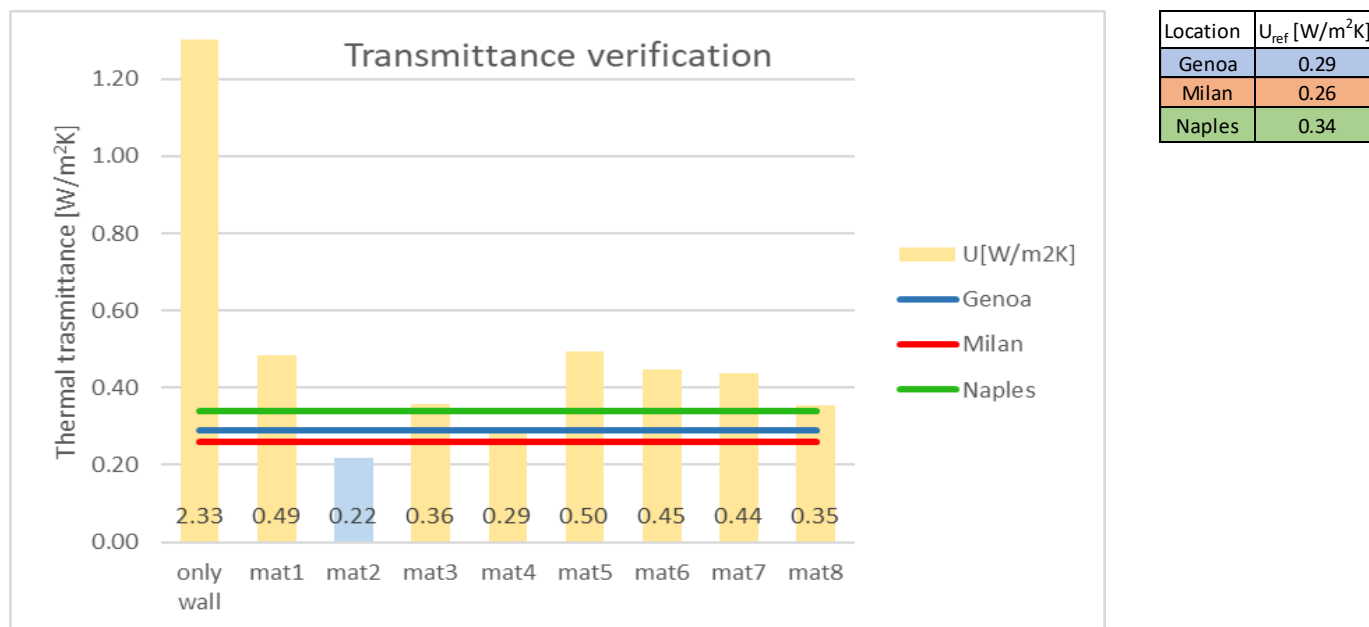


Figure 7. Thermal transmittance in stone walls with different heat reflective insulating layers. The red, blue, and green lines represent the threshold for different cities.

More generally, all the configurations concerning the inner insulation determined an increase in the wall thickness of about 6 cm, and accounted for finishes such as plasters and drywalls. This in turn implies a not negligible reduction in the useful surface of the flats in existing buildings. Only the case of heat reflective insulator inside the cavity wall could overcome such an issue, but it clearly represents a solution suitable only for new constructions.

On the other hand, assuming an expanded polyurethane with an average conductivity of 0.023 W/mK, 6 cm thick (the same thickness of the heat reflective insulating package) provides a thermal resistance of about 2.6 m²K/W which is equal or higher than the declared one of 6 out of 8 heat-reflective materials investigated (Table 6). In addition, the heat reflective insulators are usually provided with at least an aluminum layer which acts on the reflection mechanism, but it has the side effect of a very high vapor resistance (order of magnitude 300.000).

As a consequence, problems about interstitial condensation might arise when adopting heat reflective insulators, whereas other solutions (e.g., expanded polyurethane) are very likely to bypass the problem (a vapor resistance of about 100 for such insulators). In the case studies considered above, no condensation occurred, except for the stone wall, where this issue might become relevant also according to the standard use of the building, the climatic zone, and the vapor resistance of the heat reflective material.

Indeed, each stratigraphy was tested by means of a commercial program implementing Glaser's method. For reasons of synthesis, the full results are omitted in the present work, and the case in which condensation occurred is reported on only (Figure 8). In any case, the issue of interstitial condensation shall be the topic of further, specific studies.

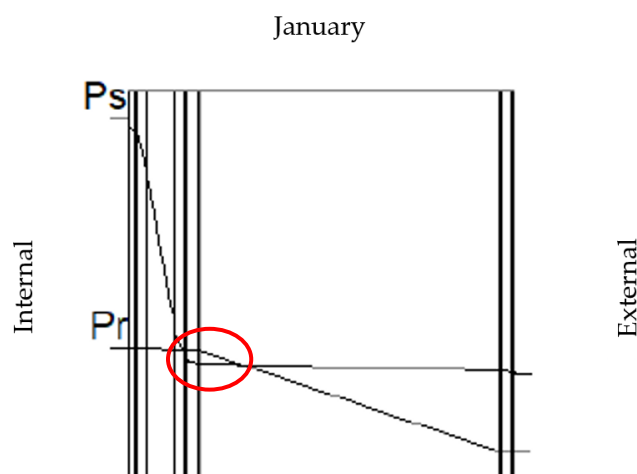


Figure 8. Extract from the diagram of monthly pressures referred to the month of January for wall type 5.1 (see also Annex A for further information). Condensation occurs in the region where the lines representing, respectively, the saturation (P_s) and relative (P_r) pressure intersect (red circle).

