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The "Cost Optimality" Approach for the Internal Insulation of Historic Buildings

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Abstract

The Directive 2010/31 UE (EBPD) introduced the "Nearly Zero Energy Buildings" linked to cost optimality, where energy benefits are related to economic benefits. The "Cost Optimality" methodology is applicable both to new and existing buildings, as introduced in the Regulation 244/2012. This methodology was largely applied to existing building, but the literature on historic buildings lacks. However, given the potential of energy retrofit of this kind of buildings, it would be appropriate to develop a specific methodology for the economic valorization of the heritage, considering also the conservation and the historic value of the patrimony. In fact, on the one hand this methodology could be useful for the "energy valorization" of a historic building in relation to the minimum requirements of European and national legislations and budgets. However, on the other hand, we noted the absence of shared information at national level and examples of the "historic reference buildings". For this reason, case studies on historic buildings become an important starting point to create common typological and repeat-able models for applying this methodology. This research aims at evaluating the economic benefits of energy retrofit of a traditional historic masonry, using the "Cost Optimality" methodology. This method is structured into the following parts: (i) definition of the type of masonry; (ii) selection of the insulation systems; (iii) assessment of the energy benefits related to the insertion of various insulation materials; (iv) evaluation of the Life Cycle Costing; (v) evaluation of the optimal insulation performance and cost-effectiveness; and (vi) comparison of energy consumption and Life Cycle Cost to de-fine the most appropriate interventions for the historic wall.

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1. Introduction

European policies on energy efficiency in buildings gave a high effort for obtaining ambitious requirements of energy performance and use of renewable energy sources, to get strong benefits for the reduction of greenhouse gas emissions, both on new and existing buildings. They suggested increasing the rate of the total renovation of the existing buildings, which represent the sector with the greatest potential for energy savings and environmental sustainability (1). In line with the European programs, several studies confirmed that is not enough to build new high-performance buildings for reducing the carbon dioxide emissions (CO_2) and for improving the energy efficiency (2; 3; 4). In this context, the European Directive 2010/31/EC set the minimum requirements of energy performance, both for new construction and existing buildings. Particularly, it defined the target of the nearly Zero Energy Building (nZEB) as "(…) *a building that has a very high energy performance (...). The nearly zero or very low amounts of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*" (5, art. 2). This ambitious target concerns also existing buildings that require major renovations in order to meet the minimum energy performance requirements, to reduce the greenhouse emissions related to construction and to make the construction market independent from imports. The directive promotes with the Cost-Optimality considerations minimum requirements, which target not only short-term payback, but promote long-term convenience and economic optimization. This methodology is called cost-optimality approach and aims at reducing the costs over the estimated useful life of the building, maintaining high-energy performance standards. The high potential of this method encouraged its use as a decision making tool for selecting the optimum intervention in different energy scenarios. The Directive defined the "cost-optimal level" as "(…) *the energy performance level, which leads to the lowest cost during the estimated economic lifecycle*" (5, art. 2). It is determined taking into account the energy-related investment, maintenance, and operating costs (5, art. 2). Each Member State has to estimate the economic lifestyle for the whole building or the building element. In general, the "building" is considered as a "product" with a programmable and predictable life cycle over a period of 20 or 30 years. The Regulation 244/2012 set out the methodology for comparing energy efficiency measures and costs for new constructions and building renovations (6). The Regulation defined two schemes for the calculation of global costs to be applied in the cost-optimality approach: (a) "financial calculation" and (b) "macroeconomic calculation". The relevant criteria to be taken into account for the financial calculation are: (i) energy needs and (ii) overall costs in terms of Net Present Value (NPV). The overall costs to be considered are: (i) initial investment costs; (ii) running costs such as costs for periodic replacement of building elements; (iii) energy costs that reflect the overall energy cost, including energy price, capacity tariffs and grid tariffs; and (iv) disposal costs if appropriate. In addition to the energy needs and the overall costs, the macroeconomic calculation included the (v) costs of the greenhouse gas emissions. However, specific suggestions for cultural heritage buildings are missing. In Italy, the law 63/2013 set the minimum requirements for nZEB, both for new and existing buildings. Listed buildings are excluded, while existing buildings (also, historic but not listed buildings) are fully subjected to the legislation (7). In general, it considers the same requirements of the Regulation (6).

The cost-optimality approach started in the industry sector and only in a second time was applied to the building sector. In the last case, the Regulation was investigated at European (8) and national levels (4; 9; 10) mainly for new buildings or for the energy retrofit of post-war buildings. BPIE (8) studied the energy benefits related to different energy efficiency solutions for residential buildings in Austria, Germany and Poland. At national level, ENEA (4) applied the cost-optimality approach to the energy retrofit of typical residential buildings located in the climatic zones B and E. Typical buildings were selected from the European Project Tabula. The energy retrofits regarded building envelope and systems, and respected the national standards for energy efficiency. The University of Salento (9) applied this methodology to an office building, comparing different energy efficiency solutions with the macroeconomic calculation scheme. This comparison showed a potential reduction of energy consumptions (39 %) and greenhouse gas emissions (41 %), also demonstrating the suitability of this approach for the design process. The University of Sannio (10) applied this approach to a historic building, using the macro-economic calculation scheme. The building is located in Benevento and was refurbished with different interventions on building envelope (replacement of existing glasses, interior insulation with insulation plaster, insulation of the basement and the roof) and systems (installation of new HVAC and lighting systems). The cost-optimality approach permitted to re-duce energy consumptions (50 %), CO_2 emissions (53 %) and global costs (20 %). In addition, the installation of HVAC systems resulted the most cost-effective solution for energy saving purposes.

