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Case study

Economic and environmental assessment of thermal insulation. A case study in the Italian context

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ABSTRACT

An analysis of the state of the art has shown how current European policy underpins the importance of assessing the impact of different energy efficiency strategies during the life cycle of buildings. In this study a framework is developed for the identification of the optimal material to be used to achieve the highest level of energy efficiency in building retrofits, taking into account environmental and economic elements and comparing different scenarios. For each of these scenarios the Life Cycle Cost Analysis was applied together with related environmental analysis in terms of the production of CO_2. The research was applied to an industrial factory in Italy. Results showed that, among ten material with different origin, namely plant, animal, mineral and fossil origin, the optimal thickness varied between 0.023 m of the line fiber, and 0.082 m of the rock wool. From the economic point of view, saving was between 1.58 €/m^2 with the linen fiber, and 9.63 €/m^2 with the rock wool. Finally, considering the environmental aspect, savings in terms of CO_2 was possible only for three of the ten materials, namely cork, sheep wool and fiber glass, respectively equal to 0.14 Kg/m^2, 0.65 Kg/m^2 and 0.34 Kg/m^2. The study has important implications mainly regarding the issue of energy efficiency. Specifically, the opportunity to analyse and compare economic and environmental aspects of a series of alternative materials to improve energy efficiency may provide stakeholders with calculated and objective input for the support of sustainable actions. Sum up, this research has identified a "result oriented" methodology comparing traditional and sustainable materials and measuring the benefits from the correct insulation of a building. These benefits are mainly of an economic and environmental nature and, in this regard, the study helps to strengthen the leadership of the EU for a sustainable use of natural resources within an efficient bioeconomy, essential to achieve Sustainable Development Goals.

1. Introduction

European directive 2018/844/EU modified previous directives 2010/31/EU on energy performance in buildings and 2012/27/EU on energy efficiency, with the objective of promoting greater use of energy efficiency and renewable energies in buildings, thereby contributing to the reduction of greenhouse gas emissions and aiming at a decarbonised and highly efficient energy system by 2050. Over the years much of the focus of European policy has been centred on the construction sector, due to the fact that around 36 % of all

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Nomenclature

$C_{c\ (ins)}$	Total cooling cost following the intervention [€/m^2]
$C_{c(\ no-ins)}$	Total cooling cost in the absence of the intervention [€/m^2]
C_e	Cost of electricity [€/kWh]
C_f	Cost of natural gas [€/kg]
$C_{h\ (ins)}$	Total heating cost following the intervention [€/m^2]
$C_{h\ (no-ins)}$	Total heating cost in the absence of the intervention [€/m^2]
C_{ins}	Cost of insulation [€/m^2]
C_m	Cost of insulating material [€/m^3]
$CO_{2\ (ins)}$	Embodied carbon of the insulation [kg CO_2/kg]
$C_{t\ (ins)}$	Total cost following the intervention [€/m^2]
$C_{t\ (no-ins)}$	Total cost in the absence of the intervention [€/m^2]
CDD	Cooling degree-days [°C-days]
CK	Cork
COP	Performance of cooling system
DDs	Degree-days
E_c	Annual energy loss for cooling [J/m^2]
E_h	Annual energy loss for heating [J/m^2]
EPS	Expanded polystyrene
f	Inflation rate [%]
FG	Fiber glass
H_u	Lower heating values of natural gas [J/kg]
HDD	Heating degree-days [°C-days]
HF	Hemp fiber
i	Interest rate [%]
LF	Linen fiber
$m_{CO_2\ (ins)}$	Total CO2 emissions, associated to heating and cooling of the building following the intervention [kg/m^2]
$m_{CO_2\ (no-ins)}$	Total CO_2 emissions, associated to heating and cooling in the absence of the intervention [kg/m^2]
m_{CO_2-c}	CO_2 mass produced by ambient cooling [kg/m^2]
$m_{CO_2-c\ (ins)}$	CO_2 mass produced by the building by cooling following the intervention [kg/m^2]
$m_{CO_2-c\ (no-ins)}$	CO_2 mass produced by the building in the absence of the intervention [kg/m^2]
m_{CO_2-h}	CO_2 mass produced by the consumption of natural gas for ambient heating [kg/m^2]
$m_{CO_2-h\ (ins)}$	CO_2 mas produced by the consumption of natural gas for ambient heating in the building following the intervention [kg/m^2]
$m_{CO_2-h\ (no-ins)}$	CO_2 mass produced by the consumption of natural gas for ambient heating in the building in the absence of the intervention [kg/m^2]
$m_{CO_2-m\ (ins)}$	CO_2 mass produced related to the production of thermal insulation materials [kg/m^2]
m_f	Annual fuel consumption [kg/m^2]
N	Lifetime [years]
N_d	Number of heating or cooling days of a certain time period
PUR	Expanded polyurethane
PWF	Present Worth Factor
q	Heat flux [W/m^2]
R_{tw}	Total thermal resistance of the wall in the absence of the intervention [(m^{2}K)/W]
RW	Rock wool
S_{C_t}	Cost saving [€/m^2]
$S_{m_{CO_2}}$	CO_2 emissions avoided following the intervention [kg/m^2]
SW	Sheep wool
T_b	Base temperature [°C]
T_d	Daily-mean temperature [°C]
T_e	External temperature [K]
T_i	Internal temperature [K]
U	Transmittance [W/(m^2·K)]
WF	Wood fiber
x	Insulation thickness [m]
x_{opt}	Optimum insulation thickness [m]
$R_{tw} + x/_{\lambda}$	Thermal resistance of the wall following the intervention [(m^{2}K)/W]

XPS	Extruded polystyrene
η_h	Efficiency of the heating systems
ρ	Density of the insulating material [kg/m3]
λ	Thermal conductivity of the insulation [W/(m·K)]

CO_2 emissions in the European Union [1] are attributable to buildings. According to a report by Abergel, Dean [2] the construction and subsequent use of buildings represents 36 % of global final energy use and almost 40 % of CO_2 emissions [3]. This means that almost half of the total energy requirement is absorbed by the construction sector. Furthermore, the link between construction and harmful emissions is now globally recognized and acknowledged and many authors concentrate their research and studies on this topic. For example, Röck, Saade [4] demonstrate how buildings contribute to the climate crisis being the main source of greenhouse gas (GHG) emissions. Lee and Lee and Estiri emphasize the link between emissions and population density [5,6]. Kylili and Fokaides [7] underline how a reduction in emissions in the construction sector could make a significant contribution to global efforts to reduce resource depletion and global warming; Mirabella, RÖCk [8] support the importance of investigating the impacts that different energy efficiency strategies can make during the entire life cycle of a building. There are various study and development scenarios but an area that cannot be neglected is that related to existing buildings [9–11]. In fact, 2018/844/EU has among its main goals the one of integrating long-term renovation strategies of buildings and making them more effective both in terms of emission reduction and cost control (Article 2bis, paragraph 2 and paragraph 4). In this context, Life Cycle Cost Analysis (LCCA) is an economic evaluation method able to determine the overall cost of a product whilst taking into account its life cycle [12–14].

This overall cost is derived from the initial investment, from all running costs during its life-cycle and from any disposal and recovery costs. The estimate of the overall cost facilitates an assessment of the economic viability of introducing innovative solutions that can lead to eventual savings in management and maintenance costs together with a reduction of the impact on the environment. This approach is adopted in different study areas because the LCCA is a valid instrument for the evaluation of proposed solutions and choices. For example Kannan, Tso [15] use it to analyse an oil fired steam turbine power plant, Kulczycka and Smol [16] for the evaluation of investment projects, Shankar Kshirsagar, El-Gafy [17] as a management tool for institutional buildings and [18] in support of the 2030 agenda in a context of safeguarding of cultural heritage. On the other hand, Moran, Goggins [19] and Luerssen, Gandhi [20] use LCCA to evaluate different design options and [21,22] to determine the optimum insulation thickness of residential buildings in Turkey.

This article focuses on the analysis of building materials used which can improve the energy efficiency of buildings [7] and specifically thermal insulators [23,24] which contribute to a reduction of energy consumption for heating and cooling, bringing both a saving of precious resources and a decrease in the emission of substances harmful to the climate.Some authors have focused their attentionon the insulation material used together with air gap. For instance, Ertürk researched on the effects of insulation thickness on the life cycle costs of steel pipes [25,26] and with others [27] analyzed in particular different pipe materials for HVAC pipe applications. On the same topic, but in the construction field, in [28] Ertürk calculates the optimal insulation, the optimal cost, savings and depreciation in reference to the masonry of Ankara; in [29] presented an innovative approach to define the exergetic optimum insulation thickness and the payback period; in [30] the effect of optimum insulation thickness on the environment and energy was calculated for Izmir, Turkey. Finally [31] studied the energy performance of walls with hemp wool insulation and air gap layers.