3.4. Cost-Effectiveness Analysis

3.4.1. Heat-Reflective Materials

Table 7 and Figure 9 present the costs for each material and its installation, with the correspondent cost-effectiveness index. The installation cost accounts for the case of internal insulation with a plasterboard covering:

Table 7. Material, installation, and total cost, with the cost-effectiveness index for the heat-reflective materials.

Material Number	Material Cost [€/m ²]	Installation Cost [€/m ²]	Total Cost [€/m ²]	CE _i [€/m ⁴ K]
2	30.00	49.00	79.00	19.31
3	11.80	48.32	60.12	26.16
4	18.00	42.07	60.07	20.02
5	4.46	47.01	51.47	33.64
6	15.50	48.32	63.82	36.47
7	11.40	48.32	59.72	33.31
8	17.60	40.00	57.60	24.71

The cost for the materials varies from a minimum of 4.46 €/m² (material number 5) up to a maximum of 30 €/m² (material number 2) whereas the costs for installation are within the range between 40 and 49 €/m². The most convenient heat reflective insulators among the ones under study is material number 2. Besides the highest material cost, the relevant contribution to the total thermal resistance makes it the most eligible material (4 m²K/W against an average of 2 m²K/W for other heat reflective insulators, see Table 6 for more information). On the other hand, cases number 5, 6, and 7 have to be discarded due to their poor convenience.

Figure 10 plots the total cost against the obtainable thermal resistance, superposing a second-degree polynomial approximation. The yellow region identifies the minimum of the plot where a thermal resistance between about 2.3 and 2.6 m²K/W corresponds to a minimum total cost between about 55 and 62 €/m². Such a region can be conceived as a starting point to compare heat reflective insulators to most diffused ones such as EPS. Indeed, the value of the range between 2.3 and 2.6 m²K/W can be obtained with 6 cm thick EPS with a maximum thermal conductivity of 0.023 W/mK. Such thickness is comparable to the required one by the heat reflective insulators, including the air cavity, the frames, and the finishes. Even from an economical point of view, the total costs can be considered as comparable.

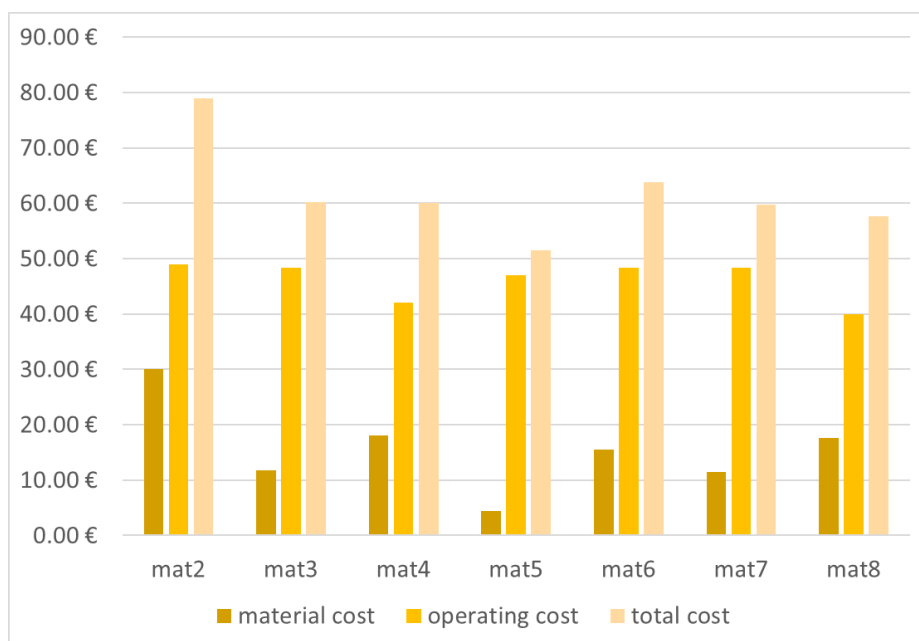


Figure 9. Graphical representation of costs for the heat-reflective materials reported in Table 7.

