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[Impact of grey energy on optimal wall insulation thickness]

[**Summary: max. 1500 characters incl spaces**] For decades efforts have been made to reduce the greenhouse gases emissions of buildings by reducing their energy demand with governmental regulations in Europe, pushing towards very low thermal transmittances (U-values) with ever thicker insulation layers for new buildings. However, there is no linear relationship between the insulation thickness and the heat losses. Therefore, above a certain thickness the consumption of buildings does not decrease significantly. Hereafter a life cycle analysis, including emissions before the building becomes operational is applied to evaluate the impact of the increasing thickness of components on the overall emissions. Publicly available product data sheets are used to compare four insulation materials under three scenarios. These analyses yield interesting results showing that energy-intensive insulation materials lead to a negative impact in the overall energy balance after a certain thickness. Even though there is not always a pronounced optimum insulation thickness, it is logical that further reductions in U-value for new buildings should hence be carefully evaluated. The results show that the optimal thickness is around 20 cm for most materials, while the important major savings come from the first 10 cm.

Keywords [Insulation materials; grey energy; parameter study; optimal thickness; renovation]

Optimale Wanddämmstärke unter Berücksichtigung der grauen Energie

[Abstract: max. 1500 characters] *Seit Jahrzehnten wird versucht den Ausstoß von Treibhausgasen von Gebäuden zu reduzieren, indem der Energiebedarf durch staatliche Vorschriften in Europa gesenkt wird, wobei bei Neubauten sehr niedrige Wärmedurchgangskoeffizienten (U-Werte) mit immer dickeren Dämmschichten angestrebt wurden. Es besteht jedoch kein linearer Zusammenhang zwischen der Dämmstärke und den Wärmeverlusten. Ab einer gewissen Dicke sinkt der Verbrauch von Gebäuden daher nicht mehr signifikant. Im Folgenden haben wir eine vollständige Lebenszyklusanalyse durchgeführen, die alle Emissionen berücksichtigt, also auch die aus vorgelagerten Prozessen, um die Auswirkungen der Dämmstärke auf die Gesamtemissionen zu bewerten. Informationen über graue Energie sind heute für fast alle Produkte öffentlich zugänglich. Wir verwenden die Produktdatenblätter und vergleichen Dämmstoffe in drei verschiedenen Szenarien, um Unsicherheiten zu berücksichtigen. Diese Analysen liefern interessante Ergebnisse und zeigen, dass energieintensive Dämmstoffe ab einer bestimmten Stärke zu einem negativen Einfluss auf die Gesamtenergiebilanz führen. Auch wenn es nicht immer eine ausgeprägte optimale Dämmstärke gibt, ist es logisch, dass weitere Absenkungen des U-Wertes bei Neubauten sorgfältig geprüft werden sollten. Die Ergebnisse zeigen, dass die optimale Dicke für die meisten Materialien bei etwa 20 cm liegt, während die wichtigen großen Einsparungen von den ersten 10 cm erzielt werden.*

Stichworte [Dämmstoffe; graue Energie; Parameterstudie; optimale Dicke; Renovierung]

1 Introduction

Despite all efforts in the past decades, the greenhouse gas (GHG) emissions in the EU across all sectors reduced only by around 30% in the past 30 years [1], while carbon dioxide (CO_2) global concentration are rising ever faster [2]. Considering that the building sector was still responsible for almost 30% of the EU's total final energy consumption in 2021 [3], European Directives for the reduction of CO_2 emissions in the sector have been constantly tightened in recent decades. The directive 2010/31/EU sets minimum requirements for the energy performance of new and existing buildings [4], pushing local authorities to enhance regulations to improve energy efficiency. As a result, the U-values of building components have been progressively reduced, to reduce thermal losses. In 2021, Luxembourg set the strictest requirements in Europe, with reference values for the thermal transmittance coefficient (U-value) of 0.13 W/m^{2}K [5].

However, the relationship between the U-value and insulation thickness is non-linear, requiring increasingly larger components to reach the target reference. The thermal transmittance coefficient is inversely proportional to the total thermal resistance of a component, that also includes the surface thermal resistances. The surface thermal resistances only depend on the surface characteristics and wind speed conditions [6]. Therefore, thermal losses can be greatly impacted by the first centimetres of insulation, but after a certain thickness, the effect on the overall resistance of the component is no longer expressive [7-10]. Many studies [7-8][11-16], evaluated the optimum insulation thickness, yet with an economic approach, disregarding the energy used for producing and transporting insulation materials, the so-called grey energy aspect and the related carbon emissions.

