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Analysis of different typologies of natural insulation materials with economic and performances evaluation of the same in building

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Abstract:

Considering the significant impact that the residential sector has on energy consumption, it is particularly important to implement policies aimed at improving energy efficiency in buildings for saving primary energy, and also to spread the concept of sustainable development through the use of appropriate technology and proper project criteria both for new constructions and for the rehabilitation of existing ones. It is in this context and in an attempt to reduce as much as possible the consumption of resources that fits the possibility of utilizing "natural" materials for the insulation of buildings.

In this work they have been analyzed the natural insulation materials present on the Italian building market, where for "natural" it is meant the ones that are derived from renewable materials, which emit no pollutants and that are recyclable or biodegradable. Then it has been created a database which highlights the physical and thermohygrometrical characteristics (density, conductivity, specific heat, vapor permeability, etc.), as well as the possible applications (ceiling, wall, roof).

Then it has been carried out a performing and economic comparison related to the replacement of the traditional insulation of a residential building located in Perugia (Central Italy) with the majority of the insulating materials identified in relation to its type of use. The synthetic insulating materials have been replaced in order to reach, for the analysed building, the same thermal performances obtained with the application of traditional insulators. From the analysis of dynamic thermal parameters has been deduced that the building envelope insulated with natural products has better thermal summer performances compared to the same insulated with traditional materials such as XPS, with the same thermal winter performances. This improvement is mainly due to the high value of the specific heat characteristic of the natural insulators.

Finally, it has been carried out an economic comparison between the two types of insulation from which it has been possible to deduce that the utilize of natural insulation products have meant an increase in the costs which is widely variable depending on the type of natural insulator used.

Keywords:

sustainability, building, insulation materials, energetic performances

1. Introduction

The slowdown which hit the world economy and trade have played an important role in the decrease of overall energy consumption, especially in countries, such as Italy, where the manufacturing sector still plays an important role.

In 2009, energy consumption decreased by 5,6% compared to 2008, even though domestic consumption grew by 3,6% [1].

In this context, the implementation of policies aimed at improving energy efficiency in buildings is particularly important, with the subsequent saving of primary energy and the dissemination of the concept of sustainable development, through the use of appropriate technologies and project criteria both for new constructions and for renovation of existing buildings.

The insulation of buildings through the use of "natural" materials falls into this category, in an attempt to reduce as much as possible the consumption of resources.

A new approach has made its way in the construction industry, where the main goal is to realize buildings which provide maximum living comforts and maximum energy efficiency in a strict respect of the environment, through the use of building materials made by predominantly natural and renewable raw materials, which are characterized by a reduced environmental impact in terms of consumption of natural resources and energy.

The building envelope regulates the contacts and exchanges of matter and energy with the exterior. A very important aspect in the construction of a building envelope aimed at minimizing heat loss is the insulation of the same, obtained with a high degree of thermal insulation. The thickness increase of the insulating material layer in walls and roofs is therefore an essential solution, as is the importance of paying maximum attention to discontinuity points in the insulating layer, i.e. thermal bridges, where in addition to the risk of substantial losses of energy there is also the risk of condensation and mould [2].

In the light of these considerations, both the importance of knowing the performance characteristics of the "natural" materials and the importance of assessing their application within the building envelope become evident; the reason being that only an appropriate project of the structural elements and a proper placement and installation of the insulating material, according to its characteristics, can provide a long and efficient duration of the material inside the building.

This choice must take into account not only the quantitative aspects, but also the quality of the building and the environment. The assessment of the materials' characteristics becomes thus fundamental to evaluation of their impact on the environment

To this end, a number of product certifications exist, such as the EPD (Environmental Product Declaration) and the Ecolabel that span every product category, but also specific certifications for building products., For example, the Natureplus label, promoted by a European group consisting of the major institutions working in the field of quality control of products for green building, and the ANAB (National Association for Bioecological Architecture) - the only institution in Italy that has developed standards for assessing the sustainability of the building industry products - bioecological label, are among those [3].

In addition to the environmental impact, monetary cost is essential in the choice of a material, while taking into account that the additional spending due to the realization of a good thermal insulation is offset in a short time by cost savings of climate control.

In this article, a database of natural insulation materials available on the Italian market is presented, divided according to their main applications.

Furthermore, through a specific calculation software (MC4), which complies to the UNI TS 11300:2008 standards parts 1 and 2, as according to D.P.R. 2 April 2009 n.59, a building used for residential purposes located in the city of Perugia has been analyzed from an energy consumption point of view. This was done in order to carry out an efficiency and economic comparison analysis between the use of traditional insulating materials and natural insulating materials. The thicknesses of the natural insulations were chosen so that they could achieve the same energy performance of the building's envelope obtainable with traditional materials.

2. Development of a natural insulating materials database

Insulation materials can be classified according to various aspects, for example in relation to their origin, (synthetic, mineral, plant or animal), and according to their structure, (fibrous or cellular). In particular, one might have[4-5]:

- *totally synthetic materials,* mainly polyester fiber, expanded polystyrene, extruded polystyrene foam, polyurethane foam and polyethylene foam, which are thermosetting or thermoplastic polymers obtained by a long and complex processing of petroleum oil, raw material base;
- *totally mineral materials,* mainly natural granular materials (pumice) and expanded (clay, perlite, vermiculite and glass granular), cellular limestone-cement insulation and cellular glass, derived

from the processing of raw materials such as clay minerals , limestone, volcanic rocks, quartz sands, recycled glass, without the addition of binders and resins;

- *totally plant-based materials*, like cork, reed, wood fiber, coir, jute, maize, and some products in kenaf and flax, in which the plant material undergoes a process that does not require the addition of binders and synthetic support .