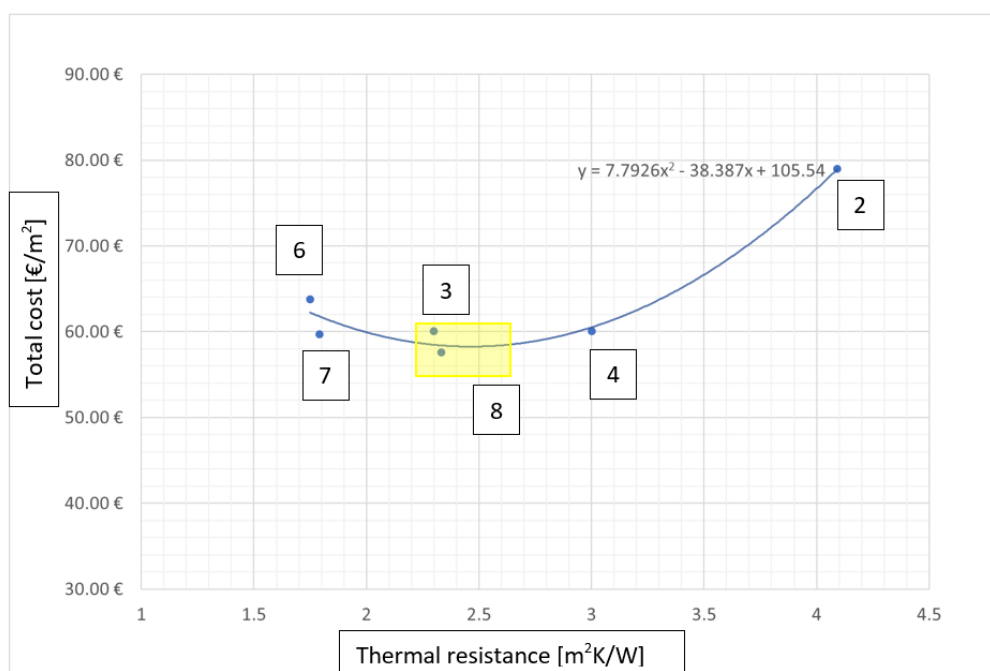


Figure 10. Total cost of the heat-reflective materials (numbered in the squares) with the correspondent thermal resistance. Approximation of the results with a second-degree polynomial equation.

From this starting point, the materials falling on the left of the yellow region have to be discarded because they provide a lower thermal resistance and require a higher total cost.

On the contrary, the materials on the right (e.g., 4 and 2) present a higher total cost (up to 25% higher than the minimum obtained cost) in front of a thermal resistance which is almost doubled, resulting in the most convenient ones, as already outlined by the cost-effectiveness index (Table 7).

The polynomial approximation provides a useful tool to assess the cost effectiveness of other thermal insulators not investigated in the study by entering the graph with the total cost and the thermal resistance.

3.4.2. Traditional and Heat Reflective Thermal Insulation Materials–Cost Comparison

This paragraph describes the cost comparison between traditional and reflective thermal insulation materials by means of the cost-effectiveness approach.

The information about heat-reflective materials is the average of the costs reported in the previous Table 7, whereas the costs for traditional materials in Table 8 have been estimated referring to the regional price lists and the manufacturers' data.

Table 8. Costs of traditional and heat reflective thermal insulation materials.

Insulating Material	Material Cost [€/m ²]	Total Cost (Including Installation) [€/m ²]
Rock wool panels	12.00	47.50
Calcium silicates panels	22.50	125.00
Wood fiber panels	30.00	65.00
EPS panels	11.50	37.50
Glass wool	3.75	55.00
Heat reflective panels (average)	15.54	61.69

Figure 11 shows that the total cost for heat reflective insulation is on average comparable to a traditional insulating solution. Therefore, the cost effectiveness of heat-reflective materials needs to be computed case by case and in accordance with the required thermal resistance.

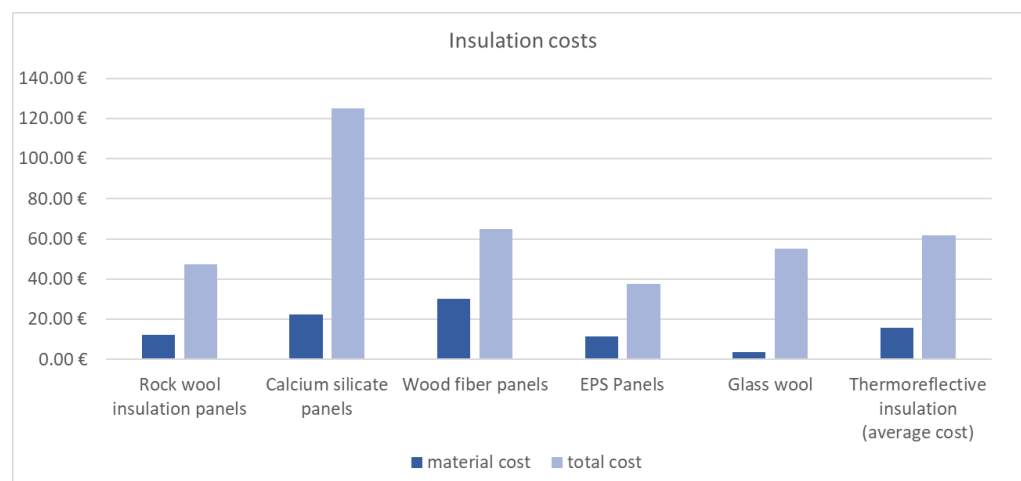


Figure 11. Total cost for insulation with different materials of the heat-reflective materials with the correspondent thermal resistance. Approximation of the results with a second-degree polynomial equation.

4. Conclusions and Future Developments

The energy efficiency strategy concerning insulating coatings in existing buildings introduces many issues (e.g., limited space for insulating coating and maximum limit transmittance) which require the use of innovative insulators, instead of traditional ones.

This present work provides a general overview about the available thermal insulation materials, with a specific insight into heat reflective ones. Their theoretical thermal resistance was computed by means of the presented numerical approach and was used to verify the accuracy of the measured performances declared by the producers. A very good agreement with different anonymized brands has been found. Only one out of eight investigated materials, representing the main heat reflective insulators on the market, presented a variation higher than 5% between declared and estimated performance.

Then, the application of the heat reflective thermal insulation materials to different walls in the most common Italian climatic zones (C, D, and E) was simulated. According

to the results, most of the reflective insulators cannot satisfy the required limits in terms of transmittance themselves, almost independently from the climatic zone. The use of reflective materials only as an integration into a thinner external coating is the most effective strategy (Figures 5–8). Indeed, all considered heat-reflective materials lead to transmittances below the limits for all considered climatic zones. Concerning the external integration insulator, the required thickness (about 3 cm) reduces the impact of the insulation on the external façade, whereas the maximum conductivity (about 0.04 W/mK) is highly compatible with most traditional and cheap insulators. Regardless, all considered reflective materials present an intrinsic flaw concerned with the risk of interstitial condensations due to the aluminum layers inside. The reported case studies have shown only one case (stone wall) where interstitial condensation occurred.