A life cycle analysis of buildings including grey energy is needed to identify the real benefit of thick components in reducing global CO_2 emissions in the sector. [10] shows that depending on the climate and the mass of the wall, when considering the grey energy of a generic high standard insulation material, the optimal U-value is not necessarily the lowest. Our study investigates the impact of four types of insulation materials on energy savings over the life cycle of the building, depending on their thickness. For this purpose, grey energy reference values from publicly available databases were used in three scenarios - a conservative, a realistic, and an optimistic scenario - over the lifetime of the building in the Luxembourg climate heated by a heat pump.

It should be noted, however, that although a further economic analysis would be possible, it is not included in this document. The investigation of the economic optimum thickness requires a prognosis of the energy price, which comprises many assumptions and can have great variability. Nevertheless, it is important to evoke that in general economic optimum thickness, even when disregarding the cost of lost living space, is lower than the energetic optimum thickness [6][17].

The assumptions used in this study do not take into account the potential for recycling, avoiding the uncertainties related to the limited practical implementation and variation in the reference data. Although recycling can represent savings on primary grey energy, in some cases it might also represent a significant increase, depending greatly on the quality of the demolition material or the specifications of the final products [18].

The aim of this research is to show that more importantly than the U-value reference alone, the optimal thickness of the insulation layers must consider the materials, their grey energy, and their impact on energy savings over the life cycle of the building. The result is shown in a graph compiling materials and scenarios, giving an indication of an optimal thickness range where the impact on energy savings is effective.

2 Materials and Methods

Operational requirements, heat gains, and heat losses determine the heating needs of a building. They are influenced by many factors including the desired internal temperature, orientation, internal and solar gains, construction materials, insulation, ventilation, and air infiltration. The analysis of the impact on energy savings due to the insulation thickness is done considering a building located in the Luxembourg climate, heated by a heat pump to keep the internal temperature constant at 20°C. Three scenarios are defined to allow an extensive evaluation under a broad range of conditions. The scenarios are called ‘conservative’, ‘realistic’, and ‘optimistic’. These express a variation of typical values regarding the climate conditions, the thermal transmittance of the building before insulation, the mean annual Coefficient of Performance (COP) of the heating system, the primary energy factor for electricity, and the life cycle operational span.

The climatic conditions of a particular location are used to determine the energy requirements of buildings. The $HDD_{20/15}$ indicates how many days the daily average outside temperature is below 15°C, therefore requiring heating to reach the desired 20°C inside the building. As above mentioned, the building is situated in Luxembourg, where the average Heating Degree Days ($HDD_{20/15}$) is 3510 Kd. This value changes every year according to the weather conditions, hence in this study, a ± 10% variation is considered between the three scenarios.

The characteristics of the materials used for the building envelope will influence its thermal conductivity, directly influencing its energy demand related to transmission losses. In this context, the three scenarios are stablished considering three different building components, with three different thermal transmittances of masonry before the application of an insulation layer (U_0). The chosen building materials are timber for the optimistic scenario due to its low thermal transmittance, a component based on calcium silicate brick for the realistic scenario, and a precast concrete structure for the conservative scenario.

The operational energy requirements of the building are also affected by the efficiency of the heating system, in this case, a heat pump. Heat pumps have good COPs for low-temperature heating systems. The mean annual COP adopted for this study is around 3.5±0.5. Heat pumps are powered by electricity. Therefore, the increasing availability of renewable production can represent an opportunity for reducing carbon emissions from the operation of a building. However, for the moment most heat pump systems are connected to the grid, and their carbon emissions are directly related to the primary energy factor for the electricity mix. The primary energy factor for electricity (f_{prim}) considered in this study is 2±0.5. Since 2021, Luxembourg adopted a 1.5 factor, considering the expected increase in renewable shares in Luxembourg and Germany between 2020-2040, while supporting the adoption of solutions that do not depend on fossil fuels [19].

The analysis of the energy demand over the life cycle of the building is directly dependent on the number of operational years. In this case, scenarios are analysed for a 30±10 years operation. Table 1 summarizes the reference parameters for each scenario.