There are also a wide range of mixed materials that arise from the combination of different raw materials, in order to improve their performance:

- *mixed-synthetic minerals*, in particular mineral wools (glass wool and rockwool), in which the mineral raw materials (quartz sand, recycled glass, rocks of volcanic origin) is added a percentage of synthetic resins functioning as binder;
- *mixed plant-synthetics and animal-synthetics*, in particular soft fibre panels (cellulose fibers, hemp, sheep wool, and in some cases kenaf and flax) to which a synthetic fiber is added (usually the extent of 10-15 %, in some cases even 30-50%) that links the material and gives greater stability;
- *mixed vegetable-mineral*, in particular mineralized wood wool, in which a percentage of mineral binder (Portland cement or magnesite) is added to the plant raw material, to give greater strength to the material.

This division, however, does not provide an exhaustive description of the wide range of materials on the market today. A further subdivision is based on the production process:

- *natural materials*: used as they are offered by nature, without substantial transformations, although they are also subject, before the installation, to a certain degree of processing in order to provide them with the appropriate requirements for a particular use (cutting, washing, etc..);
- *man-made (artificial) materials*: they are obtained by the specific production process which tends to give a mixture of properly dosed raw materials, certain characteristics.

Therefore, in most cases it is not correct to speak of natural materials, as all insulation materials must undergo a process of more or less complex transformation; and depending on the consistency, it is possible to identify panels, mattresses, mats, strands, flakes and granules .

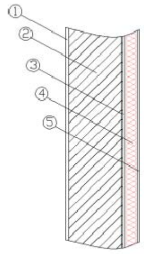
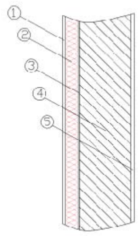
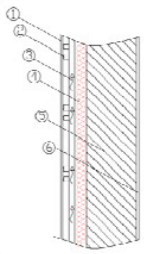
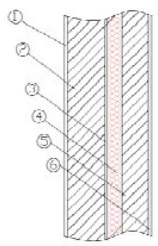
In this paper, the insulation materials have been analyzed taking into account their main features and applications with an emphasis on vertical walls, roof, floors between storeys and floors on the ground, in order to create a repertoire of insulation products available on the Italian market.

In particular, the following rules for the installation/laying of insulating materials have been taken into consideration [6-7]:

Laying of insulating materials on vertical walls (Table 1):

1. *Outer Coat:* the insulation is placed on the outer walls of the building, so as to remove the thermal bridges and reduce the induced effects in the structures and wall surfaces of rapid or significant changes in outside temperature.
2. *Interior Coat*: panels are placed on the interior surface of the wall. They consist of a layer of insulating material, a vapour barrier and a plaster slab. Unlike the outer coat, this technique does not correct the thermal bridges and it does not allow to maintain the perimeter walls at a higher temperature.
3. *Ventilated Wall*: the insulation layer is installed in direct contact with the wall and is separated from the lining by a special structure, so that, the ventilation layer reduces the risk of condensation on the interior surfaces of the building.
4. *Gap Insulation*: A gap is placed between two vertical elements, filled with air or insulating materials. Two types of insulating materials may be used:
   - paneled insulating materials, which can be fibrous panels or foam materials.
   - injected insulating materials, usually into granules, which are injected into the cavity to fill it up.

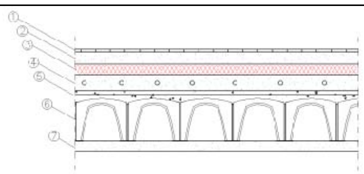
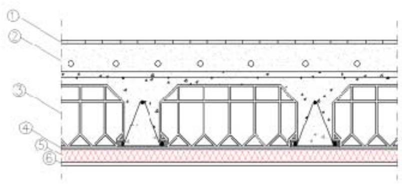
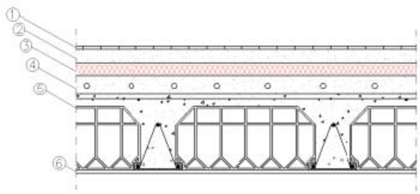
Table 1: Insulation materials on vertical wall

N.	Wall Stratigrafy	Materials
1)		1 : 1.5-cm thick Plaster.; 2 : Masonry; 3 : 1-cm thick Mortar; 4 : Insulation; 5 : Smoothing layer in which a 0.5-cm thick fiberglass net is embedded, plus an additional 0.5-cm thick smoothing compound.
2)		1 : 1,3-cm thick Plasterboard; 2 : Insulation; 3 : Metal framework; 4 : Masonry; 5 : 1.5-cm thick Plaster.
3)		1 : External coat; 2 : Fixing system; 3 : Air vent; 4 : Insulation; 5 : Masonry; 6 : 1.5-cm thick Plaster.
4)		1 : 1.5-cm thick Plaster; 2 : Brick; 3 : 1.5-cm thick Rough coat; 4 : Insulation; 5 : 8–12 cm thick Air Brick; 6 : 1.5-cm thick Plaster.

Laying of insulating materials in floors (Table 2):

1. *Floors on the ground (also known as slab on-grade) and vented crawl spaces*: the insulation of floors on the ground or on crawl space involves the application of an insulating layer on the extrados of the floor. Having to bear the weight of the screed above, the insulation must have a mechanical strength suitable for this purpose.
2. *Insulation of floor intrados (or lower surface) with coating system*: referring to the insulation of the floor which looks out onto porticoes or open spaces, it provides the placement of the insulation at the underside of the slab floor.
3. *Insulation of floor extrados (or upper surface):* it refers to the insulation of floor covering open spaces or basements, and it provides the placement of the insulation at the top face of the slab floor.