2. Aims of the study

The research aims at identifying the specific application of this methodology to a real historic building, defining the characteristics and the particular problems that should be considered. Particularly, the study focuses on the selection of the most feasible internal insulation systems from the energy and the economic point of views. These solutions have been applied to a traditional stone masonry of the north of Italy, made by irregular ashlar in marble of Varenna bedded in lime mortar. The study evaluates the cost-effectiveness of the solution really chosen by the design team (a perlite insulation with thickness 0.20 m) with commercially available products. To study exclusively the internal insulation systems, we do not consider other technologies and HVAC systems.

3. . Methodology of the cost optimality approach

The study is structured in the following phases: (i) definition of the type of masonry characteristic of the pre-alpine area of Lombardy Region; (ii) selection of the thermal insulation materials; (iii) assessment of the energy benefits related to the insertion of different insulation materials; (iv) evaluation of the Life Cycle Costing; (v) evaluation of the optimum thermal performance under the cost-effectiveness profile; and (vi) comparison between energy consumption and Life Cycle Cost to define the most appropriate interventions for the historic wall from the energy and economic points of view.

3.1. The case study

The study has been applied to a real historic building built in the XVIII Century near by the Lake of Como (Italy). The restoration and the energy retrofit are made by the Italian architecture offices “Modulo 2 Architettura” and “Solarraum”. The design project is an outstanding case of synergy between architectural heritage and energy efficiency, in order to reach nZEB performances and high indoor environmental quality, also maintaining its historical appearance (11; 12; 13). The building and its garden are protected by the heritage office. This means that no external changes can be done. Therefore, it was not possible to apply thermal insulation panels outside, but only internal insulation (Figure 1).

Fig. 1. The case study: a historic building built in the XVIII Century, located near the Lake of Como

The walls cover an area of 400 m^2. It is formed by a stonewall with a thickness of 0.60 m. It presents a complex pattern composed by irregular ashlar in marble of Varenna, covered on both sides with a historic lime plaster (14). An internal thermal insulation with 0.20 m of perlite (λ= 0,045 W/mK; ρ = 85 kg/m^3; c = 1 kJ/kgK; μ = 1) has been applied to reduce the transmission losses of the opaque envelope. The thermal transmittance (U-value) of the existing wall without the insulation is 1.84 W/m^2K. The U-value with the insulation is 0.18 W/m^2K. Where it was not possible to install such a thick insulation layer, 0.08 m of aerogel (λ= 0,016 W/mK; ρ = 150 kg/m^3; c = 1 kJ/kgK; μ = 1) have been inserted. This result in a U-value of 0.19 W/m^2K and thus a similar insulation level as the wall insulated with perlite.

3.2. Selection of the thermal insulation materials

The selection of the thermal insulation materials aims at comparing the energy benefits and the cost-effectiveness of different systems. For the Regulation, the evaluation must regard as a minimum 10 solution sets (Regulation 244/2012). As inorganic materials, we select: (i) perlite (PE); (ii) microporous calcium silicate (CS); (iii) rock wool (ROCK); (iv) glass mineral wool (GLASS); and (iv) foamglass (FOAM). As organic materials, we select: (i) mineral wood fiber (m-WOOD); (ii) flexible wood Fiber (f-WOOD); (iii) cork (CORK); (iv) XPS (XPS); and (iv) EPS (EPS). We know that some of these materials can cause problems from hygrothermal point of views, but want just compare different technologies. Furthermore, the data reported in the Environmental Product Declaration (EPD) has been analyzed to verify the sustainability of each thermal insulation material. Particularly, we reported the energy used during the product stage (section A, energy produced by non-renewable sources). We did not consider the energy consumption during use (section B) and end-of-life (section C) stages. The data refers to commercial products. The information are reported below (Table 1).

Table 1. Type and properties of the thermal insulation materials selected.

Type	Material	λ-value (W/mK)	Energy from non-renewable sources (MJ/m^3)
Inorganic natural	Perlite [i]	0.045	4245
Inorganic synthetic	Microporous calcium silicate [ii]	0.060	6748
	Rock wool [iii]	0.035	565
	Glass mineral wool [iv]	0.032	674
	Foamglass [v]	0.038	1980
Organic natural	Mineral wood fiber [iv]	0.035	2084
	Flexible wood fiber [vi]	0.037	1584
	Cork [vii]	0.040	821
Organic synthetic	XPS [viii]	0.034	2868
	EPS [ix]	0.036	1613

Sources:
[i]= Sto [ii] = Calsitherm [iii] = Rockwool [iv] = Knauf Insulation [v] = Pittsburgh Corning Europe
[vi] = BetonWood and Sto [vii] = Biofiber and Silvestre et al., 2016 (15) [viii] = Exiba [ix] = Isover