Table 1 Definition of different scenarios

	unit/scenario	'conservative' (1)	'realistic' (2)	'optimistic' (3)
Heating Degree Days ($HDD_{20/15}$)	Kd	3860	3510	3160
Thermal transmittance of masonry prior insulation U_0	W/(m²K)	3.37	2.21	1.08
Mean annual COP	-	3	3,5	4
Primary energy factor for electricity f_{prim}	-	2,5	2	1,5
Operational time n	years	20	30	40

A layer of insulation is then added to the structure of the building. This analysis is done considering four materials, with layers varying from 0 - 40 cm. By adding the insulation layer to the walls, the initial thermal transmittance of the building (U_0) is improved, leading to energy savings. However, since producing and transporting such materials also requires energy, a life cycle assessment of the building construction and operation, including grey energy, is used to evaluate the optimal insulation thickness. The specific grey energy reference values for each material are obtained from Environmental Product Declarations (EPD) sheets, available on the German public database Ökobaudat, version 2021-II dated 25.06.2021 in accordance with standard EN 15804+A2 [20].

In the EPD, the grey energy corresponds to the total use of non-renewable primary energy resources used for production and from raw materials, referred to as PENRT. As defined in standard EN 15804, the life cycle analysis of buildings is divided into modules from A to D, representing different stages. The production stage is composed by modules A1, A2 and A3, representing raw material supply, transport and manufacturing respectively. The grey energy of the insulation material is the total consumption of non-renewable primary energy resources corresponding to modules A1 to A3.

The selected insulation materials for this analysis are mineral wool, polyurethane, polystyrene, and calcium silicate. These insulation materials represent a vast variation in their PENRT values for the production phase (A1-A3), and consequently also on their specific primary grey energy values (E_{spec}), which is the same but only converted from [MJ/m3] to [kWh/m3], as presented in Table 2. This variation allows not only to evaluate the selected materials but also further extrapolation for others by comparing a range where the most common insulation materials would be placed, including cellulose and wood fibre, for example.

Table 2 Characteristics of used insulation materials

Insulation material	Thermal conductivity λ [W/m/K]	PENRT (A1-A3) [MJ/m³]	E_{spec} [kWh/m³]	Reference
Mineral wool	0.035	822.4	228.4	[21]
Polyurethane	0.024	2389	663.6	[22]
Polystyrene	0.031	2671	741.9	[23]
Calcium silicate	0.054	7035	1954.1	[24]

The primary grey energy increases linearly with the insulation material thickness, as indicated in Figure 1. It shows that the thicker the insulation layer, the bigger the primary grey energy, and that this will have an important impact in the optimal thickness, especially for those materials with higher PENRTs.