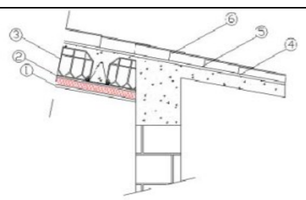
Table 2: Insulation materials on floor

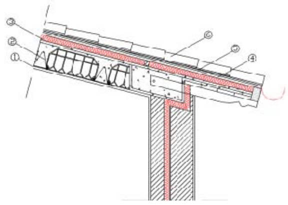
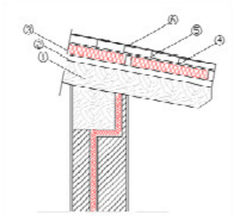
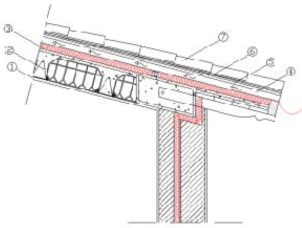
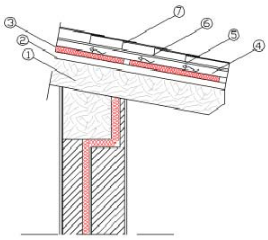
N.	Floor Stratigrafy	Materials
1)		1 : 1-cm thick Floor; 2 : 4-6 cm thick Screed; 3 : Insulation; 4: Lightened screed; 5 : about 5-cm thick Slab; 6 : Vented crawl space; 7 : 10-cm thick Lean concrete.
2)		1 : 1-cm thick Floor; 2 : 4-cm thick Screed; 3 : 20+4 cm thick Floor; 4 : Mortar; 5: Insulation; 6 : 1.5-cm thick Plaster.
3)		1 : 1-cm thick Floor; 2 : 4-cm thick Screed; 3 : Insulation 4 : 6-cm thick Lightened screed; 5 : 20+4 cm thick Floor; 6 : 1.5-cm thick Plaster.

Application of insulating materials in roofs (Table 3):

1. *Insulation at the roof intrados:* it is used with pitched roofs, that have a live-in attic, and the insulation is placed directly on the pitch structure (which can be in strips of wood, iron or precast joists).
2. *Insulation under the outer skin,or "warm roof"*: the insulation is placed just below tiles, pantiles or slabs, and is supported by the sloped pitch. It is a good rule that the insulations are laid with a sheet on the underside, which acts as a vapor barrier. Fig 2.a) shows the stratigraphy of a "warm roof" in masonry, while in (Table 3 Figure 2.b) the stratigraphy of a timber "warm roof" is shown.
3. *Insulation under the outer skin, "vented roof"*: in order to build a vented roof, a "blade" of air must be created between the covering mantle of tiles and the underneath insulating panels, so as to obtain an upward air flux. Fig 3.a) describes the stratigraphy of a "vented roof" in masonry, while in Fig 3.b) the stratigraphy of a timber "vented roof" is shown.

Table 3: Insulation materials on roof

N.	Roof Stratigrafy	Materials
1)		1 : 1.5-cm thick Plaster; 2 : Insulation; 3 : 20+4 cm thick Floor; 4 : 1,2 cm Planking; 5 : Waterproof sheath; 6 : Outer skin.

2.a)		1 : 1.5-cm thick Plaster; 2 : 20+4 cm thick Floor; 3 : Insulation; 4 : 1,2 cm thick Planking; 5 : Waterproof sheath; 6 : Outer skin.
2.b)		1 : 10 x 20 cm timber tables; 2 : 3 cm thick Planking; 3 : Insulation; 4 : 1,2 cm thick Plywood planking; 5 : Waterproof sheath ; 6 : Outer skin.
3.a)		1 : 1.5-cm thick Plaster; 2 : 20+4 cm thick Floor; 3 : Insulation; 4 : 5 cm thick Air vent; 5 : 1,2 cm Planking; 6 : Waterproof sheath; 7 : Outer skin.
3.b)		1 : 10 x 20 cm timber tables; 2 : 3 cm thick Planking; 3 : Insulation; 4: 5 cm thick Air vent; 5 : 1,2 cm Planking 6 : Waterproof sheath 7 : Outer skin.

On the basis of the main applications of the natural insulating materials described above, a Microsoft Office Excel database of insulating products available on the Italian market was created, based on the manufacturing companies [8-9].

In particular, for each structure destination (floor, wall and roof) and for each typology of installation, a range of products divided on the basis of their origin (plant, animal and mineral) was been chosen. In addition, for each insulating material, the data template shown in Table 4 was included into the database.

Table 4: Data classification in the Database

Data	Units of Measurement
Product name	
Manufacturing or distributing company	
Price (2010 price list)	€/m^2
Using typologies	
Description	
Thickness	mm
Density (ρ)	kg/m^3

Thermal conductivity (λ)	W/m·K
Specific heat (Cp)	kJ/kg·K
Water vapor diffusion resistance (μ)	

The present work does not consider any products made of natural materials coupled with panels of petrochemical origin (expanded polystyrene, extruded polystyrene, polyurethane, etc.).

Commercial products included in the database are 100% natural or they contain a small percentage of synthetic binder in polyester fiber. The polyester fiber is an innovative material that derives largely from recycled PET bottles. In this way, the eco-sustainability of the selected insulating materials was been guaranteed.

The following is an excerpt of the database related to vertical walls, on the ground and perimetral, This analysis indicates the possible applications of natural insulating materials both in new constructions and in renovation and recovery of existing buildings. The proposed construction details summarize the instructions of use suggested by the manufacturers based on green building design evaluations.

Criteria for choosing between different insulating materials are clearly identifiable on the basis of the prevailing and/or specific application requirements that materials must meet.