3.3. Assessment of the energy benefits related to the insulation materials

The energy performance is calculated in accordance with the framework provided in the Directive 2010/31/EU. It means "(…) *the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting*" (5, art. 2). The Energy Performance Indicator (EPI) defines the energy needs after the retrofit works. It has been calculated, departing from the past Italian legislation (16) where the formula for calculating the EPI was:

$$EPI = (Qh/A)/\eta g \quad [\text{kWh/m}^2] \qquad (1)$$

It considered: the thermal energy needs (Qh), the area (A) of intervention and the performance of the system (ηg). Particularly, the calculation of Qh considers: heating degree day (GG) of the place, overall heat transfer coefficient for transmission (Ht) and ventilation (Hv), a specific index that considers the heat gains (fx, that for the “simplify method” is 0.95), solar heat gains (Qs) and internal heat gains (Qi):

$$Qh = 0.024 \cdot GG \cdot (Ht + Hv) - fx \cdot (Qs + Qi) \tag{2}$$

Then, we calculated the EPI for the building envelope only, considering the U-value of each insulation system (U), the area of the intervention (A), and the presence of a common oil boiler system typical for old buildings, with an average efficiency (ηg) of 0.8. Furthermore, we simplified the calculation without considering the internal heat gains. The EPI of the building without the insulation system is 46’334 kWh. We decided to calculate the EPI for: (i) thickness of 0.20 m as used by the architecture office; (ii) reduced thickness of 0.10 m for comparison; (iii) target U-value for the design project of 0.20 W/m^2K; and (iv) target U-value for the minimum requirements in the climatic zone of 0.30 W/m^2K. The U-values and the EPI of the wall with different insulation materials with a thickness of 0.20 m and 0.10 m are reported below (Table 2).

Table 2. U-value and EPI of the different thermal insulation materials with a thickness of 0.20 m and 0.10 m.

Material	Thickness 0.20 m		Thickness 0.10 m	
	U-value (W/m^2K)	Epi (kWh	U-value (W/m^2K)	EPI (kWh)
No insulation	1.84	46334	1.84	46334
Perlite	0.19	4997	0.35	8941
Microporous calcium silicate	0.25	6411	0.44	11139
Rock wool	0.15	3991	0.29	7296
Glass mineral wool	0.14	3679	0.27	6770
Foamglass	0.17	4299	0.31	7806
Mineral wood fiber	0.15	3991	0.29	7296
Flexible wood fiber	0.16	4197	0.30	7638
Cork	0.17	4501	0.32	8138
XPS	0.15	3888	0.28	7123
EPS	0.16	4094	0.29	7468

Source: Elaboration of the author

The thickness and the EPI of the wall with different thermal insulation material with a U-value of 0.20 W/m^2K and 0.30 W/m^2K are reported below (Table 3).

Table 3. Thickness and EPI of the different thermal insulation materials with a U-value of 0.20 W/m^2K and 0.30 W/m^2K.

Material	U-value 0.20 W/m^2K		U-value 0.30 W/m^2K	
	Thickness (m)	Epi (kWh)	Thickness (m)	Epi (kWh)
No insulation	-	46334	-	46334
Perlite	0.20	4997	0.12	7722
Microporous calcium silicate	0.26	5110	0.16	7722
Rock wool	0.15	5160	0.09	7611
Glass mineral wool	0.14	5067	0.08	7747
Foamglass	0.16	5241	0.10	7681
Mineral wood fiber	0.15	5160	0.09	7611
Flexible wood fiber	0.16	5119	0.10	7638
Cork	0.18	4943	0.10	7644
XPS	0.15	5030	0.08	7631
EPS	0.16	4997	0.09	7789

Source: Elaboration of the author

3.4. Evaluation of the Life Cycle Costing

The prices of the insulation materials are evaluated from local price lists and commercial prices. In particular, the prices of XPS, EPS, rock wool, mineral wood fiber have been taken from the price list of Alto Adige Region. However, the prices of other materials have been taken from the companies’ price lists, according to energy performances and EPD certifications. We considered the cost of the insulation itself and an average value for finishing materials like plaster, gluing or paint (10.000 €). To consider also "system" costs specifically for each material – e.g. also vapor barriers where needed – will be a task for a follow up study. According to Regulation 244/2012, the Life Cycle Costing (LCC) follows the calculation methodology of the standard UNI EN 15459 (17) using the financial perspective. The global cost of the whole building is calculated in VAN, which defines the present value of an expected series of cash flows, discounted at the rate of return (or discount rate) (18). In this case, the LCC regards: (i) initial investment costs; (ii); energy costs, while we decided to not consider running and disposal costs that are not appropriate for the specific case. Since in Italy there is not yet an official discount rate. Thus, we decided to hypothesize several discount rates, from 0 % to 6 %, to understand their influence on the global cost of the investment. The selected discount rates are: 0 % when the capital is hold; 3 % required by Regulation (6); 1 % and 6 % taken from a research on this theme (8). According to the Regulation 244/2012 (6), the evaluation period for residential buildings is 30 years, but since our building is preserved, it has been decided to increase the evaluation period to 50 years.