The use of traditional materials, compared to natural and renewable materials, is not justified by their performance. Based on the results of Durakovic, Yildiz [32] "natural insulation materials are recommended in building design due to their low thermal conductivity that causes high thermal resistance, saves energy dissipation and reduces environmental impact".

For a correct choice of the most suitable material, the intended use and type of building need to be taken into account, the properties of the material and above all its cost [33] and impact on the environment. In fact, the choice of insulating material is based on a holistic approach taking into account thermal characteristics, sound insulation, fire resistance, water vapour permeability, costs and impact on the environment [34]. This aspect has become more important in recent years and has led to the replacement of conventional insulators which had high environmental impact, with materials that are environmentally friendly and guarantee the same thermal performance; this is considered the correct way to achieve environmental sustainability in the construction sector [7].

Environmental sustainability is one of the elements which needs attention, where also costs have a key role in the selection of insulating materials. In particular, the calculation of the optimal insulating thickness is necessary, because, due to insulation measures, if on the one hand the operating costs decrease, on the other the cost of insulation should be borne. For this reason, it is essential to choose the thickness of insulation that allows to minimise total costs. Therefore, determining the optimum thickness of insulation both in relation to economics and environmental criteria is very important and is more reliable [35]. Various studies were conducted in order to determine the optimum thickness of insulation [36–39].

What is subsequently required is the correct definition of the mix of sustainable insulating material and its optimal thickness. The optimal thickness guarantees the correct level of energy efficiency and minimises costs. If the thickness is not optimal this can cause diseconomies at all levels. The use of insulating materials better than those considered optimal will mean higher and unnecessary initial investment as well as eventual higher disposal costs. On the other hand, if less than optimal insulating material is used this will mean higher energy costs during the life of the building. The approach through the search for optimal thickness is very topical today. Recent studies [40] analyze the effect of insulation thickness on residential and population sourced energy demands, while [41] use it to achieve NZEBs by energy renovation of thermal envelopes of existing multi-family buildings in Spain, also using LCCA. In fact, through the use of the LCCA, the optimal isolation level may be defined keeping costs to a minimum. This article is part of a wider area of research: in the previous phase a case study was made on an existing building and 10 different energy efficiency options with different materials, were analysed [42].

In this paper a framework for the identification of the optimal solution is defined, to achieve the best combination of: energy efficiency, taking into account not only the nature of the materials and costs associated with the intervention and the eventual life cycle, but also the cost savings deriving from the energy redevelopment of the building; the cost of cooling system during the life of the building; the environmental impact assessment in terms of CO_2 emmissions associated to the individual scenarios. So, this research adds to existing knowledge by identifying a "result oriented" methodology that, enabling a comparison [43] between traditional and sustainable materials, allow to quantify the benefits related to the correct insulation of a building. These benefits are mainly of an economic and environmental nature and, thereby, they give a contribution to make the sustainability not only a legal obligation but also an opportunity for all stakeholders. In this paper various elements of relevance and novelty can be found, which, although tested locally, can have consequences at a national level. The research (based on an annual and meticulous phase of investigation and data collection) and the successful results obtained made it possible to define: an analysis and best practices framework in the context of reducing emissions from existing buildings. This research topic appears to be in line with the latest European regulatory updates. In addition, the results achieved allow us to overcome the sectoral approach in terms of energy efficiency: from the analysis of the state of the art, this approach was erroneously widespread. In fact, the methodology developed takes into account numerous variables and is applicable in any climatic context since it takes into account both the heating and cooling costs (modifying the input parameters allows the framework to be applied in any international context). It also analyzes both traditional and sustainable materials, with a view to an assessment that is as complete and comprehensive as possible. In this way, the developed methodology, even if validated in a specific case study, can be used in any contest and in any country, helping to increase knowledge on the field from an international perspective.

As already argued, the developed methodology was validated through the case study of a factory in the Abruzzo region, Italy.

This choice is based on a number of reasons. Firstly, Italy has a high consumption rate of natural fuel for heating residential, commercial and industrial structures; an optimal energy efficiency solution is therefore desirable, that will contribute to the reduction of consumption levels. Results of the 2011 population and housing census estimate that in Italy 25.5 million houses are equipped with heating systems and among these, 17.5 million (69 %) are fuelled by natural gas, highlighting a limited use of alternative energy sources [44]. Secondly, the use of internal cooling systems is increasing, and at present, air conditioners and electric fans are already responsible for about one fifth of total electricity consumed in buildings. It is estimated that this will continue to grow leading to a sharp increase in electricity consumption in Italy [45]. It is clear that these trends need to be reversed for a more responsible and sustainable management of non-renewable resources and to achieve the eco-city goals [46].

The study presented in the article search for the optimal solution to improve the energy response of the building walls following a thermal insulation intervention. It is able to respond simultaneously to economic issues and sustainability and energy saving ones and in line with the new Directive (EU) 2018/844 of the European Parliament [47]. It also introduces further elements of novelty compared to previous work [42] represented by the introduction of the cooling cost, the CO_2 analysis and the use of the metacriterion [38].

The study can be easily replicated in other contexts and can contribute to bridge the numerous research gaps highlighted by the research background. Among these, the most evident are:

- the gap between LCCA estimates and reality [41], especially from a regulatory and legislative point of view;
- the non-simultaneous evaluation of the main issues, namely the environmental, economic aspects and the value of thermal resistance [48] and transmittance, which are particularly important parameters for building owners as they affect consumption and comfort conditions;
- the need for strategies and procedures that are multidisciplinary, able to help policy makers when they have to intervene on existing buildings to allow green energy transition.

The following chapters illustrate: the methodology used to ensure the replicability of the results, the case study and the results, the discussion, the conclusions.

2. Methodology

The LCCA is an evaluation method able to identify the best solution from alternatives, taking into account economic variables for an estimate of the global cost of each option under analysis and considering its entire life-cycle.

The method was used to identify the optimal solution for an energy efficiency intervention on the external building walls, requiring the best combination of the type of material and its thickness to optimise the energy performance of the masonry minimising the cost.

For each solution the related environmental analysis in terms of the production of CO_2 were also made.

The aim of the work is therefore to identify the optimal solution that allows to maximise the savings deriving from the energy requalification of a building both in environmental and economic terms.

The methodology is illustrated in two sections. The first outlines the preliminary analysis, the variables and the dimensions used in the study; the second one describes the calculation method.

2.1. Preliminary analyses

Firstly, for a proper use of the LCCA analysis, the cost of each intervention option needs to be defined, taking into account the investment, heating and cooling costs. Running costs, maintenance and recovery value [42] were not considered. Installation costs were calculated considering the material cost of each insulation panel. Labour and transportation costs are the same regardless of the type of insulation panels [49].

Therefore, the total cost is obtained by:

- The cost of the insulating material;
- The cost of natural gas chosen as a fuel for heating;
- The cost of electricity for cooling. The total cost, expressed in €/m2

These cost items were estimated over the entire life cycle by considering 10 different insulating materials. Insulators of plant, animal, mineral and fossil origin were analysed. Specifically:

- Wood fiber (WF) -Plant origin;
- Hemp fiber (HF) - Plant origin;
- Linen fiber (LF) - Plant origin;
- Cork (CK) - Plant origin;
- Rock wool (RW) - Mineral origin;
- Fiber glass (FG) - Mineral origin;
- Expanded polystyrene (EPS) - Fossil origin;
- Expanded polystyrene (XPS) - Fossil origin;
- Expanded polyurethane (PUR / PIR) - Fossil origin;
- Sheep wool (SW) - Animal origin.

The LCCA method requires some preliminary analyses aimed at defining:

- properties and cost of the insulating material;
- efficiency of the cooling and heating system;
- cost of natural gas and electricity;
- Present Worth Factor (PWF);
- The position of the building and the characteristics of the wall under analysis.

Therefore, for each insulator it was necessary to define the thermal conductivity of the material expressed in W/m K which allows performance calculation of heat transmission. In fact, in the choice of thermal insulation materials, thermal conductivity is one of the most important parameters [50].

The estimation of heating and cooling energy requirements for buildings is based on degree-days (DDs). The DD value represents the cumulative sum of the only positive difference between the fixed internal reference temperature and the average daily external temperature registered over time. The reference temperature for buildings is a known variable and corresponds to the outdoor temperature at which the heating/cooling systems do not have to operate to maintain internal comfort within a building [51].

Heating Degree Days (HDD) and Cooling Degree Days (CDD) are two indicators that respectively indicate the thermal needs for heating and cooling buildings in a given location over a given period [52]. A high HDD or CDD value indicates a higher energy requirement to maintain comfortable conditions within a building. If the DD index is not calculated correctly, the building's energy performance results will be inaccurate.