In order to make the most appropriate choice, it is necessary to know the materials' performance characteristics and assess materials in relation to their application type within the building envelope. Finally, an economic assessment is also required to properly choose the right insulating material. with gap insulation.

3. Economic evaluation of natural insulating materials utilization in a building in Central Italy

A residential building located in the municipality of Perugia was assessed in energetic terms by using the software MC4. The objective was to carry out an economic and efficiency assessment of the selected building realized with conventional insulation materials in comparison with the same building constructed by using natural insulation.

3.1. Case Study

The single-family house has three floors consisting of an attic that is not heated nor air-conditioned, a garage in the basement, and a heated apartment. The building envelope dimensional characteristics are presented in Table 5.

Table 5 Building envelope data

Data	
Vertical closures area	233 m^2
Transparent surfaces area	25,57 m^2
Effective surface area (unheated)	122 m^2
Effective surface area (heated)	94,67 m^2
Gross surface area	388,95 m^2
Heated gross volume	378,38 m^3
S/V	1,0147 m^{-1}

Inside the building two different heating zones were outlined, a heated area (Figure 1) and an unheated area (Figure 2).

Extruded polystyrene foam XPS, was selected to insulate the building envelope, a widely-used material of petrochemical origin. Different currently available insulating panels XPS (Table 6) were chosen, depending on their application typology.

Table 6: Selected Building Insulations

Insulation typology	ρ (kg/m^3)	λ (W/m K)	C_p (kJ/kgK)	μ	Laying
XPS_styrodur 250 CNL	28	0,034	1,45	100	Vertical walls gap
XPS_expandit	33	0,0304	1,6	100	Under the roof outer skin
XPS_styrodur 2800 CS	30	0,032	1,45	100	Floor estrados

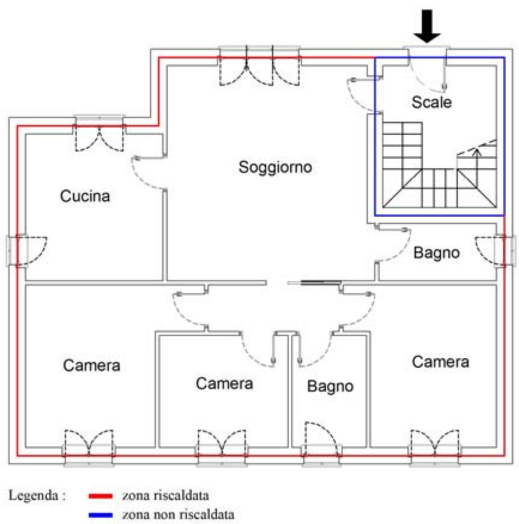


Figure 1: Ground floor thermal zone

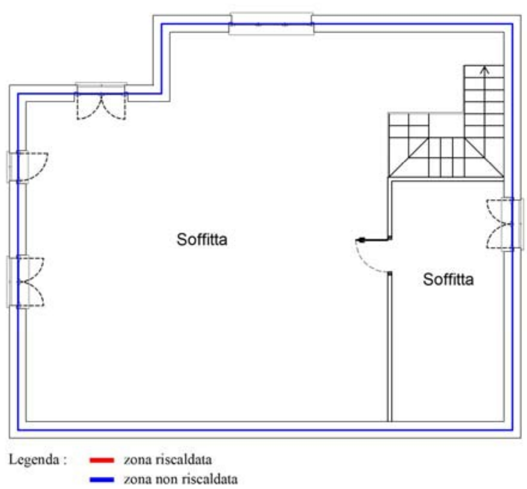


Figure 2: Attic thermal zone

Stratigraphies of the opaque components used in the case study are reported as follows.

1. *Perimeter separation wall between heated zone and unheated staircase*; starting from the outside, the wall is composed of the following layers: plaster, Poroton thermal brick, rough coat of plaster, cavity filled with insulation panels 5 cm. thick, hollow bricks, plaster. Table 7 shows the stratigraphy, while in Table 8 the thermal characteristics are presented.

Table 7: Perimeter wall stratigraphy

Layer Description	S (cm)	λ (W/m°C)	C (W/m²°C)	ρ (kg/m^3)
Lime and gypsum plaster	1,50	0,700		1.400
Air brick F120	12,00		2,28	775
XPS styrodur_250 CNL	5,00	0,034		28
Cement mortar	1,00	1,400		2.000
POROTON	20,00		1,04	845
Lime mortar or cement lime	1,50	0,900		1.800

Table 8: Thermal and inertial characteristic

Total thickness (cm)	41,00	Superficial mass (kg/m²)	263,40
Unit conductance		**Unit resistance**	
Internal surface [W/(m²·K)]	7,69	Internal surface [(m²·K)/W]:	0,13
External surface [W/(m²·K)]:	25,00	External surface [(m²·K)/W]:	0,04
Transmittance		**Thermal resistance**	
Tot. [W/(m²·K)]:	0,32	Tot. [(m²·K)/W]:	3,09

2. *Ground floor on crawl space with igloos*; the floor is composed of a lean concrete layer, crawl space of 30 cm igloos, 5 cm reinforced concrete slab, cellular concrete lightened substrate, XPS insulating layer, preformed panel in EPS for floor heating, high thermal conductivity screed layer where a 2 cm. diametre pipe of the radiating heating system is embedded and, finally, the upper surface of floor. Tables 9 and Table 10 respectively show stratigraphy and transmittance values.