4. RESULTS AND discussion

The results of the study are reported below, in order to compare: (i) the thermal performance of the different insulation material under the cost-effectiveness profile; (ii) evaluation of the energy life cycle; and (iii) comparison between energetic and cost life cycle.

4.1. Evaluation of the thermal performance under the cost-effectiveness profile

First, we compared the cost-effectiveness of thermal insulation materials with a thickness 0.20 m (Figure 2) and 0.10 m (Figure 3). Obviously, the EPI is lower for the high investment (0.20 m) and vice-versa. The material with the best cost-effectiveness profile is the glass mineral wool, thanks the good energy performance (λ = 0.32 W/mK) and the low cost. Also, XPS, mineral and flexible wood fibers, rock wool, and EPS, have a good cost-effectiveness, due to the λ-values in the range 0.034÷0.037 W/mK and the similar costs.

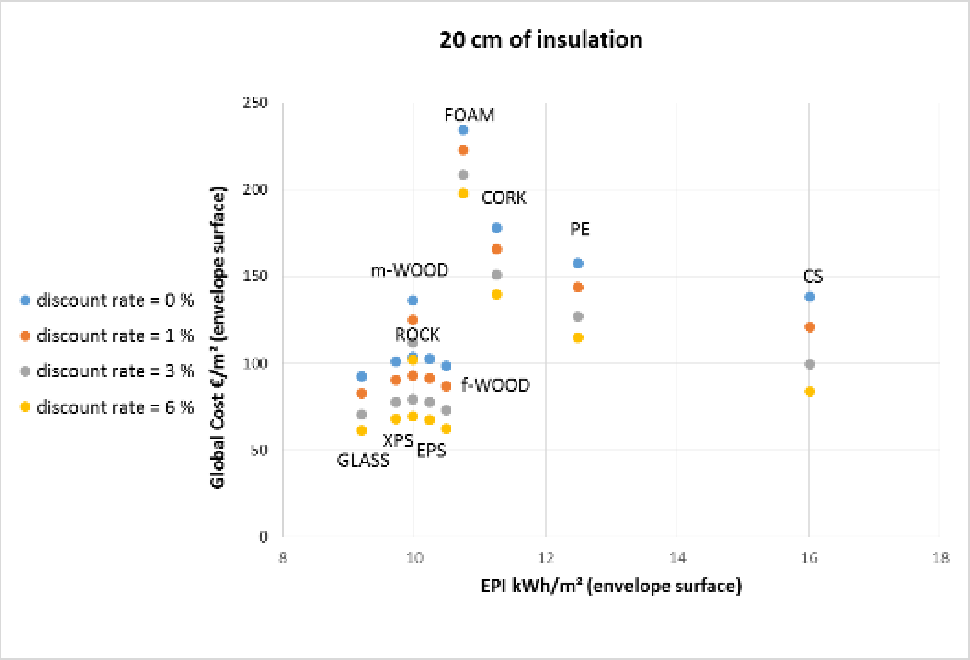


Fig. 2. The cost-effectiveness profile of the selected thermal insulation materials for a thickness of 0.20 m.