Numerically HDD and CDD are calculated with the following formulas:

$$HDD = \sum_{i=1}^{N_d} (T_b - T_d)^+ \tag{1}$$

$$CDD = \sum_{i=1}^{N_d} (T_d - T_b)^+ \tag{2}$$

Where:

N_d : number of heating or cooling days over a given period of time

T_b: base temperatures [° C]

T_d: daily-mean temperature [° C]

$+$: plus symbol means that only positive differences between T_b and T_d are taken into account

The Present Worth Factor (PWF) facilitates the estimation of the cost of heating and cooling over the life of the insulation material. The PWF value depends on the interest rate (i) which represents the price paid for the use of borrowed money, the inflation rate (f) and the duration of the insulation material (N). The PWF can be estimated using the following formula [53]:

$$PWF = \begin{cases} \dfrac{(1+r)^N - 1}{r \cdot (1+r)^N} & for\ i \neq f \\ (1+r)^{-1} & for\ i = f \end{cases} \tag{3}$$

$$r = \frac{i - f}{1 + f} \tag{4}$$

with:

i: interest rate [%]

f: inflation rate [%]

N: insulation material lifetime [years].

Lastly, the heat flow meter method was used by following the Uni Iso 9869 standard [54] to define the characteristics of the wall typology under analysis. The technique was carried out in an neutral and undisturbed part of the wall, in the absence of thermal bridges, a condition verified by means of a thermographic analysis in accordance with standard (ISO 6781:1983). Subsequently, the method of progressive averages was applied, a procedure already illustrated previously [55], which defined the most probable transmittance value of the wall, using the following formula:

$$\mathrm{U} = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{ij} - T_{ej})} \tag{5}$$

where "U" is the transmittance, "q" the thermal flux, "Ti" the internal temperature, "Te" the external temperature.

2.2. The calculation method

After the definition of the quantities and the variables referred to in previous paragraph, it is possible to proceed with the LCCA analysis to determine the economically optimal thickness of the insulating material applied to the wall.

The total cost, expressed in €/m^2, is given by the sum of the components related to insulation material, heating and cooling costs in relation to 1 m^2 of the wall area under the intervention:

$$C_{t\ (ins)} = C_{h\ (ins)} + C_{c\ (ins)} + C_{ins} \tag{6}$$

where:

$C_{t\ (ins)}$: total cost following the intervention [€/m^2]

$C_{h\ (ins)}$: total heating cost following the intervention [€/m^2]

$C_{c\ (ins)}$: total cooling cost following the intervention [€/m^2]

C_{ins}: cost of insulation [€/m^2]

In particular, cost of insulation, total heating and cooling costs following the intervention were calculated respectively by formulas 7–9 [39]:

$$C_{ins} = C_m \bullet \mathrm{x} \tag{7}$$

with:

C_{ins}: cost of insulation [€ / m^2]

C_m: cost of insulating material [€ / m^3]

x: insulation thickness [m]

$$C_{h\ (ins)} = \frac{86400 \bullet HDD \bullet C_f \bullet PWF}{\left(R_{tw} + x/\lambda\right) \bullet H_u \bullet} \eta_h \tag{8}$$

Where:

$C_{h\ (ins)}$: total heating cost following the intervention [€ / m^2]

86400: conversion factor (1day = 86,400 s)

HDD: heating degree-days [° C-days]

C_f: cost of natural gas [€ / kg]

PWF: Present Worth Factor

R_{tw}: total thermal resistance of the wall in the absence of the intervention [(m^{2}K)/W]

x: insulation thickness [m]

λ: thermal conductivity of the insulation [W/(m·K)]

$R_{tw} + \frac{x}{\lambda}$: total thermal resistance of the wall following the intervention [(m^{2}K)/W]

H_u: lower heating values of natural gas [J/kg]

η_h : efficiency of the heating systems

$$C_{c\,(ins)} = \frac{86400 \cdot CDD \cdot PWF \cdot C_e \cdot 2.778 \cdot 10^{-7}}{\left(R_{tw} + x/_{\lambda}\right) \cdot COP} \tag{9}$$

with:

$C_{c\,(ins)}$: total cooling cost following the intervention [€/m^2]
86400: conversion factor (1day = 86,400 s)
CDD: cooling degree-days [° C-days]
C_e : cost of electricity [€ / kWh]
PWF: Present Worth Factor
R_{tw}: total thermal resistance of the wall in the absence of the intervention [(m^{2}K) / W]
x: insulation thickness [m]
λ: thermal conductivity of the insulation [W / (m K)]
$R_{tw} + \frac{x}{\lambda}$: total thermal resistance of the wall following the intervention [(m^{2}K) / W]
COP: performance of cooling system
$2.778 \cdot 10^{-7}$: conversion factor (1 J = $2.778 \cdot 10^{-7}$ kWh).
Explaining C_{ins}, $C_{h\,(ins)}$ and $C_{c\,(ins)}$, the total cost $C_{t\,(ins)}$ is given by:

$$C_{t\,(ins)} = \frac{86400 \cdot PWF}{\left(R_{tw} + x/_{\lambda}\right)} \cdot \left(\frac{\mathrm{HDD} \cdot \mathrm{C_f}}{\mathrm{H_u} \cdot \eta_h} + \frac{\mathrm{CDD} \cdot \mathrm{C_e} \cdot 2.778 \cdot 10^{-7}}{\mathrm{COP}}\right) + \mathrm{C_m} \cdot \mathrm{x} \tag{10}$$

Once the total cost is known, it is possible to calculate the economically optimal thickness of the insulating material (x_{opt}) from the minimization of the $C_{t\,(ins)}$ function. Specifically, x_{opt} is obtained by setting at zero the derivative of the $C_{t\,(ins)}$ function with respect to the thickness of the insulating material x:

$$\frac{\partial}{\partial x}\left(\frac{86400 \cdot PWF}{\left(R_{tw} + x/_{\lambda}\right)} \cdot \left(\frac{\mathrm{HDD} \cdot \mathrm{C_f}}{\mathrm{H_u} \cdot \eta_h} + \frac{\mathrm{CDD} \cdot \mathrm{C_e} \cdot 2.778 \cdot 10^{-7}}{\mathrm{COP}}\right) + \mathrm{C_m} \cdot \mathrm{x}\right) = 0 \tag{11}$$

By carrying out Eq. 11 it is possible to obtain the formula useful to calculate x_{opt}:

$$x_{opt} = \left[\frac{PWF \cdot 86400 \cdot \lambda}{C_m} \cdot \left(\frac{\mathrm{CDD} \cdot \mathrm{C_e} \cdot 2.778 \cdot 10^{-7}}{\mathrm{COP}} + \frac{\mathrm{HDD} \cdot \mathrm{C_f}}{\mathrm{H_u} \cdot \eta_h}\right)\right]^{½} - \lambda \cdot \mathrm{R_{tw}} \tag{12}$$

However, it is essential to check that the second derivative of the function is greater than zero with respect to the thickness of the insulating material x. Formula 13 allows to demonstrate whether x_{opt} is the minimum function value:

$$\frac{\partial^2}{\partial^2 x}\left(\frac{86400 \cdot PWF}{\left(R_{tw} + x/_{\lambda}\right)} \cdot \left(\frac{\mathrm{HDD} \cdot \mathrm{C_f}}{\mathrm{H_u} \cdot \eta_h} + \frac{\mathrm{CDD} \cdot \mathrm{C_e} \cdot 2.778 \cdot 10^{-7}}{\mathrm{COP}}\right) + \mathrm{C_m} \cdot \mathrm{x}\right) > 0 \tag{13}$$

By carrying out formula 13 it is possible to obtain:

$$x_{opt} > -\lambda \cdot \mathrm{R_{tw}} \tag{14}$$

From the convex function condition, it emerges that x_{opt} must be greater than a negative value. Since x_{opt} represents the insulation thickness and therefore a positive value, this condition is always verified. Consequently, it can be concluded that x_{opt} is optimal value of insulation thickness that minimises total costs.

The economically optimal thickness was calculated for each of the 10 insulation materials, as once this is known, the monetary savings following the intervention can be determined.