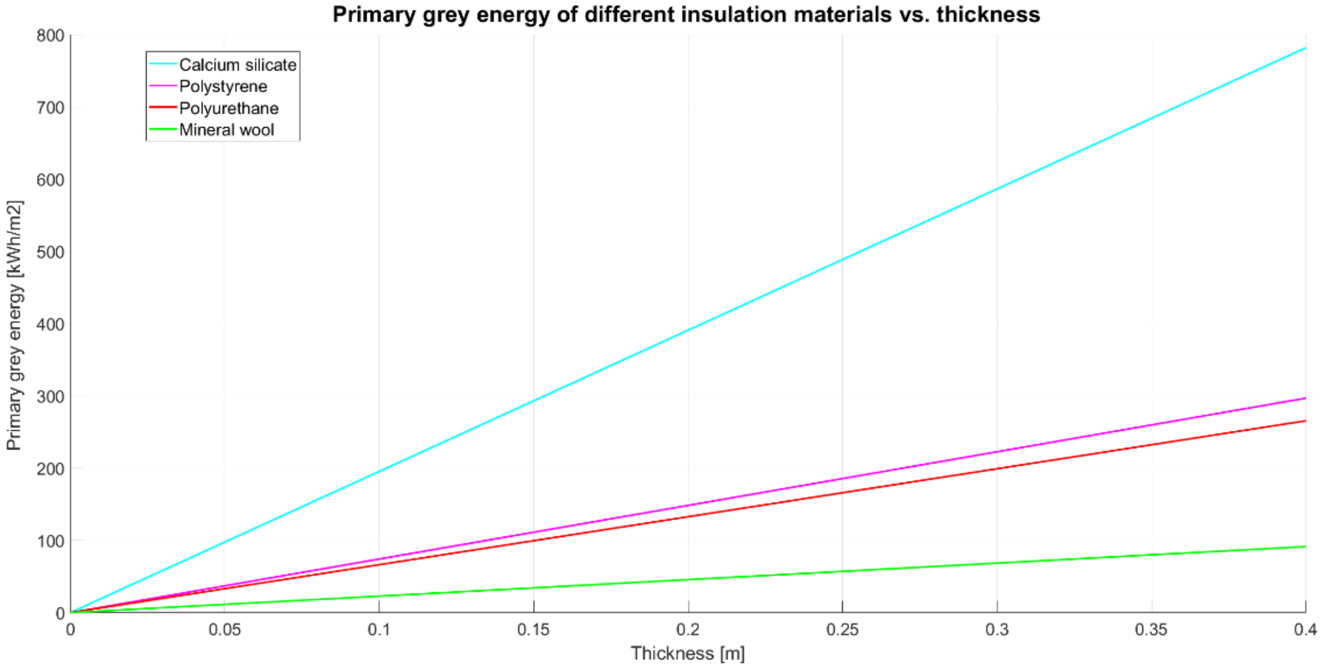

Fig. 1 Primary grey energy versus material thickness.

It is interesting to note, that large differences in the specific grey energy can be observed if recycled material is used. For instance, when producing polystyrene using recycled materials, only 200 kWh/m³ of non-renewable primary energy are necessary [25], compared to a range between 750 kWh/ m³ and 1050 kWh/ m³ required for other productions [26-29]. However, the recycling potential is not considered in this study, as the practice of separating materials at building sites is not widespread at present. This would broaden the discussion and greatly increase the number of variables, in addition to the uncertainties. The energy required for this process varies greatly depending on the previous construction method used and the material conditions.

The total primary energy counts for the energy demand over the construction and operational phases of the building. The total primary energy (PE), as a function of the insulation thickness (d) can now be calculated for the three scenarios from Table 1, considering the four different materials from Table 2. The heating demand in this study is calculated only taking into account transmission losses. Ventilation and infiltration losses are not affected by the thickness of the insulation and would therefore be the same in all scenarios.

$$PE(d) = E_{spec} \cdot d + \frac{HDD_{20/15} \cdot n \cdot U}{COP} \cdot f_{prim} \qquad \text{Eq.(1)}$$

PE is the total primary energy expressed in [kWh/m2], which is the sum of the primary grey energy and the primary energy necessary to heating the building for the complete building lifespan. The primary grey energy is the energy used to produce and transport the insulation material. It is calculated by multiplying Espec in [kWh/m3] by the thicknesses of the analysed insulation material d in [m]. The primary energy for conditioning the building is calculated by multiplication of the heating degree days HDD20/15 expressed in [Kd], with the number of operational years and the thermal transmittance U in [W/m2K], considering the Coefficient of Performance (COP) of the heat pump and the primary energy factor for electricity (fprim).

However, the thermal transmittance U of the component, in this case the external wall, also varies with the thickness d [m], as it can be observed in Equation 2. It is calculated considering the initial thermal transmittance of the building without insulation U0 in [W/m2K], and the increment provided by a thickness d in [m] of thermal insulation with a thermal conductivity λ expressed in [W/m/K].

$$U^{-1} = \frac{1}{U_0} + \frac{d}{\lambda} \qquad \text{Eq.(2)}$$

Replacing Equation 2 in Equation 1 leads to:

$$PE(d) = E_{spec} \cdot d + \frac{HDD_{20/15} \cdot n \cdot f_{prim}}{\left(\frac{1}{U_0} + \frac{d}{\lambda}\right) \cdot COP} \qquad \text{Eq. (3)}$$

Equation 3 is used to determine the primary energy demand including grey energy for the three scenarios, as a function of the insulation material thickness. This procedure allowed us to identify optimal insulation thicknesses ($d_{optimal}$) in terms of primary energy savings. Furthermore, this thickness is used in Equation 2 to identify the thermal transmittance ($U_{optimal}$). These results allow the comparison between the performance of the different materials considering their grey energy.

3 Results

Insulation materials are used to improve the thermal transmittance of the components in a building, due to their low thermal conductivity. The thermal transmittance decreases proportionally to the insulation thickness. However, this is not a linear relation, and after a certain thickness, the impact on the thermal transmittance is no longer effective. The thermal transmittance of the walls in this study was calculated for each material, in each scenario, using Equation 2. The results presented in Table 3 and Table 4 confirm that the improvement of the thermal transmittance of the wall is less expressive after 10 cm. This is important in the context of the present study to analyse the impact of thermal transmittance on the primary energy savings when including the impact of grey energy needed to produce insulating materials.

