



# Life Cycle Environmental and Economic analysis of polyurethane insulation in low energy buildings

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## 1. Executive Summary

Environmental and cost performances are two of the main selection criteria for the specification of construction products. Along with social performance, they also represent the three pillars of sustainable development.

Policy makers, industry, NGO's and end-users agree on the need for the construction industry to move towards more sustainable building concepts and designs. The dividing question is how sustainability can be best assessed and which tools should be used to enable builders, specifiers, architects or policy makers to make more informed material choices.

Most experts recognise that the sustainability of construction products can only be assessed at the level of the functional unit, which is the building or, in certain cases, the building element. This approach is supported by CEN/TC 350 – the technical committee in charge of developing the European standards for the sustainability assessment of buildings.

Some still set performance requirements on building products or materials themselves, in the belief that sustainable buildings can be achieved by simply assembling so-called “green” products. This is the perspective used in the development of most eco-label and green public procurement criteria for construction products and in establishing ready-to-use guides to influence construction material choices. However, it can be demonstrated that this approach does not necessarily lead to the most sustainable solution in practice.

Over the past years, PU Europe commissioned two studies to quantify the overall environmental and economic costs of using polyurethane (PU) and other insulation materials in low energy building designs. The studies were conducted by the BRE, the UK’s Building Research Establishment (2010) and PriceWaterhouseCoopers – PWC (2013), respectively.

#### **The following conclusions can be drawn from the studies:**

- Insulation is a key contributor to sustainable construction.
- The selection of the insulation material cannot be disconnected from the specific building context. Setting environmental requirements or benchmarks at the product level or assessments based on one single indicator (embodied energy, bio-sourced) do not provide a guarantee for “greener” buildings.
- Insulation materials contribute only little to the building’s overall environmental burdens. In low energy buildings, operational energy consumption can still represent between 50% and 70% of total primary energy (see **Figure 1**).
- When compared to one another, the most common insulation materials show a very similar environmental performance when assessed at the building level over the whole life cycle.
- The choice of insulation materials should therefore first and foremost be based on their ability to provide highest energy performance at the building level and maintain specified performance levels over their whole life cycle.
- Wood fibre (WF) was intended to be included in both studies. In the BRE study, this material had to be omitted since no suitable LCI data were available in the public domain. For the PWC study, EPDs were taken from the German EPD scheme. However, these EPDs show a negative global warming potential for wood fibre insulation. This interpretation of the “carbon sink” function of wood-based products is not shared by many scientists and practices in other countries and makes it impossible to provide a clear picture of their environmental performance. The issue needs to be addressed in the revision of the TC350 standards.
- Thermal conductivity and, in some cases, product density are critical properties to consider in LCA and LCC assessments as they define the material intensity and knock-on effects on the building structure and, hence, its overall environmental and cost performance.

- Where specific mechanical properties need to be achieved, such as in a flat roof, the use of PU can lead to a significantly better environmental performance.
- PU insulation solutions in low energy buildings offer low life cycle costs and can be more cost-effective than other insulation solutions.
- Future research work should quantify the impact of larger building footprints due to thicker walls in terms of both environmental and cost performance.

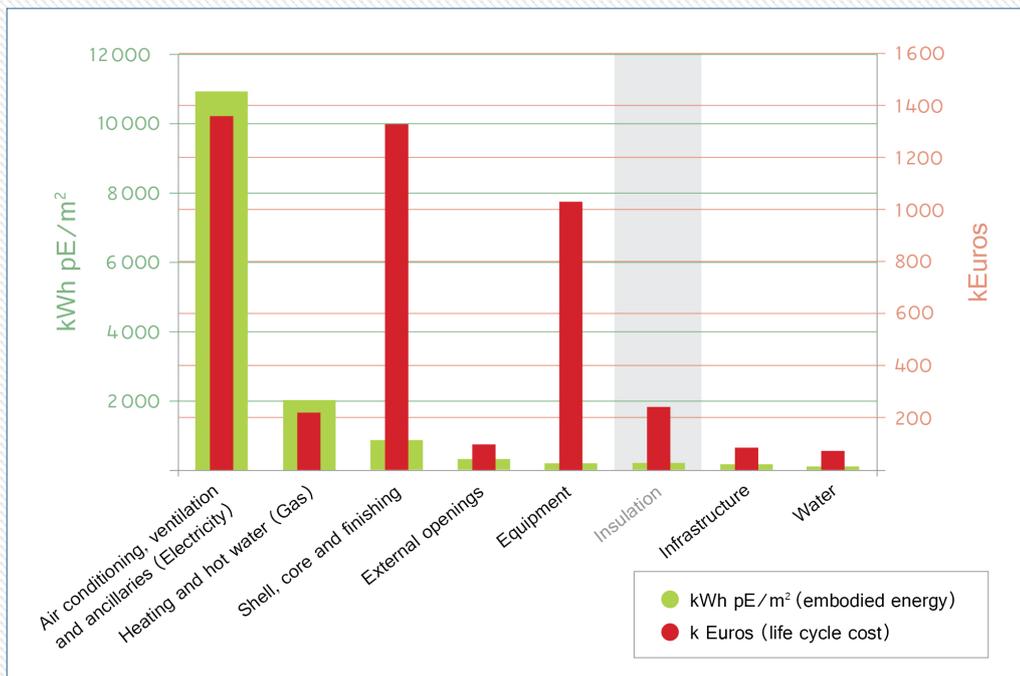


Figure 1: Total costs and primary energy cross-analysis of a large new commercial building, as modelled by PWC (impact over 50 years)

**Note:**

The two studies were conducted with a three-year interval. During that time, updated EPDs became available for most of the products covered by this research work. The absolute values calculated in the studies can therefore not be directly compared.