The cost saved S_{C_t} is calculated from the difference between the total cost in the absence of the intervention $C_{t\,(no-ins)}$ and the total cost following the intervention $C_{t\,(ins)}$:

$$S_{C_t} = C_{t\,(no-ins)} - C_{t\,(ins)} \tag{15}$$

Where $C_{t\,(no-ins)}$ is given by the following formula:

$$C_{t\,(no-ins)} = C_{h\,(no-ins)} + C_{c\,(no-ins)} \tag{16}$$

with:

$C_{t\,(no-ins)}$: total cost in the absence of the intervention [€/m^2]
$C_{h\,(no-ins)}$: total heating cost in the absence of the intervention [€/ m^2]
$C_{c(\,no-ins)}$: total cooling cost in the absence of the intervention [€/m^2]
In particular, $C_{h\,(no-ins)}$ and $C_{c(\,no-ins)}$ are determined by formulas 17 and 18 respectively:

$$C_{h\ (no-ins)} = \frac{86400 \bullet PWF \bullet HDD \bullet C_f}{R_{tw} \bullet H_u \bullet \eta_h} \tag{17}$$

$$C_{c\ (no-ins)} = \frac{86400 \bullet PWF \bullet CDD \bullet C_e \bullet 2.778 \bullet 10^{-7}}{R_{tw} \bullet COP} \tag{18}$$

Therefore, the total cost in the absence of the intervention $C_{t\ (no-ins)}$ is given by:

$$C_{t\ (no-ins)} = \frac{86400 \bullet PWF}{R_{tw}} \bullet \left(\frac{\mathrm{HDD} \bullet \mathrm{C_f}}{\mathrm{H_u} \bullet \eta_\mathrm{h}} + \frac{\mathrm{CDD} \bullet \mathrm{C_e} \bullet 2.778 \bullet 10^{-7}}{\mathrm{COP}} \right) \tag{19}$$

Explaining $C_{t\ (no-ins)}$, and $C_{t\ (ins)}$ the cost saving (S_{C_t}) is given by:

$$S_{C_t} = 86400 \bullet \mathrm{PWF} \bullet \left(\frac{\mathrm{HDD} \bullet \mathrm{C_f}}{\mathrm{H_u} \bullet \eta_\mathrm{h}} + \frac{\mathrm{CDD} \bullet \mathrm{C_e} \bullet 2.778 \bullet 10^{-7}}{\mathrm{COP}} \right) \bullet \left(\frac{1}{\mathrm{R_{tw}}} - \frac{1}{\mathrm{R_{tw}} + \mathrm{x_{opt}}/\lambda} \right) - \mathrm{C_m} \bullet \mathrm{x_{opt}} \tag{20}$$

Clearly, each of the 10 insulating materials will have a different cost saving.

In addition to evaluating the financial savings, reductions in CO_2 emissions following the intervention may be estimated. Once the economically optimal thickness for each insulating material is known (x_{opt}), the CO_2 emmissions associated with the heating and cooling of the building under study and the CO_2 emissions related to the production of thermal insulation materials may be determined. CO_2 emissions were assessed in kilograms per unit area. Before estimating CO_2 emmissions, the energy consumption per unit area needs to be known.

For heating, annual energy loss (J/m^2) from the wall was calculated as follows [53]:

$$E_h = \frac{86400 \bullet HDD \bullet U}{\eta_h} \tag{21}$$

with:

E_h: annual energy loss for heating [J / m^2]
86400: conversion factor (1day = 86,400 s)
HDD: heating degree-days [° C-days]
U: transmittance [W / (m^2· K)]
η_h : efficiency of the heating systems
Annual fuel consumption (kg / m^2) is given by:

$$m_f = \frac{86400 \bullet HDD \bullet U}{\eta_h \bullet H_u} \tag{22}$$

with:

m_f annual fuel consumption (kg / m^2)
H_u: lower heating values of natural gas [J / kg]
Since natural gas is mainly composed of methane (CH_4), this energy source is converted into heat by the combustion of CH_4 using air as a comburent [53].

$$CH_4 + 2\ O_2 + 7.52\ N_2 \rightarrow CO_2 + 2H_2O + 7.52\ N_2 \tag{23}$$

Nitrogen molecules in the air are inert and do not react to the combustion process. For each molecule of fuel that burns, 2 molecules of water (H_2O) and 1 of carbon dioxide (CO_2) are formed. Therefore, the mass of CO_2 produced by the consumption of natural gas m_{CO_2-h} expressed in kg / m^2 is given [53]:

$$m_{CO_2-h} = 2.75\ m_f \tag{24}$$

Explaining m_f gives:

$$m_{CO_2-h} = 2.75\ \frac{86400 \bullet HDD \bullet U}{\eta_h \bullet H_u} \tag{25}$$

Since the value U of thermal transmittance changes following the intervention, the mass of CO_2 produced by the consumption of natural gas in the absence $m_{CO_2-h\ (no-ins)}$ and following the intervention $m_{CO_2-h\ (ins)}$ are respectively:

$$m_{CO_2-h\ (no-ins)} = 2.75\ \frac{86400 \bullet HDD}{\eta_h \bullet H_u \bullet R_{tw}} \tag{26}$$

$$m_{CO_2-h\ (ins)} = 2.75\ \frac{86400 \bullet HDD}{\eta_h \bullet H_u \bullet \left(R_{tw} + x_{opt}/\lambda\right)} \tag{27}$$

For cooling, annual energy loss (J/m^2) from the wall was calculated as follows:

$$E_c = \frac{86400 \bullet CDD \bullet U}{COP} \tag{28}$$

with:

E_c: annual energy loss for cooling [J/m^2]
86400: conversion factor (1day = 86,400 s)
CDD: cooling degree-days [°C-days]
U: transmittance [W /(m^2·K)]
COP: performance of cooling system

Considering electricity-specific factors (kgCO_2/kWh) equal to 0.4109 [56] for the calculation of CO_2 emissions from electricity and the conversion factor from Joule to kilowatt-hours, the mass of CO_2 produced by room cooling m_{CO_2-c} expressed in kg/m^2 is given by the following equation:

$$m_{CO_2-c} = E_c \bullet 2.778 \bullet 10^{-7} \bullet 0.4109 \tag{29}$$

Explaining E_c the equation becomes:

$$m_{CO_2-c} = \frac{86400 \bullet CDD \bullet U}{COP} \bullet 2.778 \bullet 10^{-7} \bullet 0.4109 \tag{30}$$

Since the value U of thermal transmittance changes following the intervention, the mass of CO_2 produced by the cooling of areas in the absence and following the intervention are respectively:

$$m_{CO_2-c\,(no-ins)} = \frac{86400 \bullet CDD \bullet 2.778 \bullet 10^{-7} \bullet 0.4109}{COP \bullet R_{tw}} \tag{31}$$

$$m_{CO_2-c\,(ins)} = \frac{86400 \bullet CDD \bullet 2.778 \bullet 10^{-7} \bullet 0.4109}{COP \bullet \left(R_{tw} + x_{opt}/\lambda\right)} \tag{32}$$

On the other hand, CO_2 emissions related to the production of thermal insulation materials $m_{CO_2-m\,(ins)}$ are:

$$m_{CO_2-m\,(ins)} = x_{opt} \bullet \rho \bullet CO_{2\,(ins)} \tag{33}$$

with:

ρ: density of the insulating material [kg/m^3]
$CO_{2\,(ins)}$: embodied carbon of the insulation [kg CO_2/kg]

Therefore, the total CO_2 emissions associated with the heating and cooling of the building in the absence $m_{CO_2\,(no-ins)}$ and following the intervention $m_{CO_2\,(ins)}$ are:

$$m_{CO_2\,(no-ins)} = m_{CO_2-c\,(no-ins)} + m_{CO_2-h\,(no-ins)} \tag{34}$$

$$m_{CO_2\,(ins)} = m_{CO_2-c\,(ins)} + m_{CO_2-h\,(ins)} + m_{CO_2-m\,(ins)} \tag{35}$$

The reduction of CO_2 emissions following the intervention is:

$$S_{m_{CO_2}} = \left(m_{CO_2-c\,(no-ins)} + m_{CO_2-h\,(no-ins)}\right) - \left(m_{CO_2-c\,(ins)} + m_{CO_2-h\,(ins)} + m_{CO_2-m\,(ins)}\right) \tag{36}$$

By detailing the formula, $S_{m_{CO_2}}$ can be calculated as follows:

$$S_{m_{CO_2}} = \left(\frac{86400 \bullet CDD \bullet 2.778 \bullet 10^{-7} \bullet 0.4109}{COP} + \frac{86400 \bullet 2.75 \bullet HDD}{\eta_h \bullet H_u}\right) \bullet \left(\frac{1}{R_{tw}} - \frac{1}{R_{tw} + x_{opt}/\lambda}\right) - x_{opt} \bullet \rho \bullet CO_{2\,(ins)} \tag{37}$$

3. Case study and results

This part is organized in two sections. The first one presents the case study and the second one illustrates the results obtained by applying the methodology previously defined to the study.

3.1. The case study and the preliminary results

The optimal thickness model was applied to a case study to improve a building's energy efficiency. A factory structure was identified, where doors, windows and related products are produced and sold. The building is located in the industrial area of Castelnuovo Vomano, in the Province of Teramo, Italy (geographic coordinates: 42 ° 40′ 44,40′′ N and 13 ° 49′ 21,00′' E; altitude: 481 m on the sea level). It consists of two blocks with a rectangular plan connected to a third used for storage, loading and unloading. Each of the two blocks has a production area and an office. The part of the premises used for offices, occupied by users and employees, is the most critical because the external walls are inefficient energetically being made up of lightweight concrete blocks with surface plaster. In order to improve the thermal behaviour of these walls, it was necessary to identify the optimal insulating material to be applied using the methodology illustrated in the previous section. However, before doing this, it was necessary to perform non-destructive cognitive tests to classify the masonry and then use the heat flow meter method, as illustrated above. Lastly, by applying Eq. (5) regarding the method of progressive averages [55], the most probable transmittance value of the wall was defined. It was equal to 0.51 W/(m^2·K).