Table 9: Stratigraphy of Ground floor on vented crawl space with igloos

Layer Description	S (cm)	λ (W/m°C)	C (W/m²°C)	ρ (kg/m^3)
Clay tile	2,00	0,720		1.800,00
Heating plant screed	6,00	1,830		2.000,00
EPS performed panel	2,00	0,035		30,00
XPS styrodur_2800 CS	6,00	0,032		30,00
Cellular concrete	5,00	0,090		400,00
Common concrete	5,00	1,280		2.200,00

Table 10: Thermal and inertial characteristic

Total thickness (cm)	26,00	Superficial mass (kg/m²)	288,40
Unit conductance		**Unit resistance**	
Internal surface [W/(m²·K)]	5,88	Internal surface [(m²·K)/W]:	0,17
External surface [W/(m²·K)]:	25,00	External surface [(m²·K)/W]:	0,04
Transmittance		**Thermal resistance**	
Tot. [W/(m²·K)]:	0,30	Tot. [(m²·K)/W]:	3,31

3. *Vented covering in masonry*; the covering is made of a 1,5 cm plaster layer, 20 cm of masonry floor, 4 cm. of reinforced concrete slab, 6 cm. of XPS Expandit insulating layer, a 5 cm. ventilation cavity/gap, 1.2 cm of planks, a waterproof membrane and a covering mantle. Stratigraphy and trasmittance values are shown in Tables 11 and 12.

Table 11: Covering stratigraphy

Layer Description	S (cm)	λ (W/m°C)	C (W/m²°C)	ρ (kg/m^3)
Lime mortar or cement lime	1,50	0,900		1.800,00
Floor 20cm	20,00		3,33	950,00
Common concrete	4,00	1,280		2.200,00
XPS expandit	6,00	0,030		33,00

Table 12: Thermal and inertial characteristic

Total thickness (cm)	31,50	Superficial mass (kg/m²)	280,13
Unit conductance		**Unit resistance**	
Internal surface [W/(m²·K)]	10,00	Internal surface [(m²·K)/W]:	0,10
External surface [W/(m²·K)]:	25,00	External surface [(m²·K)/W]:	0,04
Transmittance		**Thermal resistance**	
Tot. [W/(m²·K)]:	0,40	Tot. [(m²·K)/W]:	2,49

4. *Separation floor between attic and heated zone*; the floor is formed of a plaster layer, a 24 cm thick supporting structure in masonry, cellular concrete lightened substrate, insulation layer, finishing screed layer and floor. Stratigraphy and transmittance value are given in Tables 13 and 14.

Table 13: Separation floor stratigraphy

Layer description	S (cm)	λ (W/m°C)	C (W/m²°C)	ρ (kg/m^3)
Lime mortar or cement lime	1,00	0,900		1.800,00
Floor 20cm	20,00		3,33	950,00
Common concrete	4,00	1,280		2.200,00
Cellular concrete	8,00	0,090		400,00
XPS styrodur_2800 CS	7,00	0,032		30,00
Finishing screed	4,00	1,350		2.000,00
Clay tile	2,00	0,720		1.800,00

Table 14: Thermal and inertial characteristic

Total thickness (cm)	46,00	Superficial mss (kg/m²)	428,10
Unit conductance		**Unit resistance**	
Internal surface [W/(m²·K)]	10,00	Internal surface [(m²·K)/W]	0,10
External surface [W/(m²·K)]:	25,00	External surface [(m²·K)/W]	0,04
Transmittance		**Thermal resistance**	
Tot. [W/(m²·K)]:	0,28	Tot. [(m²·K)/W]:	3,62

5. *Separation floor between heated area and garage*: this floor is composed of plaster, 24 cm thick masonry supporting structure, cellular concrete lightened substrate, XPS insulation, preformed panel in EPS for floor heating , high thermal conductivity screed layer where a 2 cm. pipe of

radiating heating system is embedded and the floor. Stratigraphy and transmittance values shown in Tables 15 and 16.

Table 15: Stratigraphy of separation floor between heated area and garage

Layer description	S (cm)	λ (W/m°C)	C (W/m²°C)	ρ (kg/m^3)
Clay tile	2,00	0,720		1.800
Heating system screed	6,00	1,830		2.000
EPS preformed panel	2,00	0,035		30,00
XPS styrodur_2800 CS	5,00	0,032		30,00
Cellular concrete	5,00	0,090		400,00
Ordinary concrete	4,00	1,280		2.200
20cm Floor	20,00		3,33	950,00
Lime mortar or cement lime	1,00	0,900		1.800

Table 16: Thermal and inertial characteristic

Total thickness (cm)	45,00	Superficial mss (kg/m²)	456,10
Unit conductance		**Unit resistance**	
Internal surface [W/(m²·K)]	5,88	Internal surface [(m²·K)/W]	0,17
External surface [W/(m²·K)]:	25,00	External surface [(m²·K)/W]	0,04
Transmittance		**Thermal resistance**	
Tot. [W/(m²·K)]:	0,30	Tot. [(m²·K)/W]:	3,30

Once materials and design building packages were defined, a three-dimensional model of the studied building was created in the software environment.

This analysis established that the building is in energy class C with a global energy performance index of 110.09 kWh/m2/year, which is very close to the legal limit of 111.86 kWh/m2/year. Its partial energy performances are reported as follows (Table 17).

Table 17: Energy partial performance

Cooling		Heating		Sanytary hot water	
Primary energy index (EPe)	-	Primary energy index (EPi)	77,72	Primary energy index (EPacs)	32,37
Primary energy index law limit	-	Primary energy index law limit (d.lgs. 192/05)	93,86		
Envelope index (EPe,invol)	12,43	Envelope index (EPi,invol)	62,46	Renewable sources	-
Plant output	-	Plant season average output (η_g)	76,39		
Renewable sources	-	Renewable sources	-		

An economic analysis was then carried out by calculating the surfaces of different structural design typologies and subsequently determining the total price of the insulation for each project structure.