Table 3 Thermal transmittance in [W/m²K] of the wall for the three scenarios, as a function of the insulation material thickness (mineral wool and polyurethane)

Thickness [cm]	Mineral wool			Polyurethane		
	Conservative (1)	Realistic (2)	Optimistic (3)	Conservative (1)	Realistic (2)	Optimistic (3)
0	3.375	2.207	1.079	3.375	2.207	1.079
10	0.317	0.302	0.264	0.224	0.216	0.196
20	0.166	0.162	0.151	0.116	0.114	0.108
30	0.113	0.111	0.105	0.078	0.077	0.074
40	0.085	0.084	0.081	0.059	0.058	0.057

Table 4 Thermal transmittance in [W/m²K] of the wall for the three scenarios, as a function of the insulation material thickness (polystyrene and calcium silicate)

Thickness [cm]	Polystyrene			Calcium silicate		
	Conservative (1)	Realistic (2)	Optimistic (3)	Conservative (1)	Realistic (2)	Optimistic (3)
0	3.375	2.207	1.079	3.375	2.207	1.079
10	0.284	0.272	0.241	0.466	0.434	0.360
20	0.148	0.145	0.136	0.250	0.241	0.216
30	0.100	0.099	0.094	0.171	0.166	0.154
40	0.076	0.075	0.072	0.130	0.127	0.120

The nonlinearity of the thermal transmittance in relation to the insulation thickness have an impact on the primary energy savings. Especially when including the grey energy in the analysis, it is clear that depending on the material, reaching the lowest thermal transmittance is not always beneficial in terms of the overall primary energy demand. Based on Equation 3 the primary energy demand including grey energy of the three different scenarios defined in Table 1 were calculated for each insulation material form Table 2, as presented in Table 5 and Table 6.

Table 5 Primary energy demand including grey energy [kWh/m²] for the three scenarios, as a function of the insulation material thickness (mineral wool and polyurethane)

Thickness [cm]	Mineral wool			Polyurethane		
	Conservative (1)	Realistic (2)	Optimistic (3)	Conservative (1)	Realistic (2)	Optimistic (3)
0	5,211	3,188	1,228	5,211	3,188	1,228
10	512	459	323	412	379	290
20	303	280	217	312	297	256
30	243	229	188	320	311	284
40	223	213	183	356	350	330

Table 6 Primary energy demand including grey energy [kWh/m²] for the three scenarios, as a function of the insulation material thickness (polystyrene and calcium silicate)

Thickness [cm]	Polystyrene			Calcium silicate		
	Conservative (1)	Realistic (2)	Optimistic (3)	Conservative (1)	Realistic (2)	Optimistic (3)
0	5,211	3,188	1,228	5,211	3,188	1,228
10	513	467	348	914	822	605
20	377	358	303	777	738	637
30	377	365	330	850	827	762
40	414	405	379	982	965	918

From the data presented on Table 5 and Table 6 it is possible to check that when analysing the energy demand of a building including grey energy to produce the insulation material and the energy demand during operational time, for more energy intensive materials, after 20 cm for insulation, the primary energy demand tend to increase, independently of the scenario. Calcium silicate is the insulation material presenting the highest grey energy level in this study. The negative effect of the high grey energy content in this material can be noted after 10 cm of insulation thickness. In the case of mineral wool, which is the material presenting the lowest grey energy value in relation to the others, the negative effect cannot be noted within the first 40 cm. However, when calculated using further thicknesses, even this material presented a negative effect. A graph of the total primary energy demand including grey energy for the three scenarios, as a function of insulation thickness in this case, calcium silicate, is shown in Figure 2.