A cost-effectiveness analysis has been carried out on the investigated materials, highlighting that the most eligible heat reflective insulator in terms of costs and performance is not always the cheapest one. The results are not relevantly influenced by the steep increase in prices for building materials occurred in Italy in the past months because the rise affected the cost of the insulators in a very similar way. The cost-effectiveness analyses also provided a comparison with the traditional insulators, showing that some heat-reflective materials (30% of the enquired ones, two out of seven materials) are never convenient due to their high cost compared to the low, provided thermal resistance. About 40% of the materials (three out of seven) resulted in being comparable to traditional insulating solutions from the points of view of the total cost, thermal resistance, and required thickness. Only 30% of the investigated materials (two out of seven) almost doubled the thermal resistance at an increase in the total price of about 25%. As a consequence, the adoption of the heat reflective insulators is not always preferable to other classic solutions and needs to be evaluated according to the specific case study.

In future developments, the remaining Italian climatic zones and other kinds of walls should be included in the simulations. Indeed, these solutions would result as being highly effective in buildings where the external outline cannot be modified, (e.g., ancient mansions, castles, or heritage-protected buildings). Another very common case is represented by buildings where there is not enough space to install an external coating and, therefore, internal insulation might result mandatory. In addition, innovative strategies to cope with the interstitial condensation should be investigated because the heat reflective mechanism is typically based on material with a very high vapor resistance (i.e., aluminum layers inside the materials). An instance might be represented by ventilation inside the cavities whereas a more interesting approach concerns the coupling of internal heat reflective insulators to mechanized ventilation systems.

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Appendix A

This appendix illustrates the eight cases analyzed reporting for each: the stratigraphy, the thermal transmittance reached by means of different heat-reflective layers and a graph where the transmittances are compared to the Italian limits for the three main climatic zones, as done previously in the paper. Please note that the numbers in each stratigraphy always start from the external one.

Wall type 1

Stratigraphy	s [m]	λ [W/mK]
1 lime-cement plaster	0.02	0.9
2 hollow brick 12 cm	0.12	0.387
3 air cavity	0.02	-
4 Thermoreflective insulation	-	-
5 air cavity	0.02	-
6 alveolated brick 20 cm	0.2	0.18
7 lime plaster	0.02	0.7

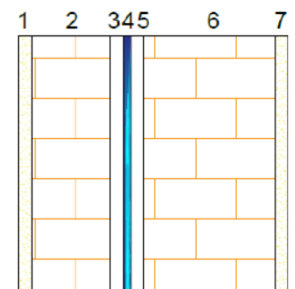


Figure A1. Wall type 1: stratigraphy with thicknesses and conductivities for the different layers. The numbers start from the outside.

Table A1. Wall type 1: thermal transmittance reached with different heat-reflective materials.

Material Number	Calculated Thermal Resistance [W/m ² K]
Only wall	0.546
1	0.311
2	0.174
3	0.254
4	0.215
5	0.315
6	0.295
7	0.291
8	0.252

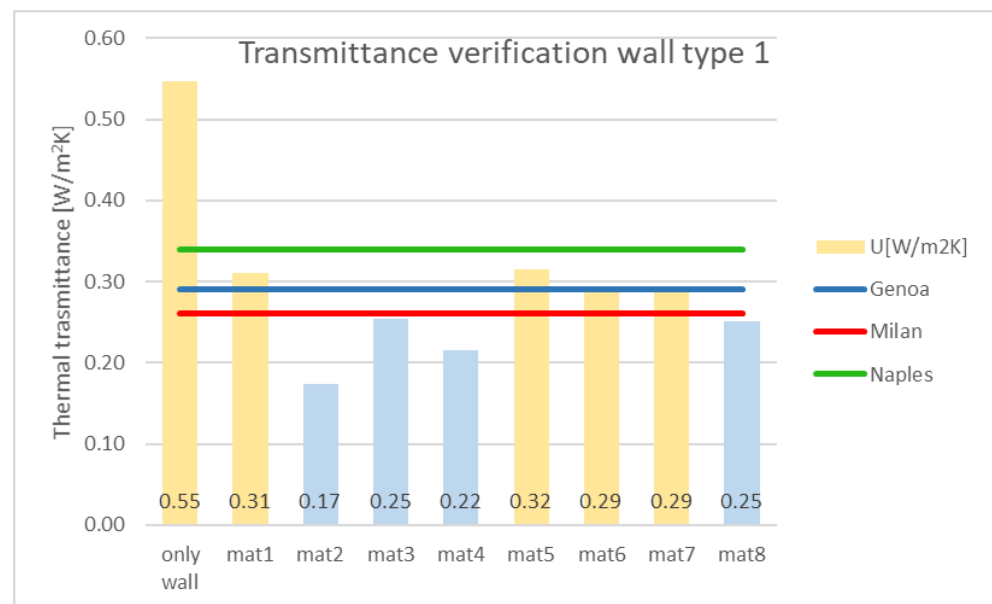


Figure A2. Wall type 1: transmittance check for the three main Italian climatic zones. In blue are the heat-reflective materials which respect all the limits.