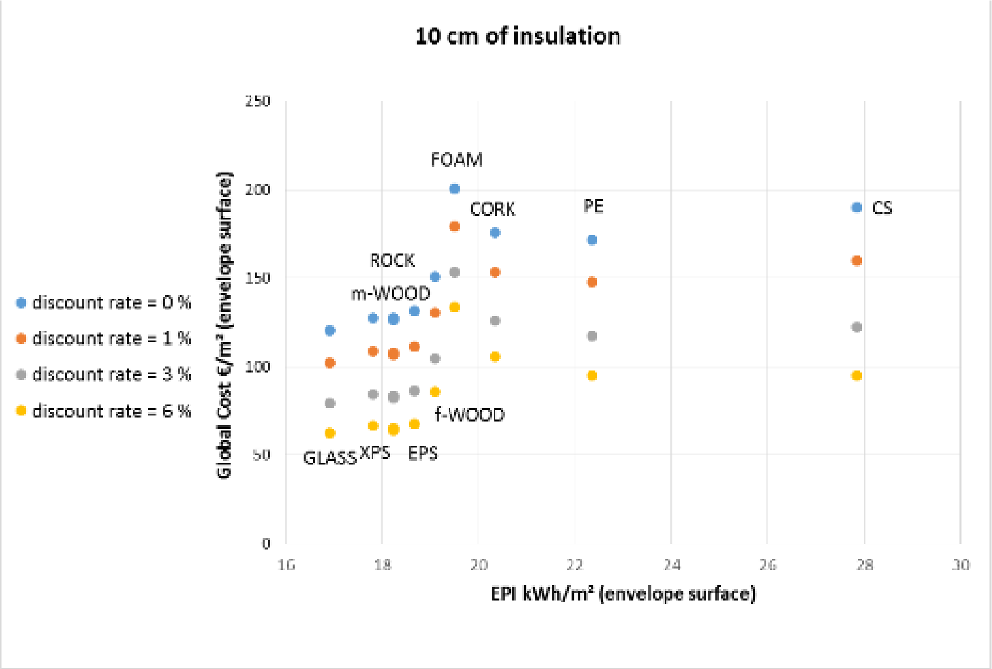


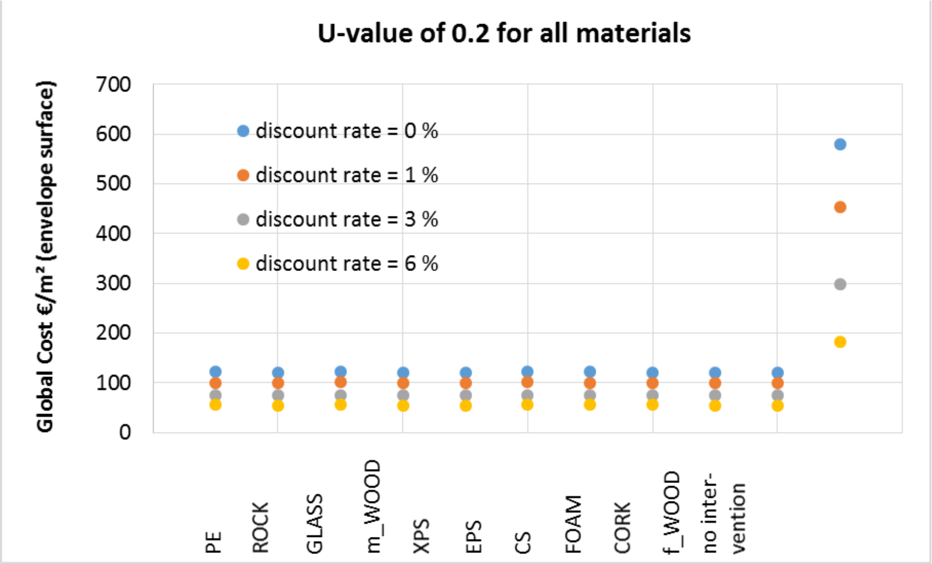
Fig. 3. The cost-effectiveness profile of the selected thermal insulation materials for a thickness of 0.10 m.

Foamglass is the material with the highest cost, but good energy performance (λ = 0.038 W/mK). Cork and perlite have medium energy performances (λ = 0.040÷0.045 W/mK) but costs higher than the first category of materials (wood fibers, rock and glass wool, XPS and EPS). Finally, calcium silicate has low performances (λ = 0.060 W/mK) and medium costs. It is more cost effective that perlite, cork and foamglass, as the “global cost” includes both investment and energy cost.

Comparing the results for 0.10 m and 0.20 m one can make three observations:

- The absolute value of global cost in €/m² is in the same order of magnitude. For high discount rates it is a bit lower for 0.10 insulation, for low discount rate a bit lower for 0.20 cm;
- Particularly where the cost of the insulation does not increase proportionally with increasing thickness, the global costs tends to decrease with thicker insulation layer (see e.g. CS with 100÷200 €/m² for 0.10 cm and 80÷150 €/m² for 0.20 m;
- There are different distance among the discount rates. Particularly, the distance among the rates is higher for thickness of 0.10 m, rather than 0.20 m. This is due to the fact, that the global cost for the case with less insulation is influenced more by the energy costs on which the discount rate acts, while the investment is compared to the high insulation case lower. This influence is higher for small thickness (difference of 75 €/m^2 between 0 % and 6 % for 0.10 m and 50 €/m^2 for 0.20 m).

Second, we compared the cost-effectiveness of the thermal insulation materials for obtaining a U-value of 0.20 W/m^2K and 0.30 W/m^2K (Figure 4). The difference in the results are due to our decision to consider only commercial thickness. Thus, we decided to not report the results.



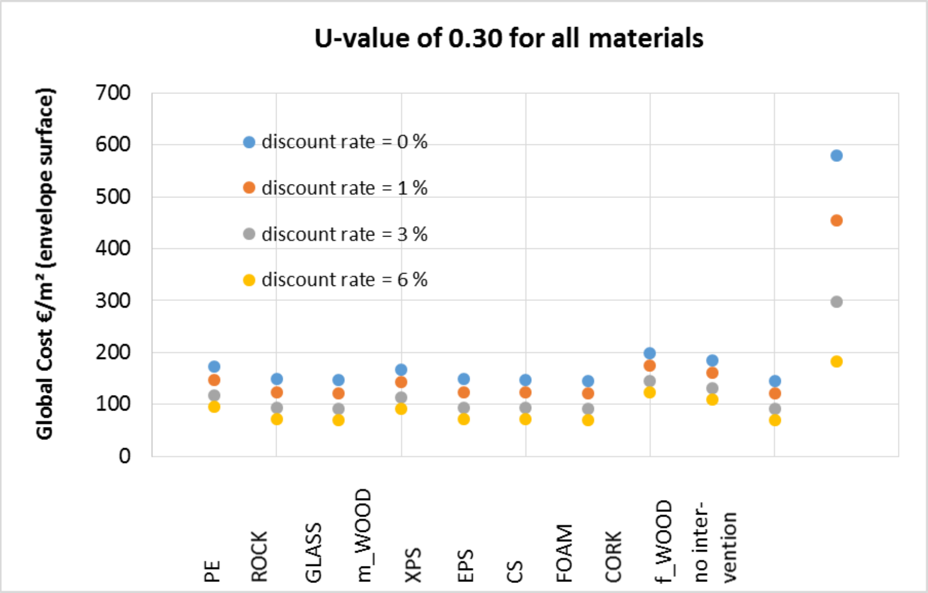


Fig. 4. The cost-effectiveness profile of selected insulation material for target U-values.