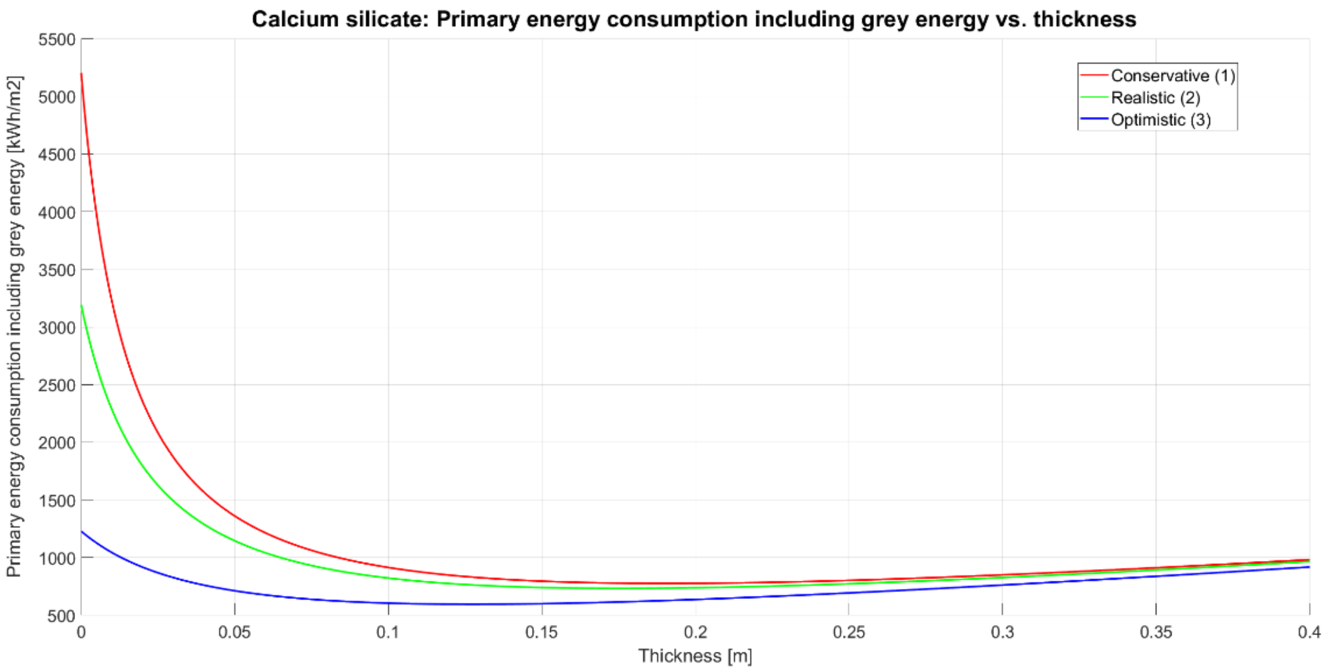

Fig. 2 Total primary energy demand including grey energy for the three scenarios, as a function of the calcium silicate thickness.

The analysis of Figure 2 allows us to state that for calcium silicate scenario 1 (conservative) is above 2 (realistic), which is always above 3 (optimistic). Therefore, the range between scenario 1 and 3 seems to cover all realistic cases. This is hence a reasonable range for the evaluation of the effectiveness of insulation thickness in terms of energy savings. The same pattern was observed for the other three materials. Based on this observation Figure 3 shows the primary energy demand including grey energy range for all four insulation materials analysed, where the shaded area highlight the uncertainties. These uncertainties have more impact until 20 cm of all insulation materials, fading away for further thicknesses.