Knowing therefore the main physical characteristics of the wall and the physical location of the building, the data necessary for the LCCA study were obtained. Fig. 1 contains the parameters used in the LCCA. In particular, in Fig. 1 there are 4 sections showing the characteristics of the wall and the physical location of the building, with the order of the characteristics that illustrates respectively the heating, cooling and finally economic parameters. In the "External walls" section the thermal resistance of the wall obtained in the current state and the HDD and CDD values for the province of Teramo are shown [57]. In Italy a base temperature used to calcolate the HDD is 20 °C, while for the CDD is 26 ° [58,59].

The "Heating system characteristics" section contains the cost of natural gas (C_f), the lower heating values of natural gas (H_u) and the efficiency of the heating systems (η_h) [42]. The "Cooling system characteristics" section presents the cost of electricity and cooling system performance (COP) [60,61]. Finally, the Economic parameters section shows: interest rate (i) inflation rate (f), lifetime (N) used in the analysis [42].

In order to identify the best solution for the optimisation of energy efficiency in the case under analysis, 10 insulating materials were examined, with their characteristics defined in Fig. 2. In particular, the thermal conductivity values reported were extrapolated directly from the reference standard [UNI 10351:2015] or, in the absence of such reference, from the product data sheets [42]. Also the cost of the insulating materials was extrapolated from [42], that, moreover, resulted in line with cost used in [62,63]. Lastly, the density of the insulating materials reported and embodied carbon of the insulation are defined as in the references [64] and [65].

Once the input data of the model are defined, in the next paragraph the results obtained through the evaluation of 10 types of insulation applied to the wall are presented.

3.2. Optimal thickness and further calculation results

3.2.1. The optimal thickness

As mentioned in the section "Preliminary analysis", the economically optimal thickness for the 10 insulating materials is defined by minimising the total cost resulting from sum of heating, cooling and insulating material costs. Applying the methodological procedure described above, it is possible to estimate the optimal thickness (x_{opt}) and the results are illustrated in Fig. 3. In the figure, the quantity, expressed in metres, is estimated for each type of material.

After defining the optimal thickness for each insulating material, it is important to calculate the final thermal transmittance of the vertical wall of the building under study. Therefore, bearing in mind that the transmittance measured on site using formula (5) was equal to 0.509 W/m^{2}K, the transmittance of the vertical wall, insulated with each of the 10 insulating materials studied, according to the optimal thickness obtained, is that of Table 1.

3.2.2. The results from an economic point of view

Once the economically optimal thickness is known, it is possible to estimate the cost of heating ($C_{c\ (ins)}$), cooling ($C_{h\ (ins)}$) and of the insulating material ($C_{(ins)}$) for the 10 alternative options of insulating material (respectively Eqs. 7–9).

Fig. 4 shows these estimates together with the total cost of each intervention ($C_{t\ (ins)}$).

The results show that the total cost of improving energy efficiency varies from a minimum of 21.32 €/m^2 (if Rock wool - RW were applied) to a maximum of € 29.37 €/m^2 (in the event that Linen fibre – LF were used). These results become more significant when compared to the total cost to be incurred if no intervention were carried out, in this case the total cost ($C_{t\ (no-ins)}$) does not include the cost of the material but the two items of cooling ($C_{c\ (no-ins)}$) and heating ($C_{h\ (no-ins)}$). If no intervention were implemented, a cooling cost of 3.82 €/m^2 and a heating cost of 27.13 €/m^2 would be borne. The total cost ($C_{t\ (no-ins)}$) of 30.95 €/m^2 is always greater than the total cost associated with the 10 options analysed (Fig. 4 - No Intervention). Furthermore, the analysis of the individual items of cooling and heating costs shows that these are higher in the case of non-intervention than for all the hypotheses analysed.

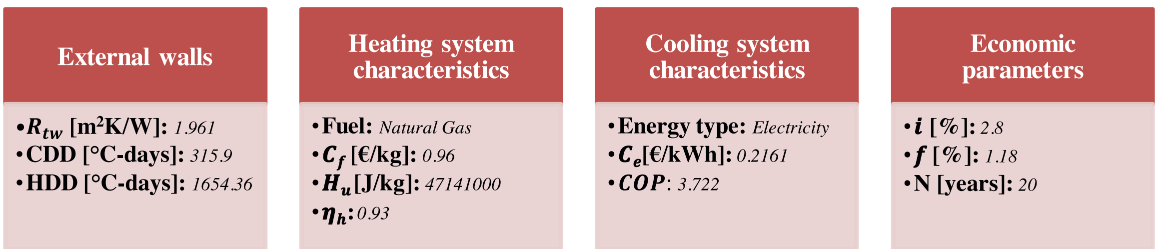
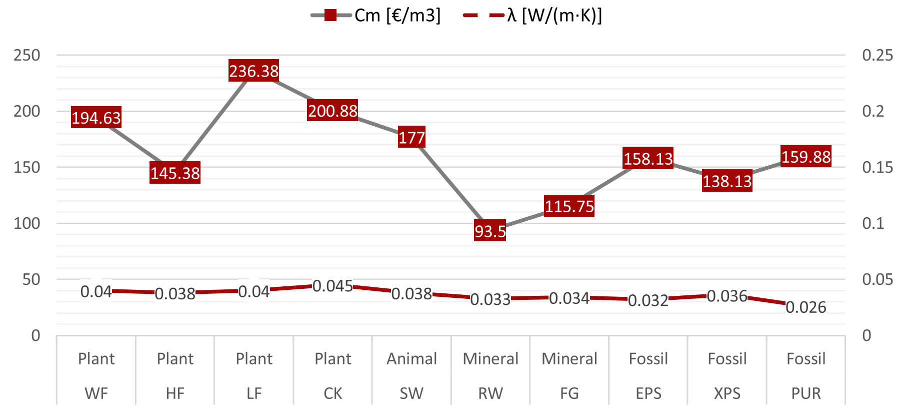


Fig. 1. Parameters used in the LCCA.



	WF	HF	LF	CK	SW	RW	FG	EPS	XPS	PUR
ρ [kg/m³]	240	38	119	200	23	150	24	32	29	29
$CO_{2\,(ins)}$ [kgCO2/kg]	0,98	1,62	1,7	0,19	1,20	1,05	1,35	2,55	3,45	3,76

Fig. 2. Thermal conductivity [W/(m K)], density [kg/m^3], embodied carbon of the insulation [kg CO_2/kg] and cost of insulating material [€/m^3] for 10 materials analysed.

If $C_{t\,(ins)}$, the total cost in the case of intervention, is greater than $C_{t\,(no-ins)}$, the total cost in the case of non-intervention, it is to be concluded that there is no advantage in carrying out the energy efficiency work. However, it always results that $C_{t\,(no-ins)} > C_{t\,(ins)}$ and therefore there is a cost saving ($S_{C_t} = C_{t\,(no-ins)} - C_{t\,(ins)}$) for each type of material used. As shown in Fig. 5, the value of this (S_{C_t}) varies from a minimum of € 1.58 €/m^2 to a maximum of € 9.63 €/m^2, the minimum saving is obtained by applying the Linen fiber (LF) while the maximum is obtained using the mineral material Rock wool (RW)

By focusing exclusively on the economic variable, therefore, there is a percentage saving between performing and not performing the intervention, as quantified in Fig. 6.

3.2.3. The results from the environmental point of view

In the previous paragraph, the economic advantage of the efficiency improvement intervention emerged with each of the 10 options analysed. However, the economic aspect is only one of the variables to be taken into account in determining the advantage and returns of an investment.

Since CO_2 is one of the major greenhouse gases [66], it is also necessary to define a model to support investment decisions with the aim of reducing not only the investment costs but also the CO_2 emissions.

Therefore, in this section, the viability of each investment alternative in environmental terms will be evaluated. An estimation of the reduction in CO_2 emissions associated with each alternative under analysis will therefore be made where the Eq. (37) previously defined, permits an estimation of this value. The basic hypothesis is represented by the emissions currently produced by the building in the absence of any intervention, the mass of CO_2 produced by heating ($m_{CO_2-h\,(no-ins)}$) and cooling ($m_{CO_2-c\,(no-ins)}$) is respectively 4.57 kg/m^2 and 0.43 kg/m^2 for a total of 5 kg/m^2 (Table 2).