Table 18: Insulation materials economic assessment

Structure	Price €/m^2	Surface m^2	Total cost €
External wall	11,75	233	**2.737,75**

Wall close to unheated Staircase zone	11,75	16,97	**199,3975**
Staircase zone			
Masonry vented roof	13,2	176,37	**2.328,084**
Attic floor	17,01	111,45	**1.895,7645**
Floor on garage	12,15	51,5	**625,725**
Floor on vented crawl space with igloos	14,58	59,95	**874,071**

Following this analysis, low environment impact, eco-sustainable, unconventional insulating materials were selected in the database, based on the type of installation.. The objective was to obtain a building envelope with the same energy performance of the envelope analyzed in the first part of the study, realized with conventional insulation materials (extruded polystyrene XPS), leaving unchanged all the other materials. For each structural package, the insulation thickness necessary to obtain a thermal transmittance as close as possible to that obtained with the extruded polystyrene XPS was then calculated, admitting a 5% margin of error. Finally, the cost per square meter of both the insulations, natural and traditional (XPS), were determined and compared in terms of percentages [10].

The calculations results are reported below.

1. *Perimeter separation wall between heated zone and unheated staircase.*

Table 19: Walls thermal characteristics

Material	Insulation	S Cm	Price €/m^2	External wall cost €	Perimeter wall cost €
	celenit FL120	6	17,2	4008	292
Timber fiber	hofatex therm	6	15,24	3551	259
	flytherm	6	11,4	2656	193
Wood wool and	PLS 120	12	25,2	5872	428
Mineral binders	celenit N	9	24,58	5727	417
	eraclit	10	35,3	8225	599
	corktherm 040	6	22,5	5243	382
Cork	corkpan	6	30,8	7176	523
	celenit LSC	6	20,18	4702	342
	vital celenit	5	15,69	3656	266
Cellulose fibre	flex CL	6	11	2563	187
	homatherm flex 040	6	14,8	3448	251
	isolmant BIO FK	5	19	4427	322
Kenaf fibre	kennevo	6	11,2	2610	190
	tecnokenaf	6	22	5126	373
	celenit LC30	6	11,53	2686	196

Hemp fibre	isolcanapa pan	6	11,08	2582	188
	canaton 35	6	19,8	4613	336
Maize fibre	biofiber	5	14,5	3379	246
Coir fibre	coccotherm	6	35,25	8213	598
	rotolo ennat	6	19,6	4567	333
Sheep wool	woolin	6	14,1	3285	239
	lankot	6	13,95	3250	237
	idroperalit	7	13,23	3083	225
Expanded perlite	biosfloor	7	10,85	2528	184
	pavaself	7	12,46	2903	211
Vermiculite	vermiculite BPB	8	14,4	3355	244

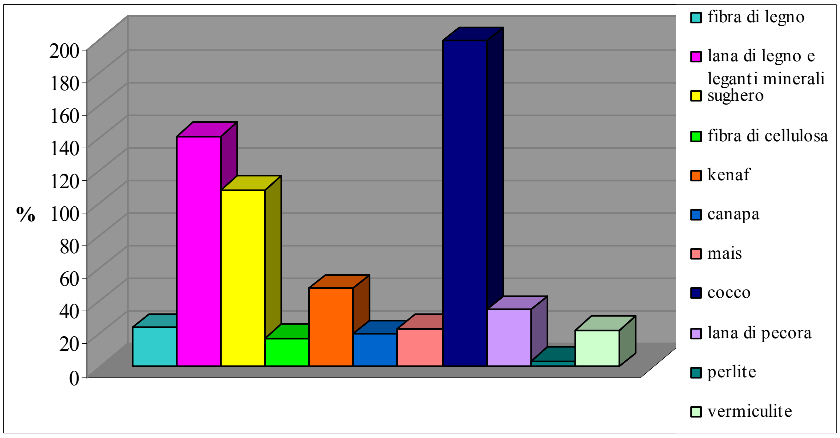


Figure 3: Chart of Percentage increase in walls cost

2. *Ground floor on vented crawl space with igloos*

Table 20: Vented floor thermal characteristics

Material	Insulation	S Cm	Price €/m^2	Floor cost €
	3therm naturel	7	16,31	978
Timber fibre	flytherm 100	8	21,7	1301
	Pavatex Pavaboard	9	25,59	1534
Wood wool	eraclit	14	49	2938
And mineral	celenit N	12	32,7	1960
bindings	novolit NL	12	27,04	1621
	celenit LSC	8	26,92	1614
Cork	selva kork	7	14	839
	natural kork	8	14,4	863