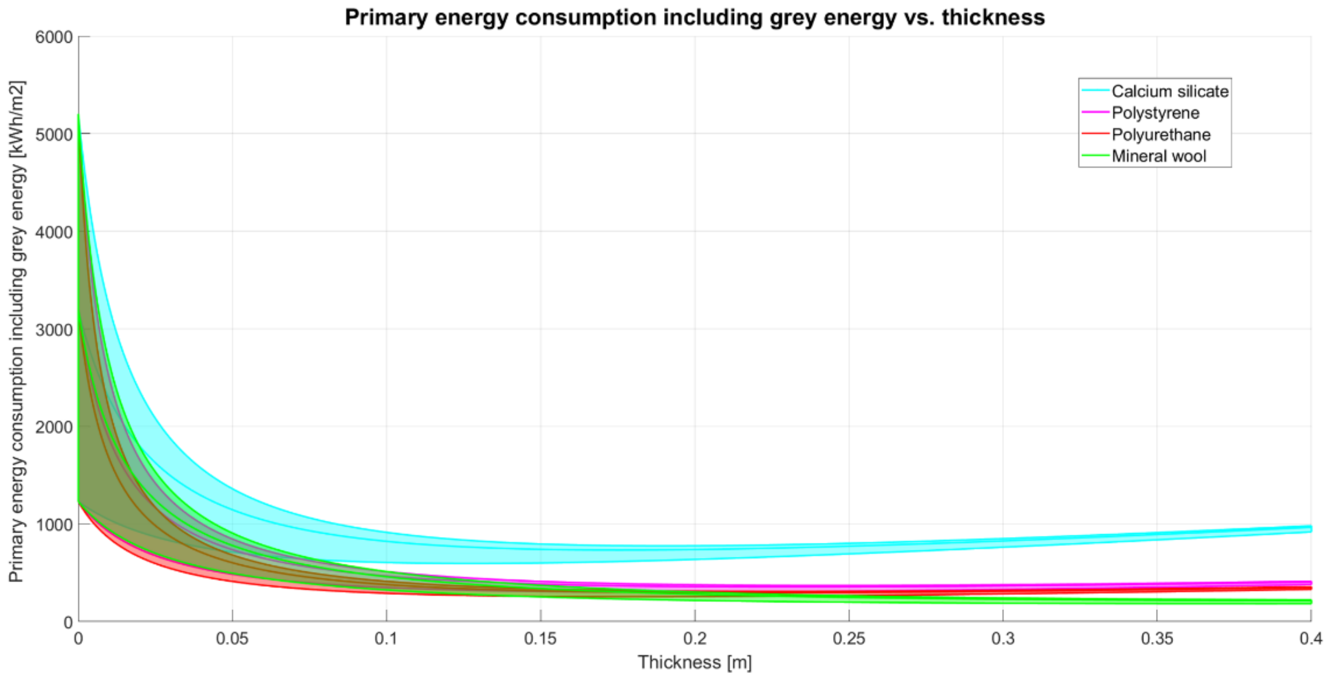

Fig. 3 Total primary energy including grey energy for all scenarios and insulation materials.

From the analysis of Figure 3 it is possible to observe that for all materials, it can be confirmed that the main energy savings occur within the first few centimetres of insulation. The calcium silicate curve is clearly above other materials due to its high specific grey energy, which is 2.5 up to 8 times higher than others. The combination of the curves shows an interesting range of results that allows to evaluate the impact of insulation thickness for the here analysed materials, as well as many others with proprieties in the same range.

The results from Equation 3 shows that with 10 cm of polyurethane in a conservative scenario primary energy savings reaches up to 92%. An additional 10 cm layer of polyurethane in the same scenario would only represent 2% improvement on energy savings. Even if we analyse the energy savings from calcium silicate in an optimistic scenario, that are much lower than the previous mentioned, reaching up to 51% savings within the first 10 cm of insulation thickness layer. This already represents 99% of the expected primary energy savings with the optimal thickness for this scenario. For mineral wool, it is also possible to observe that even if the negative impact of a thicker insulation layer in the primary energy demand of the building only starts to be noticed around 40 cm, the impact caused by the first 10 cm layer already represents around 90% savings in relation to expected primary energy savings with the optimal thickness for all the three scenarios. These results confirm the tendency showed in previous references [14-15], independently of the climate.

4 Discussion

Insulation materials are used to increase the thermal resistance of building components to reduce heat losses, and consequently the energy necessary to guarantee comfort requirements. By reducing the energy demand, the related GHG emissions are also reduced. However, energy is also used to produce any building component, and some insulation materials are very energy intensive. Besides, although the thermal resistance is directly dependent of the insulation thickness, the thermal transmittance is inversely proportional to it, and thus, the relation is not linear. Hence, after a certain thickness the impact of the insulation on the thermal transmittance is negligible. Therefore, this study adopts a life cycle analysis to identify the optimal thickness of insulation material to reduce the total energy requirements of a building.

The analysis was done for four types of insulation materials, with a wide range of grey energy. Each was analysed in three scenarios, from conservative to optimistic, providing a range covering most cases. Scenario 2 is the realistic scenario, it represents an average and is hence chosen as reference for discussion. The optimal insulation thickness ($d_{optimal}$) is identified using Equation 3 and can be observed on Figure 3. Although the minimum in the total primary energy is not always sharply defined, it is possible to see that most curves are flat after a certain thickness, showing that their impact is limited. In Equation 2 $d_{optimal}$ is used to find the optimal thermal transmittance value ($U_{optimal}$), as shown in Table 7.