4.2. Evaluation of life cycle costs

Figure 5 shows the global costs invested for the retrofit with an insulation system of 0.20 m. EPS and flexible and mineral wood fibers are the materials with the lowest payback time (PBT). EPS, XPS and glass mineral wool are the most affordable materials with 0.10 m of insulation, with a PBT less than 5 years (Figure 5).

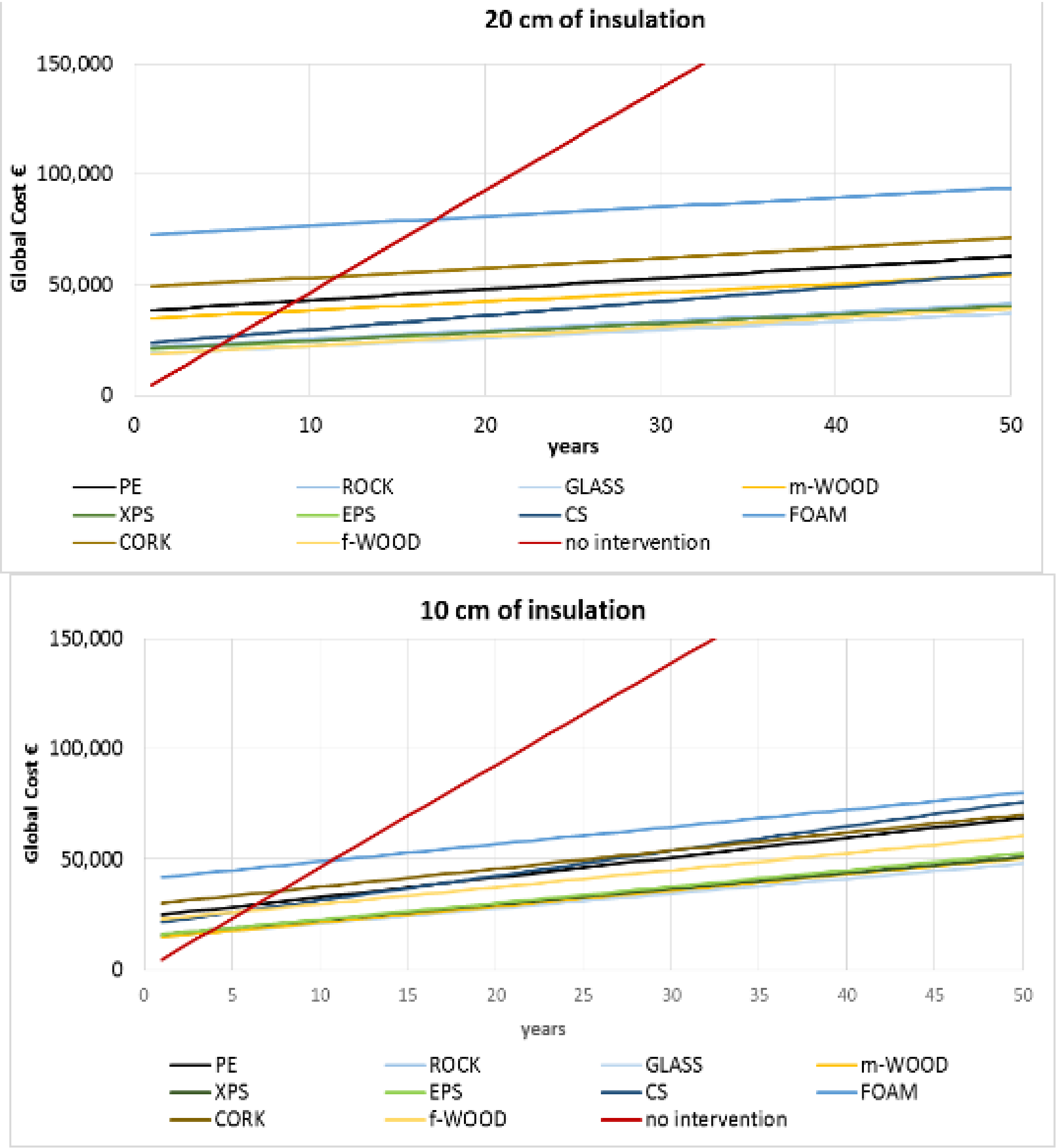


Fig. 5. Life cycle energy for an insulation system of 0.20 m and 0.10 m.

Considering the target U-value of 0.20 W/m²K the materials more affordable are wood fibers and calcium silicate with a PBT less than 5 years.

4.3. Evaluation of the energy life cycle

For the analysis of the life cycle energy demand, the "invested energy" in the retrofit measure in terms of the total non-renewable primary energy demand for the phases A1 to A3 has been summed to the annual energy demand for heating the building. Figure 6 shows the annual increasing cumulative value. Where the line of "no intervention" crosses the line with insulation, the respective intervention has its energetic payback reached. The value ranges from a few months up to 4 years, with the average at less than one year (Figure 6).