The mass of CO_2 generated by heating ($m_{CO_2-h\,(ins)}$) and cooling ($m_{CO_2-c\,(ins)}$) the building and the CO_2 emissions related to the production of thermal insulation materials ($m_{CO_2-m\,(ins)}$) were also estimated in correlation to each of the 10 insulating options under

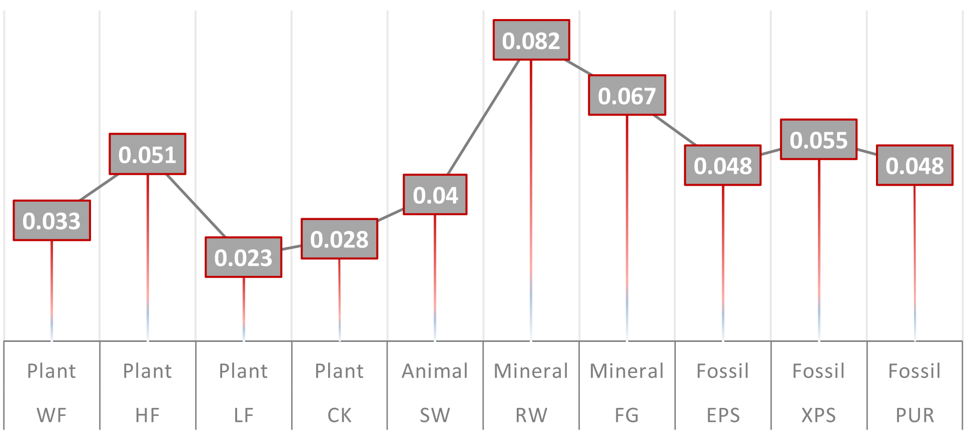


Fig. 3. Estimation results of Optimum Insulation thickness [m] (x_{opt}) for 10 materials analysed.

Table 1
Calculation of the final thermal transmittance of the wall as a function of the optimal thickness (Fig. 3).

Materials	Plant WF	Plant HF	Plant LF	Plant CK	Animal SW	Mineral RW	Mineral FG	Fossil EPS	Fossil XPS	Fossil PUR
λ [W/(m K)]	0.04	0.038	0.04	0.045	0.038	0.033	0.034	0.032	0.036	0.026
Xopt [m]	0.033	0.051	0.023	0.028	0.04	0.082	0.067	0.048	0.055	0.048
U [W/m2K]	0.36	0.30	0.39	0.39	0.33	0.22	0.25	0.29	0.29	0.26

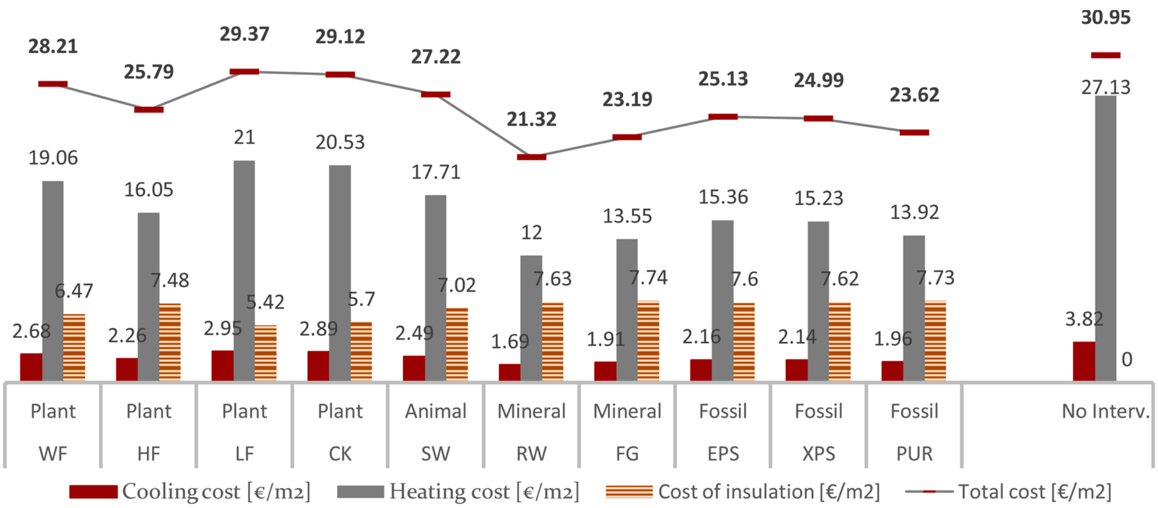


Fig. 4. Estimation results of Cooling cost ($C_{c\,(ins)}$), Heating cost ($C_{h\,(ins)}$), Cost of insulating material (C_{ins}) and Total cost $C_{t\,(ins)}$) for all materials under analysis and under the hypothesis of no intervention ($C_{c\,(no-ins)}$, $C_{h\,(no-ins)}$, $C_{t\,(no-ins)}$).

analysis (Fig. 7). The figure also shows the value of CO_2 emitted in the heating and cooling phases in the absence of any intervention. It is evident that the total CO_2 emission ($m_{CO_2\,(no-ins)}$) is always higher than that linked to the sum of mass of CO_2 generated by heating ($m_{CO_2-h\,(ins)}$) and cooling ($m_{CO_2-c\,(ins)}$). Nevertheless, if it is also considered the CO_2 emissions related to the production of thermal insulation materials, this may not be valid. As shown in Fig. 8, $S_{m_{CO_2}}$ takes negative values for most insulating materials. Only with

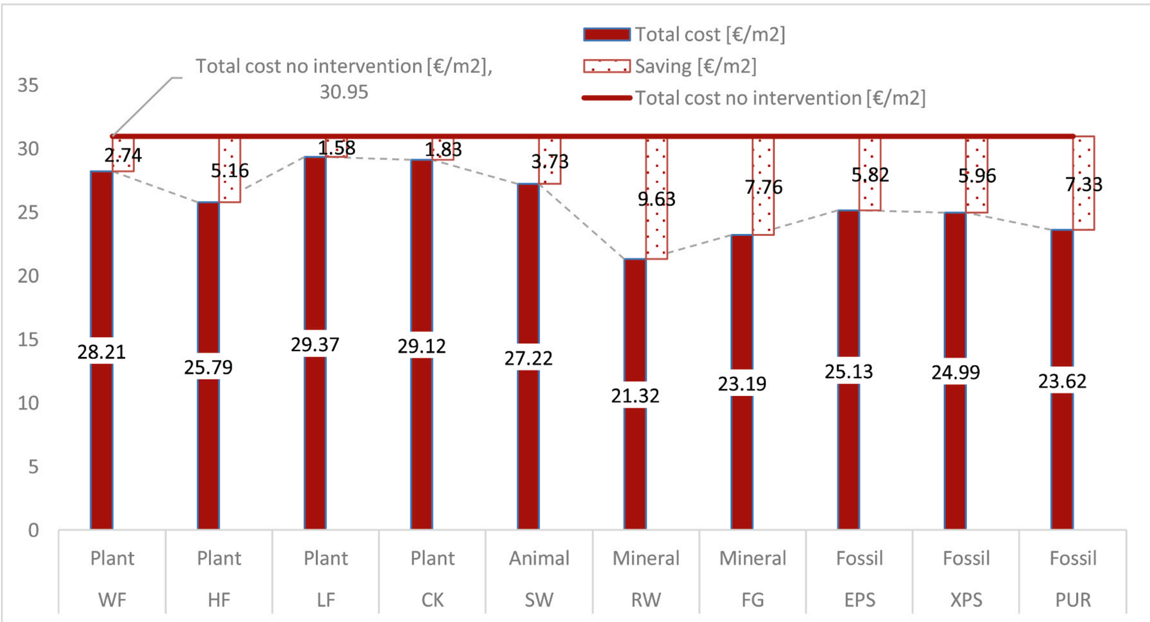


Fig. 5. Comparison between Total Cost ($C_{t\,(ins)}$) for each type of insulating material and Total Cost ($C_{t\,(no-ins)}$) in the case of no intervention.

materials CK, SW and FG it is possible to obtain $m_{CO_2\,(no-ins)} > m_{CO_2\,(ins)}$. In particular, $S_{m_{CO_2}}$ varies from a minimum of -10.07 kg/m^2 to a maximum of 0.64 kg/m^2; the minimum value is obtained by applying Rock wool (RW) while the maximum value is obtained using Sheep wool (SW).

This means that only for some materials there is a reduction in CO_2 emissions thanks to the application of thermal insulation in the building used for the case study.

4. Discussion

This analysis has led to the determination of the optimal thickness of insulating material to be applied to a wall in order to improve its energy performance. 10 different alternatives were analysed and the optimal thickness of each insulator was found to vary between 0.023 m (LF) and 0.082 m (RW), as shown in Fig. 2. For example, by applying layer of insulating material in linen fiber of 0.023 m investment costs can be minimized as well as running costs for heating and cooling. On this basis, this means that, the material linen fiber involves a thickness smaller than other material that makes it possible to minimise the total cost.