Wall type 2

Stratigraphy		s [m]	λ [W/mK]
1	lime-cement plaster	0.02	0.7
2	hollow brick 8 cm	0.08	0.387
3	air cavity	0.02	-
4	Thermoreflective insulation	-	-
5	air cavity	0.02	-
6	alveolated brick 30 cm	0.3	0.18
7	lime plaster	0.02	0.7

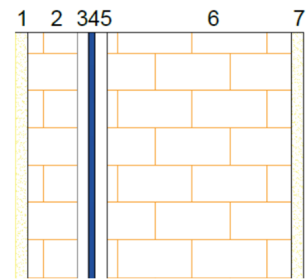


Figure A3. Wall type 2: stratigraphy with thicknesses and conductivities for the different layers. The numbers start from the outside.

Table A2. Wall type 2: thermal transmittance reached with different heat-reflective materials.

Material Number	Calculated Thermal Resistance [W/m ² K]
Only wall	0.437
1	0.272
2	0.162
3	0.228
4	0.196
5	0.276
6	0.260
7	0.257
8	0.226

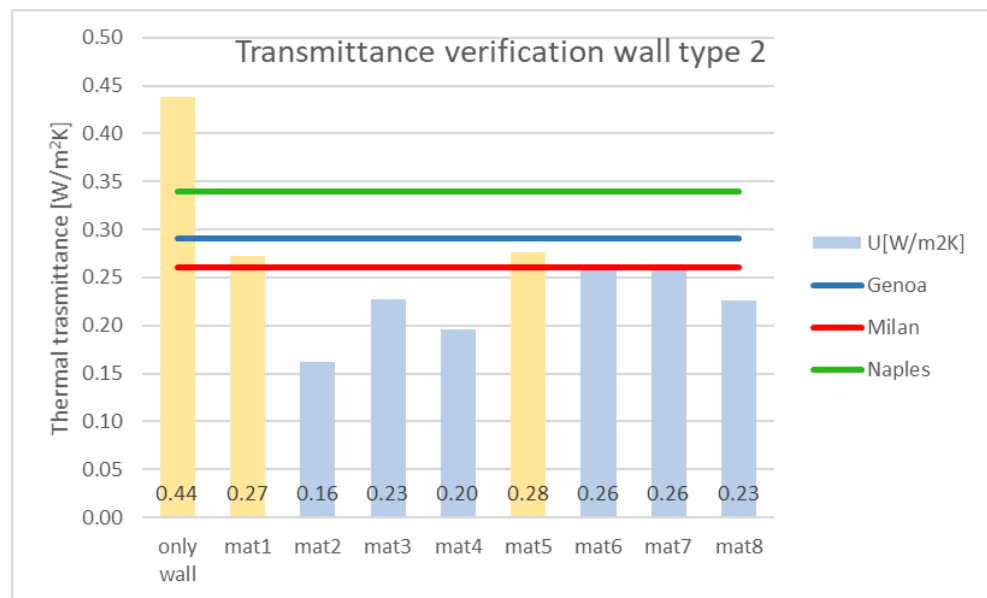


Figure A4. Wall type 2: transmittance check for the three main Italian climatic zones. In blue are the heat-reflective materials which respect all the limits.

Wall type 3.1

Stratigraphy		s [m]	λ [W/mK]
1	lime plaster	0.02	0.7
2	hollow brick 8 cm	0.08	0.387
3	air cavity	0.02	-
4	Thermoreflective insulation	-	-
5	air cavity	0.02	-
6	hollow brick 12 cm	0.12	0.387
7	lime-cement plaster	0.02	0.9

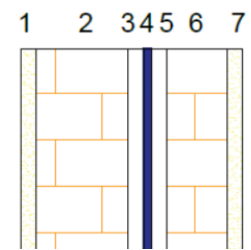


Figure A5. Wall type 3.1: stratigraphy with thicknesses and conductivities for the different layers. The numbers start from the outside.

Table A3. Wall type 3.1: thermal transmittance reached with different heat-reflective materials.

Material Number	Calculated Thermal Resistance [W/m ² K]
Only wall	1.087
1	0.433
2	0.207
3	0.329
4	0.268
5	0.441
6	0.402
7	0.395
8	0.326

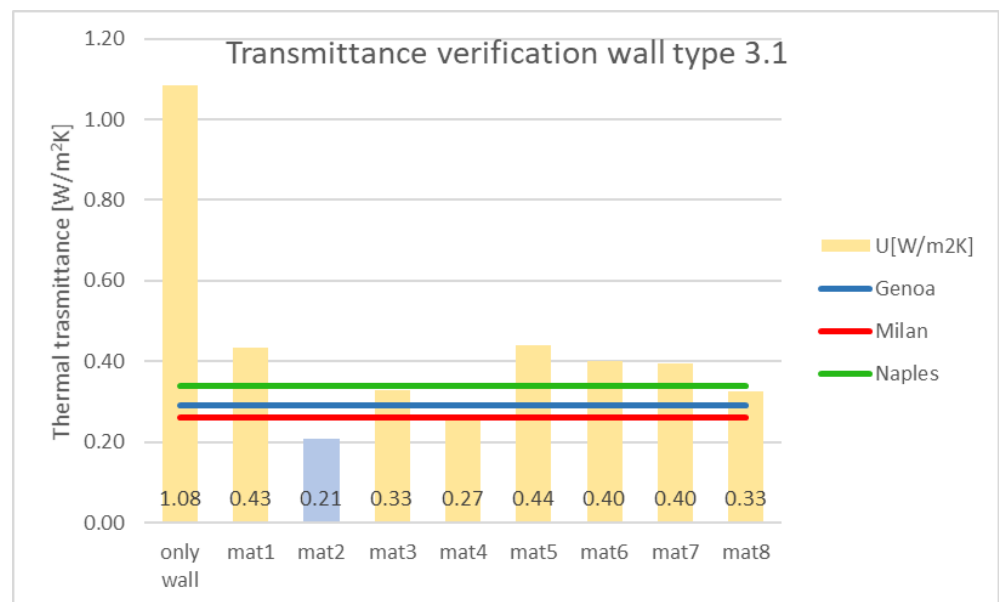


Figure A6. Wall type 3.1: transmittance check for the three main Italian climatic zones. In blue are the heat-reflective materials which respect all the limits.