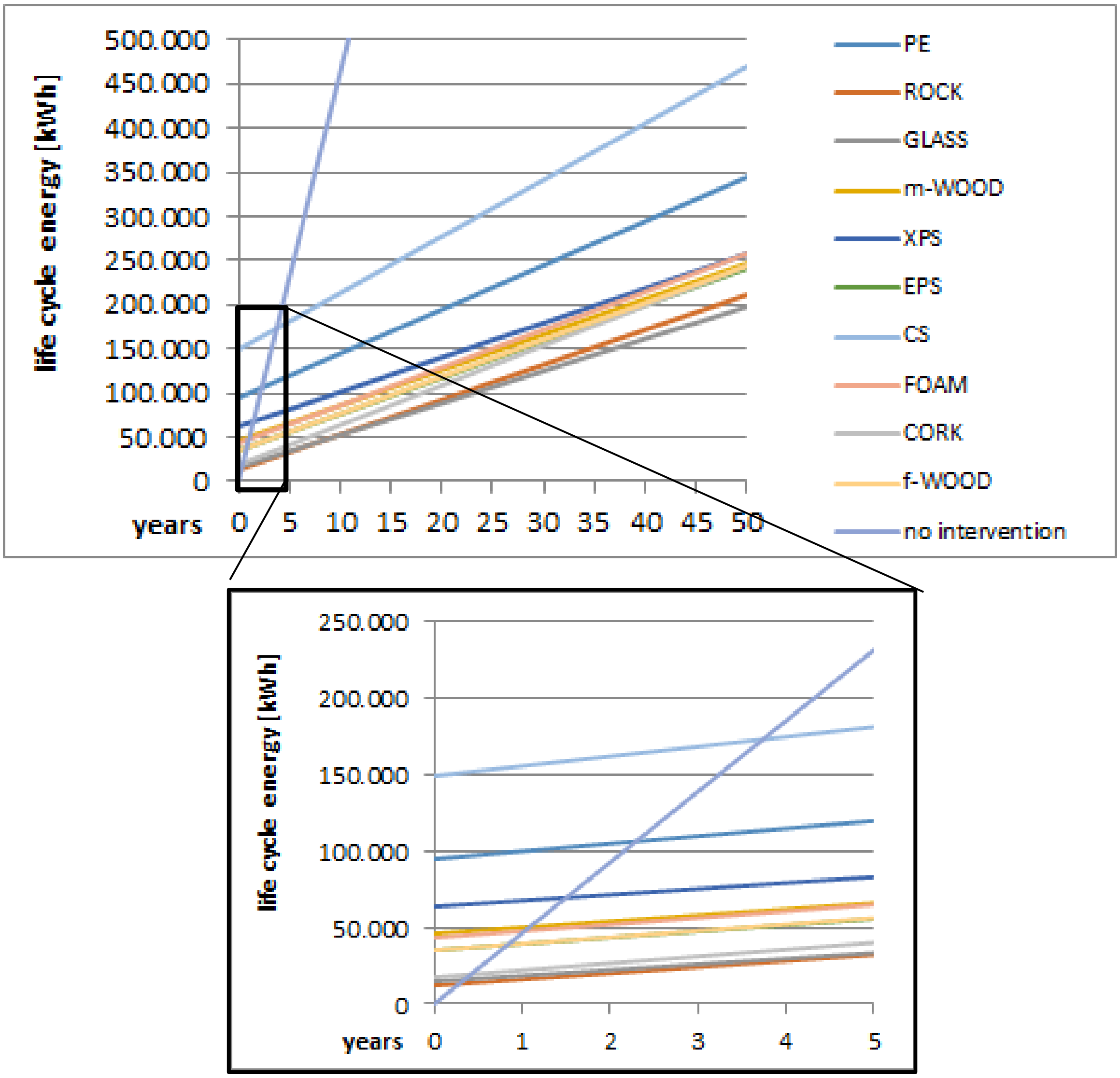


Fig. 6. Life cycle energy shown as cumulative value over a period of 50 years. At the bottom a detail showing the first five years.

4.4. Comparison of energetic and cost life cycle

In Figure 7 and Figure 8 both life cycle energy and life cycle costs, calculated over a period of 50 years are shown. In the first case, costs have been calculated with a discount rate of 0 %, in the second, with a discount rate of 3 %. For both energy and cost the “not intervention” is by far the worst scenario. Remarkable is however, that for the life cycle energy, the operational energy demand is by far dominating the overall result, while for the life cycle costs, in most cases the investment dominates the result - especially if a discount rate of 3 % is applied, which reduces the present value of the future operational costs (Figure 7; Figure 8).