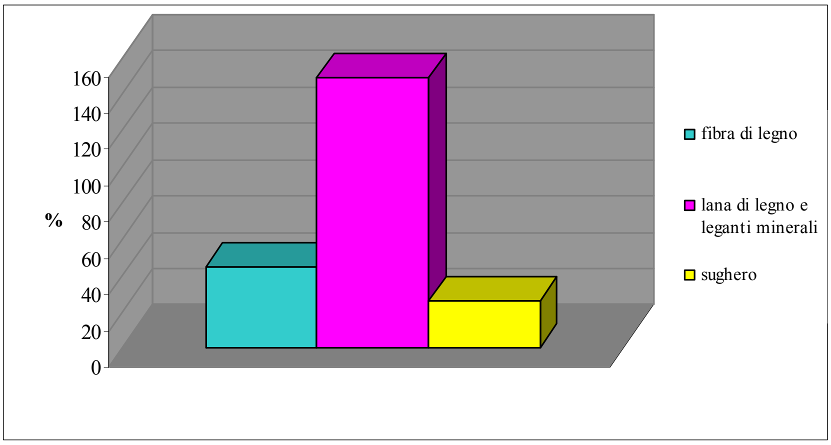


Figure 4: Chart of Percentage Growth in vented floors cost

3. Vented covering in masonry

Table 21: Vented covering thermal characteristics

Material	Insulation	S Cm	Price €/m^2	Covering cost €
	3therm naturel	8	18,64	3288
Timber fibre	flytherm	8	15,2	2681
	Pavatex Pavatherm	8	17,68	3118
Wood wool and	Eraclit	15	53	9348
Mineral bindings	Euchonit K	12	34,56	6095
	novolit NL	12	27,04	4769
	celenit LSC	9	30,28	5340
Cork	Corkpan	8	41,1	7249
	natural kork	9	16,2	2857
	flex CL	8	13,95	2460
Cellulose fibre	homatherm flex 040	8	19,7	3474
	Isolcel	8	21,6	3810
	Nafcotherm	7	13,41	2365
Kenaf fibre	Tecnokenaf	9	27,9	4921
	Isolkenaf	8	16,8	2963
	canaton 35	8	26	4586
Hemp fibre	isolcanapa pan	8	14,77	2605
Maize fibre	Biofiber	7	20,3	3580
	Coccotherm	9	52	9171
Coir fibre	cocco R	9	29,7	5238
	Lankot	7	16,3	2875
Sheep wool	isolana 100	6	13,4	2363
	wallen dach	7	14,31	1995

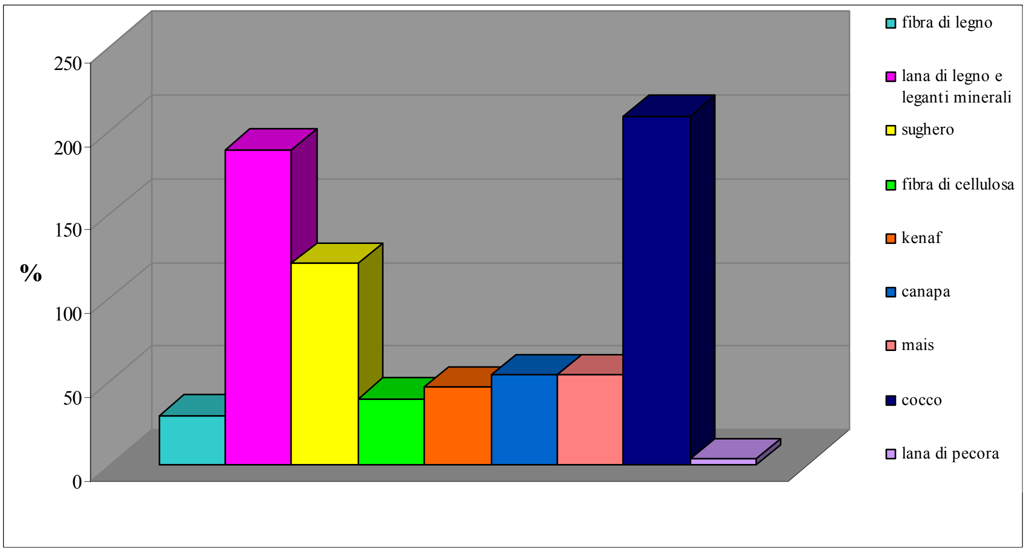


Figure 5: Chart of Percentage growth in vented covering cost per square meter

4. Separation floor between attic and heated zone

Tabella 22: Walls thermal characteristics

Material	Insulation	S cm	Price €/m^2	Floor cost €
	3therm naturel	8	18,64	2077
Timber fibre	flytherm 1000	9	24,4	2719
	Pavatex Pavaboard	9	25,59	2852
Wood wool and	eraclit	15	53	5907
Mineral bindings	celenit N	14	38,24	4262
	novolit NL	14	31,5	3511
	celenit LSC	9	30,28	3375
Cork	selva kork	8	16	1783
	natural kork	10	18	2006
	Kennevo	8	16,3	1560
Kenaf fibre	tecnokenaf	9	27,9	3109
	isolkenaf	8	16,8	1872
Flax fibre	naturaflax	8	18,06	2013
Maize fibre	biofiber	8	23,2	2586