Wall type 3.2

Stratigraphy	s [m]	λ [W/mK]
1 lime plaster	0.02	0.7
2 hollow brick 8 cm	0.08	0.387
3 Thermoreflective insulation	-	-
4 air cavity	0.04	-
5 hollow brick 12 cm	0.12	0.387
6 lime-cement plaster	0.02	0.9

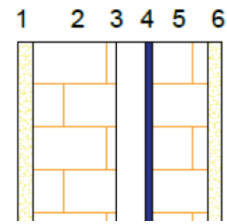


Figure A7. Wall type 3.2: stratigraphy with thicknesses and conductivities for the different layers. The numbers start from the outside.

Table A4. Wall type 3.2: thermal transmittance reached with different heat-reflective materials.

Material Number	Calculated Thermal Resistance [W/m ² K]
Only wall	1.087
1	0.600
2	0.240
3	0.422
4	0.334
5	0.624
6	0.549
7	0.543
8	0.395

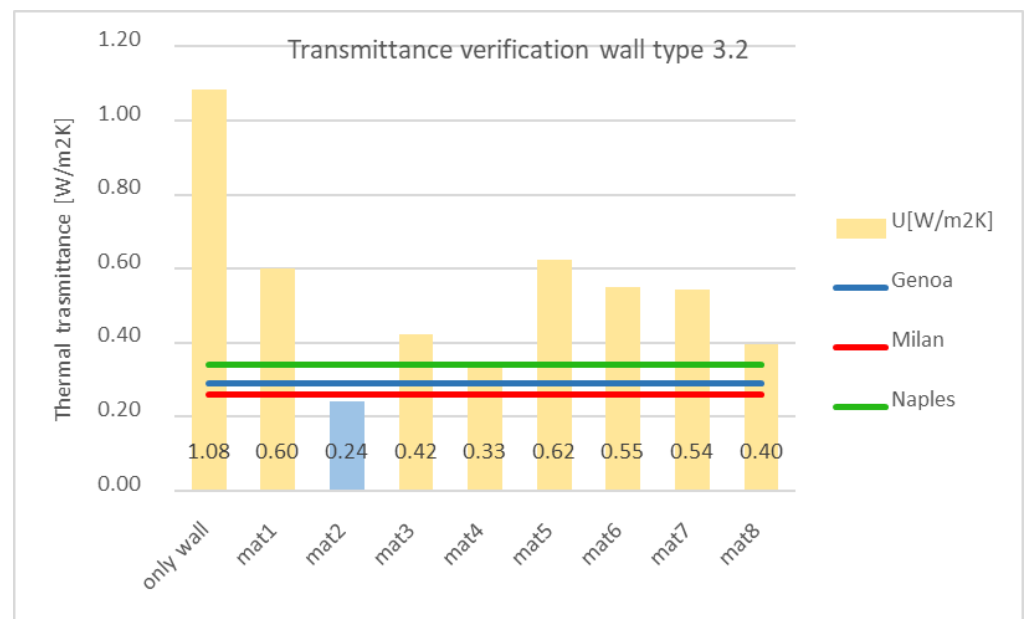


Figure A8. Wall type 3.2: transmittance check for the three main Italian climatic zones. In are blue the heat-reflective materials which respect all the limits.

Wall type 3.3

Stratigraphy	s [m]	λ [W/mK]
1 drywall	0.012	0.2
2 air cavity	0.02	-
3 Thermoreflective insulation	-	-
4 air cavity	0.02	-
5 lime plaster	0.02	0.7
6 hollow brick 8 cm	0.08	0.387
7 air cavity	0.16	
8 hollow brick 12 cm	0.12	0.387
9 lime-cement plaster	0.02	0.9

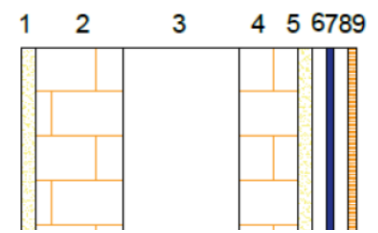


Figure A9. Wall type 3.3: stratigraphy with thicknesses and conductivities for the different layers. The numbers start from the outside.

Table A5. Wall type 3.3: thermal transmittance reached with different heat-reflective materials.

Material Number	Calculated Thermal Resistance [W/m ² K]
Only wall	1.087
1	0.392
2	0.197
3	0.305
4	0.251
5	0.398
6	0.366
7	0.360
8	0.302