Improvement work to the exterior walls of a building can be done using various types of material and results obtained demonstrate that the optimal solution is not necessarily that from the material with a lower unit cost. For example, Expanded polyurethane (PUR) is the sixth most expensive material in terms of unit cost (€/m^3 159.88 within a range from 93.5 to 236.38 – Fig. 1), but it ranks third among the solutions for economic savings. Therefore, material with the lowest unit cost does not necessarily mean that it is always the best solution in terms of reduction of the total cost of the intervention.

The lowest total cost is for RW with a value of 21.32 €/m^2, and the optimal thickness is 0.082 m, which represents a higher thickness than other materials. However, the resulting cost savings in terms of heating and cooling (by 12 €/m^2 and 1.69 €/m^2) compensate the higher investment cost more than any other solution.

From a legislative point of view, it is interesting to compare [52] the normative values relating to thermal transmittance in Italy, with those in Table 1.

The D.M. of 26.05.2015 defines the maximum transmittance values of vertical opaque structures (Annex B, Table 1) according to the six climatic zones into which Italy is divided (Presidential Decree 412 of 26.08.1993). The building under study is located in the climatic zone E and so the value to be respected was equal to 0.30 W/m^{2}K from 2015 to 31 December 2020 while it is equal to 0.28 W/m^{2}K from 1 January 2021 to today.

The transmittance values referred to in Table 1 are between 0.22 W/m^{2}K and 0.39 W/m^{2}K. As it can be seen in Fig. 9, six of the ten materials studied allowed compliance with the legal parameters in force until December 2020. Among these, there are HF, plant origin, RW and FG, mineral origin and lastly EPS, XPS and PUR, fossil origin. These materials are precisely those for which the optimum thickness value is highest (Fig. 3).

Starting from 2021, the Italian legal values have become more tightening. Therefore, today, only three insulators make it possible to comply with the aforementioned limits. In particular, these are RW and FG, the two materials of mineral origin for which the greatest optimal thickness is achieved (Fig. 3), and PUR. This last result may be attributed to the favorable value of λ of this fossil origin material (Fig. 2).

However, the technical, legislative and economic variables are only two consideration to decide whether to implement any energy improvement intervention. Environmental considerations also have to be taken into account. The analyses also quantified the reduction of CO_2 emissions compared to the pre-exisiting situation. With each of the 10 material options the improvement investment is justified as CO_2 emissions are reduced by three of them, ranging from a maximum of 0.64 kg/m^2 (SW) to a minimum of -10.07 kg/m^2 (RW). Mineral material FG achieves the greatest savings both in economic and environmental terms due to their high insulating characteristics and low value C_m. Also plant-based insulation material CK presents similar features. For instance, even if CK has a high cost C_m which is around 200 €/m^3, non negligible savings in both economic and environmental terms are possible, to a value of S_{C_t} and $S_{m_{CO_2}}$ respectively, equal to 1.83 €/m^2 and 0.14 kg/m^2. This happens because the capital invested for thermal insulation leads to

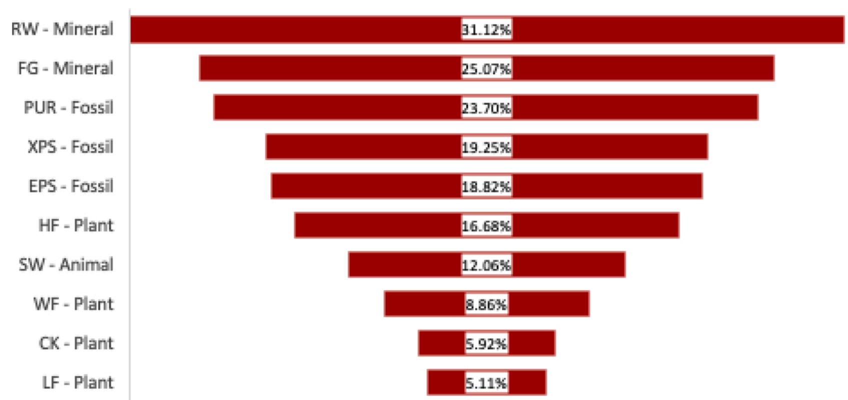


Fig. 6. Percentual variation between $C_{t\,(no-ins)}$ and $C_{t\,(ins)}$ for the 10 materials.

Table 2
Estimation results CO_2 of cooling ($m_{CO_2-c\ (no-ins)}$), CO_2 of heating ($m_{CO_2-h\ (no-ins)}$) and Total CO_2 ($m_{CO_2\ (no-ins)}$).

CO_2 mass from cooling [kg / m^2] $m_{CO_2-c\ (no-ins)}$	CO_2 mass from heating [kg / m^2] $m_{CO_2-h\ (no-ins)}$	Total mass of CO_2 [kg / m^2] $m_{CO_2\ (no-ins)}$
0.43	4.57	5.00

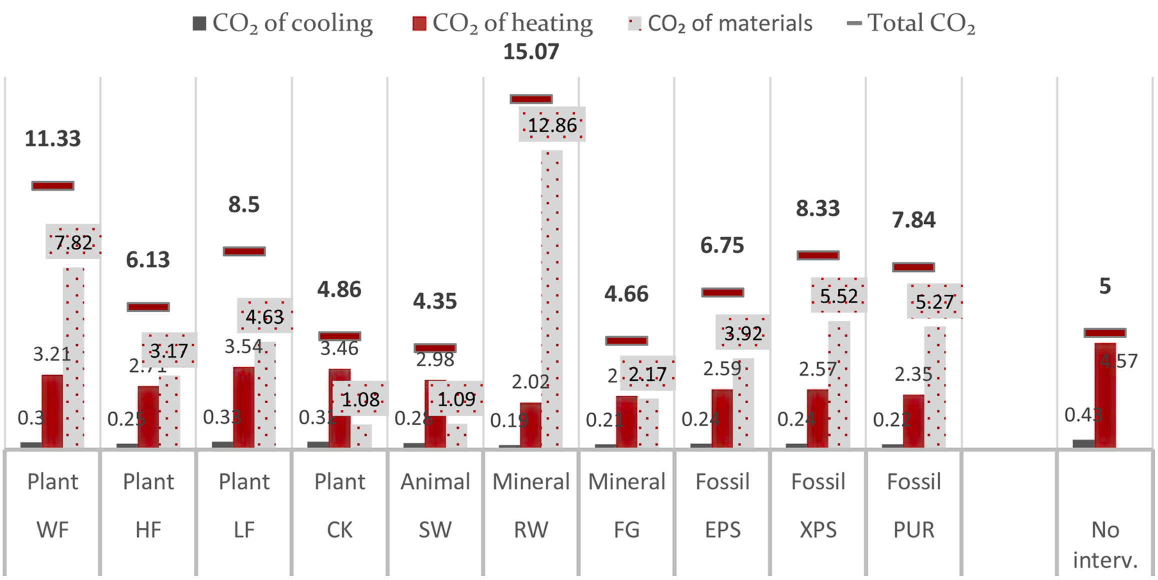


Fig. 7. Estimation of $m_{CO_2-c\ (ins)}$, $m_{CO_2-h\ (ins)}$, $m_{CO_2-m\ (ins)}$, $m_{CO_2\ (ins)}$ for the 10 materials and $m_{CO_2-c\ (no-ins)}$, $m_{CO_2-h\ (no-ins)}$ and $m_{CO_2\ (no-ins)}$.