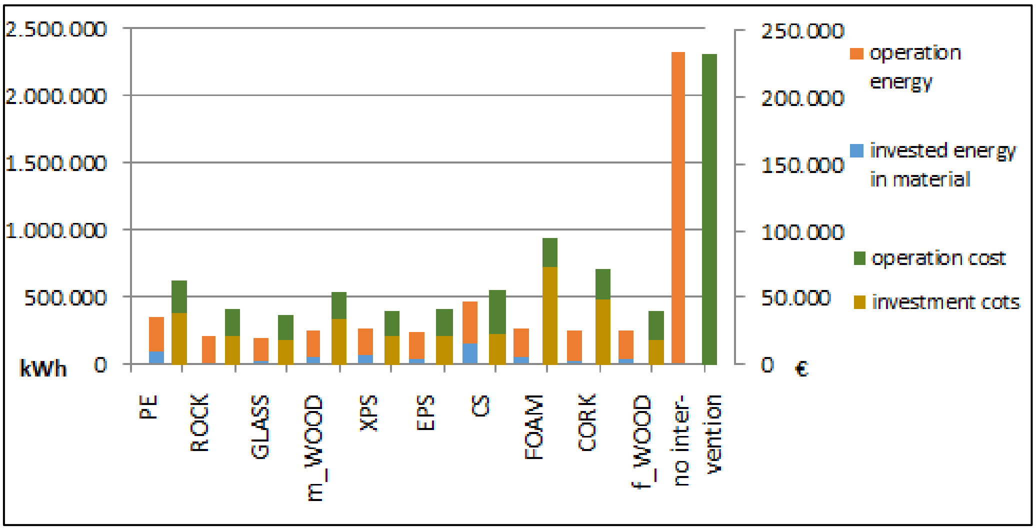


Fig. 7. Life Cycle energy (left axis) and cost (right axis) for insulation with 20cm, lifetime considered 50 years, discount rate 0%.

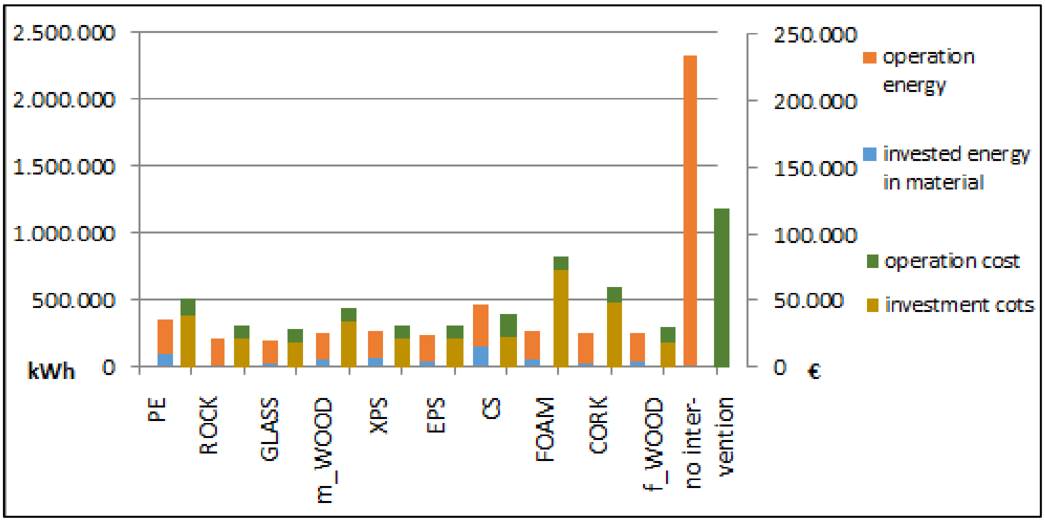


Fig. 8. Life Cycle energy (left axis) and cost (right axis) for insulation with 20cm, lifetime considered 50 years, discount rate 3%.

5. Conclusions

The evaluation of the thermal performance under the cost-effectiveness profile showed that both organic and inorganic materials have a good behavior. Generally, the cost-effective materials are glass mineral wool, rock wool, mineral and flexible wood fibers, XPS and EPS. This is due to the λ-values in the range 0.034÷0.038 W/mK and the low costs. Cork, perlite and foamglass resulted efficient from the energy point of view, but they are more expensive than other materials. They have, however, other benefits like e.g. a better hygrothermal behavior. These aspects will be included in the next step of the study. The life cycle cost demand analysis showed a PBT for the energy retrofit with an insulation system of 0.20 m from 5 years to 18 years. EPS and flexible and mineral wood fibers are the materials with the lowest PBT. With an insulation system of 0.10 m the PBT is in the range 3÷10 years. EPS, XPS and glass mineral wool are the most affordable materials. Finally, the comparison between life cycle energy and life cycle costs calculated over a period of 50 years showed that the “not intervention” is by far the worst scenario, for both a discount rate of 0 % and 3 %. For the life cycle energy, the operational energy demand is dominating the overall result, while for the life cycle costs, in most cases the investment dominates the result. The definition of the discount rate is a very important point in the cost optimal approach as it considerably influences the global cost. Since the interest rates in the financial market at this moment is however very low for an investment which in its security is comparable to energy retrofit measures (e.g. national bonds and similar, with very low interest rates) and since also for the energy prices no increase has been assumed in this study (i.e. we considered it proportional to inflation rate – which is a conservative assumptions), the authors propose to consider more reliable the lower discount rates (1 % if not even 0 %).

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