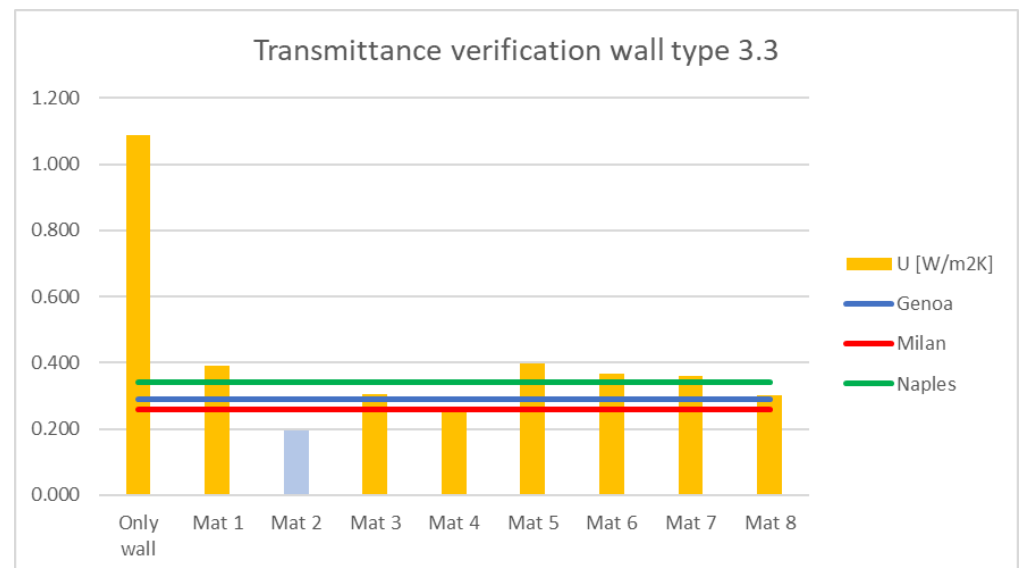


Figure A10. Wall type 3.3: transmittance check for the three main Italian climatic zones. In are blue the heat-reflective materials which respect all the limits.

Wall type 4

Stratigraphy		s [m]	λ [W/mK]
1	Expanded sintered polystyrene EPS	0.03	0.04
2	Alveolated brick 30 cm	0.3	0.18
3	Air cavity	0.02	-
4	Thermoreflective insulation	-	-
5	Air cavity	0.02	-
6	Drywall	0.012	0.2

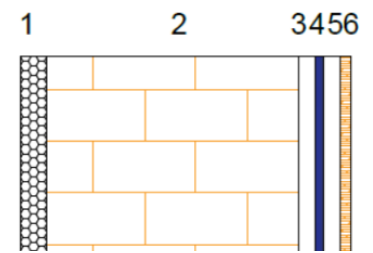


Figure A11. Wall type 4: stratigraphy with thicknesses and conductivities for the different layers. The numbers start from the outside.

Table A6. Wall type 4: thermal transmittance reached with different heat-reflective materials.

Material Number	Calculated Thermal Resistance [W/m ² K]
Only wall	0.386
1	0.237
2	0.148
3	0.202
4	0.177
5	0.239
6	0.227
7	0.225
8	0.201

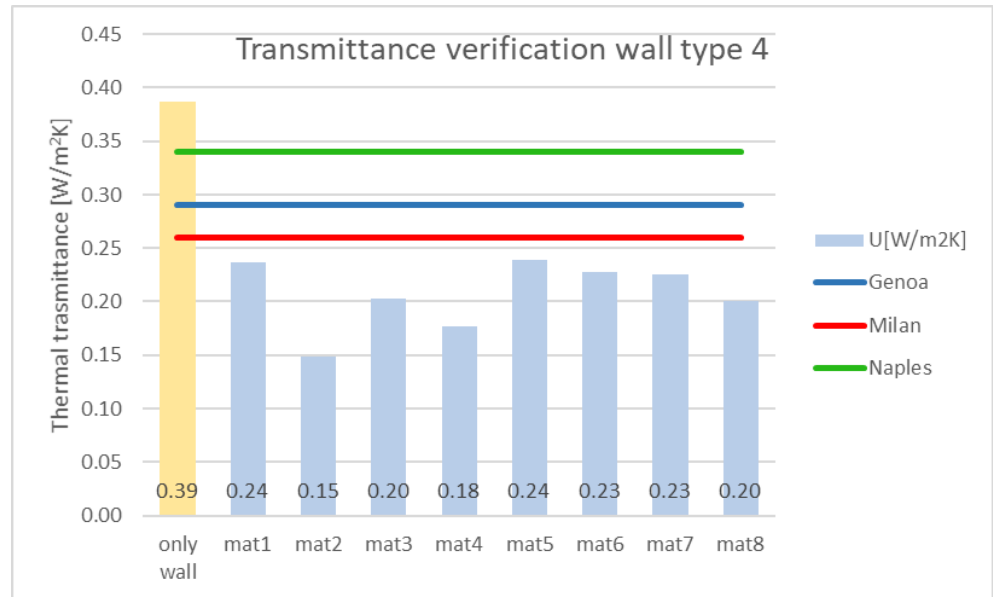


Figure A12. Wall type 4: transmittance check for the three main Italian climatic zones. In are blue the heat-reflective materials which respect all the limits.

Wall type 5.1

Stratigraphy		s [m]	λ [W/mK]
1	Stone wall	0.54	2.4
2	air cavity	0.02	-
3	Thermoreflective insulation	-	-
4	air cavity	0.02	-
5	Drywall	0.012	0.2

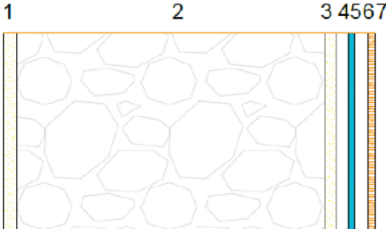


Figure A13. Wall type 5.1: stratigraphy with thicknesses and conductivities for the different layers. The numbers start from the outside.

Table A7. Wall type 5.1: thermal transmittance reached with different heat-reflective materials.