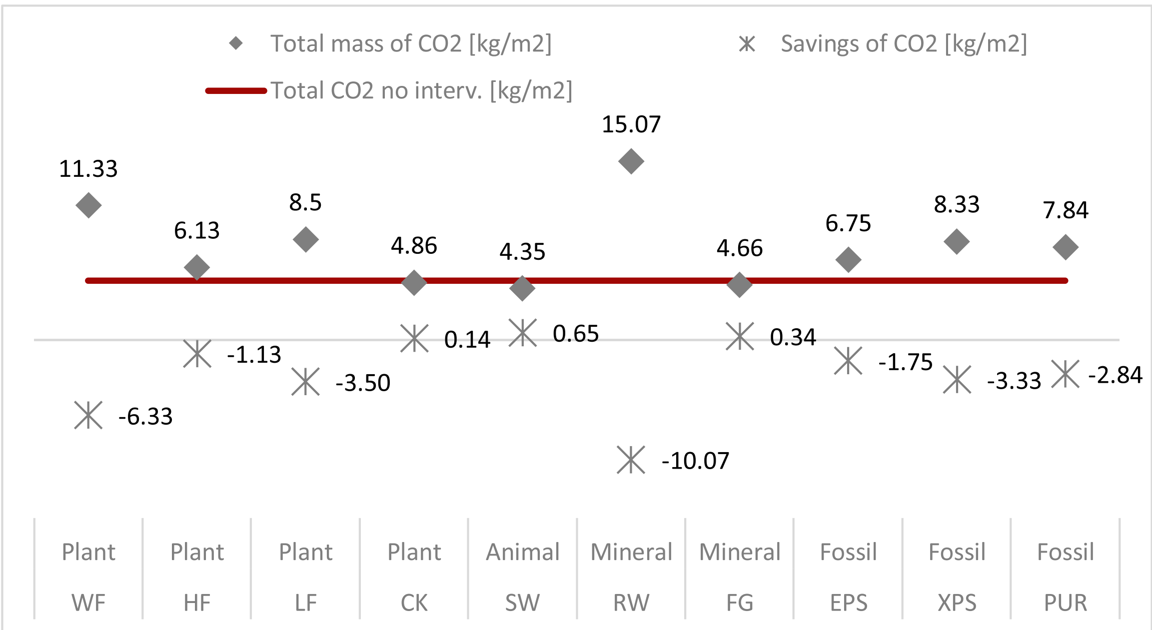


Fig. 8. Comparison between $m_{CO_2\ (ins)}$ (Total CO_2 emissions associated with the heating and cooling of the building following the intervention and the CO_2 emissions related to the production of thermal insulation materials in kg/m^2) and $m_{CO_2\ (no-ins)}$ (Total CO_2 emissions associated with heating and cooling of the building in the absence of intervention in kg/m^2).

compensation in the form of energy savings for heating and cooling. However, materials of plant and animal origin lead to less savings than the others. In fact, these products guarantee good thermal insulation but with values of λ and C_m slightly higher than the others, due to their intrinsic properties and their supply chain.

To identify the optimal solution both economically and environmentally, and to make an objective comparison between the alternatives, a RIF metacriterion should be considered, defined as follows [38]:

$$Rnk_{ec-en} = w_1 S'_{C_t} + w_2 S'_{mco2} \tag{38}$$

Where

w_i is the weight given to each criterion with i = 1,2 ($w_1, w_2 > 0$, $w_1 + w_2 = 1$)

In addition,

$S'_{C_t} = S_{C_t}/S^*_{C_t}$, $S^*_{C_t}$ is the maximum value of S_{C_t}

$S'_{m_{CO_2}} = S_{m_{CO_2}}/S^*_{m_{CO_2}}$, $S^*_{m_{CO_2}}$ is the maximum value of $S_{m_{CO_2}}$.

The index defined in this way permits an overall judgment that takes into account two values expressed with different measurement units. It has been assumed that the two aspects (economic and environmental) have the same weight, therefore $w_1 = w_2 = 0{,}5$. The results are shown in Fig. 10.

Insulators of fossil origin have intermediate values of S_{C_t} and $S_{m_{CO_2}}$ compared to the other categories.

Among the insulators with lower environmental impact, the best performance is obtained with SW. In general, insulation provided by any of the alternatives taken into account for the building analysed will guarantee improvements from an economic point of view leading to lower energy costs; on the other hand, from the environmental point of view, only three materials (CK, SW, FG) will contribute to the reduction in polluting emissions.

The results confirm that if only the environmental aspects were considered, the wall efficiency interventions (using thermal insulation) would not find justification: in fact, the CO2 savings are not always higher than in the case of non-intervention. However, it is necessary to specify that in most cases the existing buildings, especially those of older years, do not comply with current regulations. Therefore, the aforementioned interventions, although not always mandatory, would still be necessary in a perspective of energy transition and improvement of comfort.

Thus, it is evident that incentive policies must be implemented, in order to stimulate the redevelopment of existing buildings.

5. Conclusion

An analysis of the state of the art has demonstrated how current European policy underpins the importance of assessing the impact of different energy efficiency strategies during the entire life cycle of buildings. The recent Directive 2018/844/EU underlines the importance of how strategies to re-structure buildings need to be assessed in terms of both emissions and costs. In support of this, the LCCA analysis is an economic evaluation method which determines the overall cost of a product whilst taking into account its life cycle. This approach, together with an assessment of CO_2 emissions, facilitates a comparison of different alternatives from both an economic and environmental point of view. Therefore, it has to be considered a valid decisional tool for different stakeholders.

This article presents the results of a research based on the LCCA method in order to determine the optimal thickness of insulating materials to be applied to the walls of existing buildings to improve energy performance. A total of 10 different insulators were analysed and the performance results were compared. This led to the estimation of the cost savings deriving from the installation of the insulating material and was expressed in terms of reduction of heating and cooling costs. The assessment of CO_2 emissions associated with the heating and cooling of the building and the CO_2 emissions related to the production of thermal insulation materials in the individual scenarios were also made.

Economically, the research has demonstrated that for all materials analysed there are always savings and, therefore, an intervention is always advisable. Likewise, from an environmental point of view there is a reduction in the production of emissions for three tested insulating materials. Clearly, specific results were obtained for each of the different materials, which can be evaluated according to the needs of stakeholders.

The study has important implications mainly related to energy efficiency. It is clear that the research carried out could be further investigated by considering additional evaluation elements such as, for example, the cost of the insulation of the walls, a significant variable depending on the type of building, or an analysis of any tax concessions available. Furthermore, it is the future objective of the authors to implement the environmental analysis through LCA, since the one developed in this article is a preliminary type.

This research has identified a "result oriented" methodology permitting the quantification of benefits associated to correctly and appropriately insulating buildings. These benefits are both of an economic and environmental nature and as such contribute towards sustainability being not only a legal obligation but an opportunity for all stakeholders. The research helps strengthen the leadership of the EU in the sustainable use of natural resources within an efficient bioeconomy, essential in achieving Sustainable Development Goals.

Authors statement

- This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.
- The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

Materials	Plant WF	Plant HF	Plant LF	Plant CK	Animal SW	Mineral RW	Mineral FG	Fossil EPS	Fossil XPS	Fossil PUR
U [W/m2K]	0,36	0,30	0,39	0,39	0,33	0,22	0,25	0,29	0,29	0,26
Comparizon E Zone (2015-2020)	Not Verified	Verified	Not Verified	Not Verified	Not Verified	Verified	Verified	Verified	Verified	Verified
Comparizon E Zone (> 2021)	Not Verified	Not Verified	Not Verified	Not Verified	Not Verified	Verified	Verified	Not Verified	Not Verified	Verified

Fig. 9. Comparison between the transmittance calculated by the optimal thickness and the limit value.

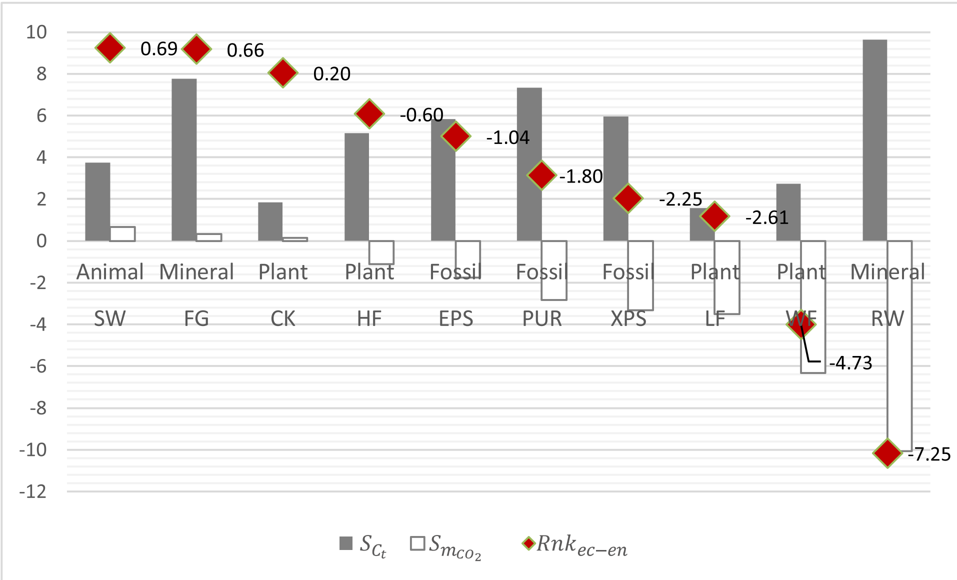


Fig. 10. S_{C_t}, $S_{m_{CO_2}}$ and Rnk_{ec-en}.

Authors contribution

F.C. and M.R. conceived the research and designed the experiments and the methodology; they defined the structure and organization of the article; they also wrote and revised the paper with the support of V.A. who carried out the economic analyses. M.R. also defined the editing of the article and she is the corresponding author.

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Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

Declaration of Competing Interest

The authors declare no conflict of interest.

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