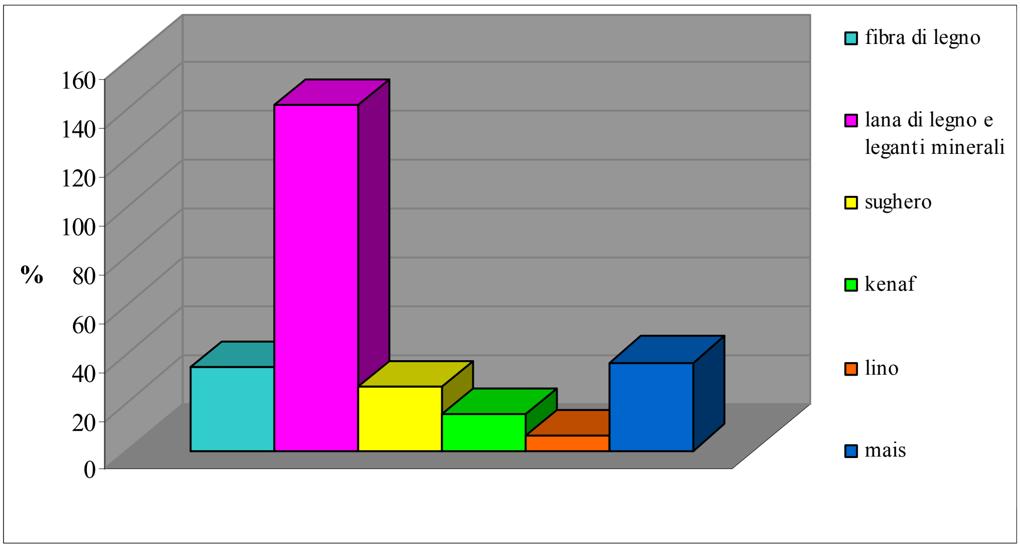


Figure 6: Chart of Percentage increase in separation floor cost

5. Separation floor between heated area and garage

Tabella 23: Walls thermal characteristics

Material	Insulation	S Cm	Price €/m²	Floor cost €
	3therm naturel	6	13,98	720
Timber fibre	flytherm 1000	7	18,99	978
	Pavatex Pavaboard	7	19,9	1025
Wood wool and	eraclit	11	38,8	1998
Mineral bindings	celenit N	10	28,56	1471
	novolit NL	10	27,6	1421
	celenit LSC	7	23,55	1213
Cork	selva kork	6	12	618
	natural kork	7	12,6	649
	Kennevo	6	11,2	577
Kenaf fibre	tecnokenaf	7	25,6	1318
	isolkenaf	6	12,6	649
Flax fibre	naturaflax	6	13,54	697
Maize fibre	biofiber	6	17,4	896

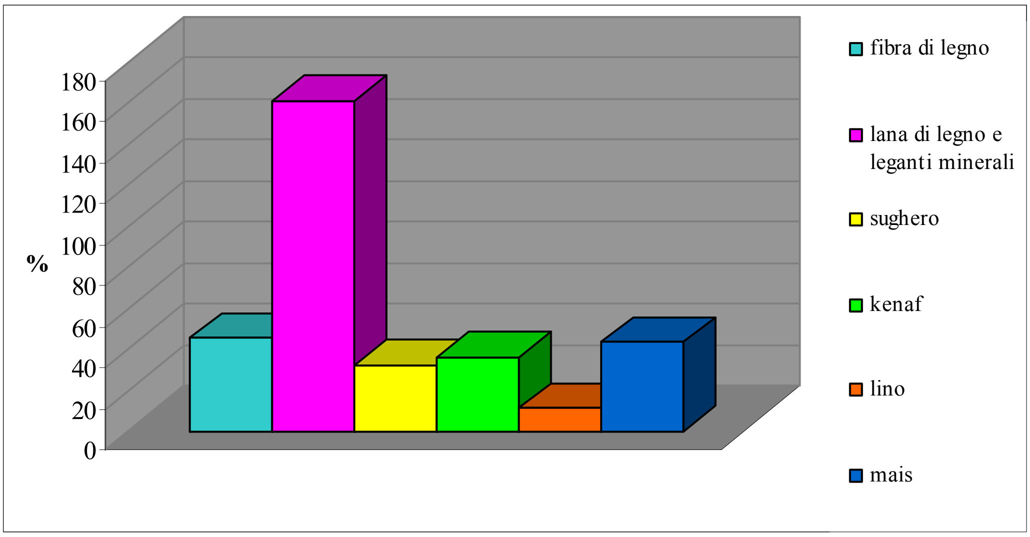


Figure 7: Chart of Percentage increase in separation floor cost

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4. Conclusions

The economic assessment of ecologically sustainable materials show that, as expected, their utilization involves a cost increase, when considering an equal thermal performance of a building's envelope. In particular, the percentage increase in the cost per square meter, compared to the XPS cost, was more important for some insulation typologies, such as wood wool with mineral binders (up to a maximum increase of 189% for the roof), coir fiber (up to a maximum increase of 209% for the roof) and cork (up to a maximum increase of 121% for the roof). In particular, for wood, wool, and mineral binders, the increase in cost is due to the considerable increase in thickness which is necessary to achieve the same insulation performances of XPS, while the considerable increase for cork and coir fiber is caused by the high cost per square meter of the insulations, considering an equal thickness.

Among the great variety of products available on market, there are nevertheless a number which offer very satisfactory performances in respect of a modest cost increase. This is particularly true for some, such as sheep wool, which has an increase in the cost per square meter of 4% when considering roof insulation, and also wood fiber with a 24% increase for perimetral walls and, finally, flax fiber with an increase of 6% for the floor of the attic. The economic analysis even demonstrates that some products cost less than the XPS given the same thermal performance of the project structure. Among these, for example, the "flytherm" wood fiber panel, which costs 0,35 €/m2 (- 2,9%) less than the XPS, and also the "kennevo" kenaf fiber panel with a lower cost of € 0,55/m2 (- 4,6%), and the "kork forest" cork panel with a lower cost of 0,15 € / m2 (-1,2%) compared to the XPS. Despite the lower cost of the aforementioned insulation products, the average cost by product typology is always higher than XPS cost. As a result, it is possible to conclude that within the range of ecologically sustainable insulation materials there is considerable cost variability.

In light of these considerations, it is clear that in order to make a proper choice, it is necessary to know the materials' performance characteristics and assess them in relation to the building envelope installation/laying typology. The reason being that only a correct design of structural elements and a proper placement and installation/laying of the insulating material, on the basis of its characteristics, can ensure a long and efficient life of that material inside the building.

It is also necessary to take into account aspects which are not easily quantifiable, such as building and environmental quality, by examining the materials' ecological characteristics. Even the material price strongly influences the choice, but it must not be the main aspect, namely because of the additional expenditure due to a good thermal insulation application is quickly offset by saving on heating and air conditioning costs, and secondly, because the cost of an insulating material with low impact on the environment contributes, even though in small part, to environmental cost savings.

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