Material Number	Calculated Thermal Resistance [W/m ² K]
Only wall	2.326
1	0.485
2	0.218
3	0.359
4	0.287
5	0.495
6	0.447
7	0.438
8	0.355

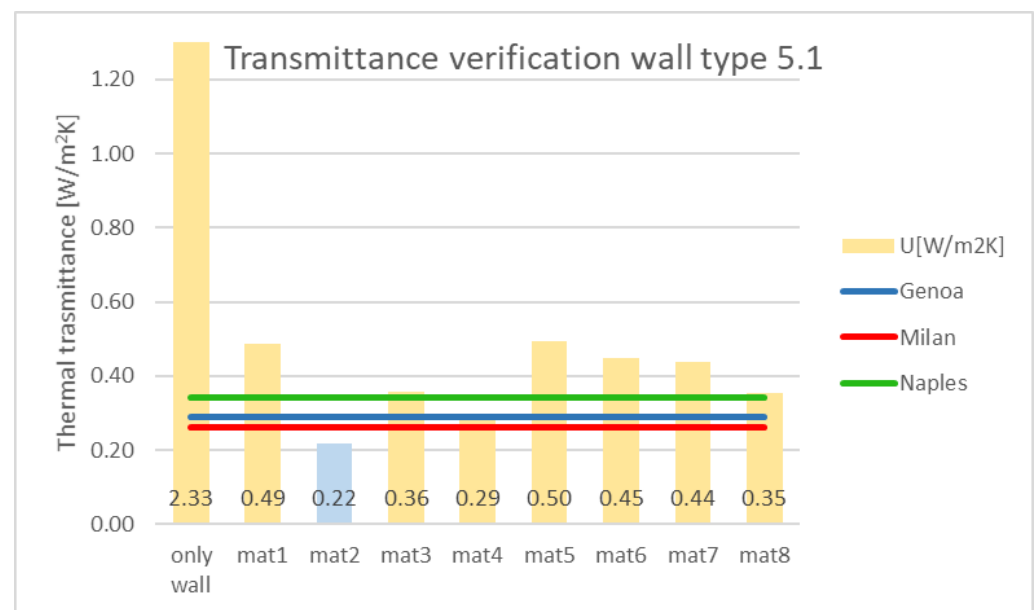


Figure A14. Wall type 5.1: transmittance check for the three main Italian climatic zones. In are blue the heat-reflective materials which respect all the limits.

Wall type 5.2

	Stratigraphy	s [m]	λ [W/mK]
1	ceramic tiles	0.01	1.2
2	air cavity	0.02	-
3	Thermoreflective insulation	-	-
4	air cavity	0.02	-
5	lime-cement plaster	0.02	0.9
6	stone wall	0.5	2.4
7	lime plaster	0.02	0.7

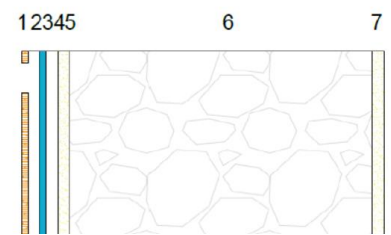


Figure A15. Wall type 5.2: stratigraphy with thicknesses and conductivities for the different layers. The numbers start from the outside.

Table A8. Wall type 5.2: thermal transmittance reached with different heat-reflective materials.

Material Number	Calculated Thermal Resistance [W/m ² K]
Only wall	2.326
1	0.737
2	0.259
3	0.485
4	0.372
5	0.773
6	0.661
7	0.652
8	0.450

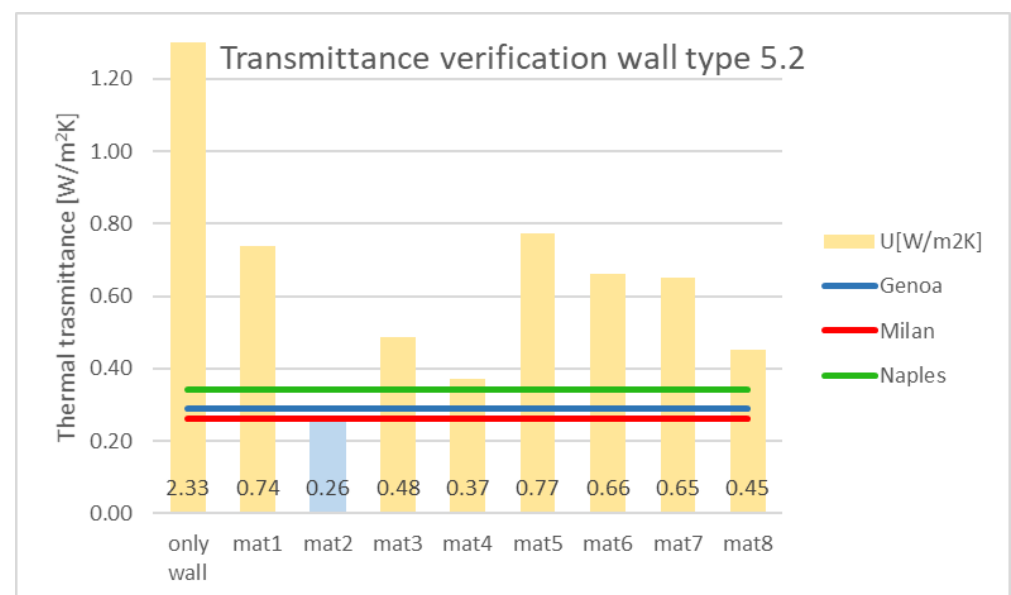


Figure A16. Wall type 5.2: transmittance check for the three main Italian climatic zones. In are blue the heat-reflective materials which respect all the limits.

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