Insulation materials less grey energy intense, such as mineral wool, only reaches the minimum primary energy demand with a thickness of 40 cm. However, as previously discussed, the greatest impact on energy savings is related to the first centimetres. In the case of mineral wool, a 20 cm insulation layer represents 91% of primary energy savings in relation to the base line case of the realistic scenario. This represents already 98% of the minimum primary energy demand. These results allow us, in the context of this study, to define the optimum insulation thickness of mineral wool for scenario 2 as being around 20 cm.

Table 7 Optimal insulation thickness and transmittance U for the analysed insulation materials

	PENRT [kWh/m^3]	λ [W/mK]	$d_{optimal}$ [m]	$U_{optimal}$ [W/m^{2}K]	$E_{optimal}$ [kWh/m^2]
Mineral wool	228	0.035	0.20	0.16	280
Polyurethane	664	0.024	0.22	0.10	296
Polystyrene	742	0.031	0.22	0.13	354
Calcium silicate	1,954	0.054	0.18	0.26	733

The optimal insulation thickness is defined around 20±2 cm depending on the grey energy and the thermal conductivity of the insulation materials. From Table 7 it is visible that 20 cm of mineral wool has a higher optimal thermal transmittance value than for instance 22 cm of polystyrene and the polyurethane, while the total primary energy ($E_{optimal}$) is minimal. It draws the attention to the importance of including grey energy into the analysis and makes clear that lowest thermal transmittance is not always beneficial. Further analysis of Table 7 shows that materials with higher grey energy and lower thermal conductivity, such as polyurethane, can still achieve comparable energy savings to materials with lower grey energy intensity and higher thermal conductivity, such as mineral wool. Nevertheless, after the optimal thickness ($d_{optimal}$) is reached, the effect of grey energy has a greater impact on the total primary energy consumption, resulting in an overall negative effect.

Furthermore, it can be questioned from economic point of view if insulation thicknesses above 20 cm and very low transmittance values really make sense, since [6][17] already showed that the financial optimum is below the energetic optimum.

Finally, insulating materials with high primary grey energy and higher thermal conductivity, such as the calcium silicate represent a very limited improvement in terms of energy savings, since it reaches maximum savings on the total primary energy requirements with small thicknesses, and has present a negative impact once the layer thickness is increased to reach lower thermal transmittance values.

5 Conclusions

The building sector represents almost one third of the final energy consumption in Europe, characterizing an important energy stock. Therefore, efforts on energy efficiency are being made both at European and national levels to address the related GHG emissions. Among other measures, thermal transmittance required values for new buildings are being reduced, to reduce heat losses and consequently the energy consumption of buildings. Because the thermal transmittance does not decrease linearly with the increment of insulation thickness, this is leading to very thick building components. However, depending on the insulation material, their thermal conductivity, and their grey energy, after a certain thickness a negative impact on the overall primary energy consumption during the entire life cycle of the building.

In this study, four insulation materials with vast variation on the grey energy intensity, were analysed in three different scenarios, providing a broad range of results from conservative to optimistic assumptions. A major conclusion from the analysis is the confirmation is that the first centimetres of insulation have the biggest impact on energy savings, independently of the insulation material, or the scenario. Of course, it also shows the importance of thermal conductivity and grey energy. However above 20 cm for materials with high specific grey energy, the total primary energy increases and hence has a negative impact on overall energy saving and reduction of carbon emissions. But our study shows that although mineral wool does not have the lowest thermal conductivity and hence not the lowest thermal transmittance, it leads to very interesting total primary energy use. Hence, the results indicate that including the primary grey energy in the analysis, when defining the type of insulation material is essential.

Scenario 2 is the so-called realistic scenario and represents the average case. The external wall defined in this scenario, with 10 cm of each insulation material, attained a thermal transmittance varying from 0.22 and 0.43 W/m^{2}K, reaching more than 90% of the possible primary energy savings. By increasing the thickness of the insulation to the optimal identified at around 20 cm, thermal transmittance of the external wall was improved to between 0.10 and 0.26 W/ m^{2}K, reaching the maximum possible savings. Hence, while the first 10 cm represented 90% of the possible primary energy savings, the second layer with the same thickness only contributed to around 10%. Therefore, a reasonable optimal thickness range is between 10 and 20 cm. Further studies on the optimum economic thickness should be conducted, including the cost of lost living space.

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