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## 2. What are LCA and LCC?

**Life Cycle Analysis (LCA)** is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle including the extraction of raw materials, manufacture, operation and eventual disposal of the different components. In this context, a building or assembled system is considered a “product” and a part of a “product system”. [1]

The LCA parts of the present studies were following CEN and ISO standards:

- EN 15643-1 Sustainability of construction works – Sustainability assessment of buildings – Part 1: General framework;

- EN 15643-2 Sustainability of construction works – Framework for the assessment of environmental performance;
- EN 15978 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method (PWC study) and ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines (BRE study);
- EN 15804 Environmental product declarations – Core rules for the product category of construction products (as far as possible).

The LCA work used a study period of 50 years in line with the life cycle costing part of the project. The results were presented as characterised and, partially, normalised data (annual impacts of a Western European citizen, covering the EU15 plus Norway and Switzerland) for the environmental impact categories of

• GWP	Global warming potential (kg CO <sub>2</sub> eq)	BRE/PWC studies
• ODP	Ozone depletion potential (kg CFC11 eq)*	only BRE study
• EP	Eutrophication potential (kg PO <sub>4</sub> )*	only BRE study
• AP	Acidification potential (kg SO <sub>2</sub> eq)	BRE/PWC studies
• POCP	Photochemical ozone creation potential (kg ethene eq)	BRE/PWC studies

\* Data not available for all products or significant discrepancies in background data

### Environmental flows:

• Input of non-renewable energy, primary energy (including feedstock) (MJ)	only PWC study
• Input of total primary energy (including feedstock) (MJ)	only PWC study
• Hazardous waste to final disposal (kg)	only PWC study
• Non-Hazardous waste to final disposal (kg)	only PWC study
• Radioactive waste to final disposal (kg)	only PWC study

**Life cycle costing (LCC)** is a technique to establish the total cost of ownership. It is a structured approach which addresses all the elements of this cost and can be used to produce a spend profile of the asset over its anticipated life span. For convenience, these costs are usually considered under three headings: initial cost, operational cost and disposal costs (if applicable).

The LCC analysis requires that year on year cash flows are discounted to reflect the time value of money. The time/present value is computed as follows:  $X/(1+r)^n$ . [2]

As regards the present studies, the specification for the elements and the cost of all components was intended to represent the typical cost incurred by building owners. The LCC results show the cumulative cost after 50 years service, at a 3.5% (BRE) and 4.0% discount rate (PWC), respectively.

The LCC of the first study used BRE's cost model, complying with BS/ISO 15686 Part 5 [3], which defines life cycle costs as the "Cost of an asset or its parts throughout its life cycle, while fulfilling performance requirements". The life cycle costs therefore allowed for normal maintenance and time expired components as appropriate.

The PWC study used EN 15643-4 "Framework for the assessment of economic performance" for the LCC calculations.

### Choosing the right order to achieve maximum results

- Although LCA and LCC are undoubtedly important considerations, the primary purpose of insulation is to make buildings more energy efficient. Hence, designers should first and foremost look at solutions that guarantee the lowest thermal conductivity of the building envelope, in order to minimise energy use and maximise CO<sub>2</sub> savings over the building's lifetime.
- Secondly, the building should be designed and its components chosen with a view to maintaining the thermal performance of this envelope over the building's life time. It is critical to reduce failure risk and choose a material fit for purpose with the right detailing. Particular attention should be paid to the material vapour permeability, moisture and condensation sensitivity, air movement and possible physical degradation.
- Thirdly, the life time cost performance for the whole component or building should be assessed in order to take into account any hidden and additional costs related to the insulation-specific installation requirements.
- It is only after these three key measures have been taken that the possible choices should be refined further by assessing the environmental credentials of the different design options at the building life cycle level.

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### 3. Why assess construction products at the building level?

At its simplest level, LCA is able to consider a whole basket of environmental impacts for a single building product. However, to make valid comparisons, designers need information about a whole building or building element, such as a wall, roof or floor. A building element is likely to be made up of several products. Eco-profiling takes this into account by adding together the contributions of all component parts.

Simply selecting products that each have a low environmental impact individually and putting them together does not necessarily give the optimum results for the building (element) as a whole. For example, an insulation product with a low environmental impact may also have a lower level of performance. In the case of a lower thermal performance, a higher thickness will be required to achieve the specified U-values. This, in turn, may lead to knock-on effects on the size and weight of the construction and the amount of other materials needed, increasing both the environmental and cost impacts of the construction as a whole. In other cases, a material with higher sensitivity to water ingress will require additional protective layers, such as a rain screen. The environmental impacts of this additional layer must be included in the LCA scope.

Density and thermal performance determine the weight of the insulation layer. Differences are substantial and lead to knock-on effects on the building structure. In certain applications and depending on the material selected, the weight of the heaviest insulation solution can be six or even ten times higher than that of the lightest solution for the same U-value of the building element.

Context therefore is vital, and having all of the relevant information allows specifiers to make valid comparisons between the environmental impacts of different design solutions in a practical and realistic way.



Figure 2: Thickness of different insulation and other materials at equal R-values

The Belgian federal government investigated the environmental impacts of ten insulation products (and materials) in different wall designs [4]. The results clearly show that higher embodied impacts in insulation products do not necessarily lead to higher impacts at the level of the building element. As a matter of example, **Figures 3** and **4** show the link between the impacts coming from insulation products, other building products and operational energy use for the impact categories "climate change" (GWP) and "eutrophication". The study covered a wide range of environmental indicators, which may be equally relevant. The letters "A" to "D" stand for different wall design solutions.

It should also be noted that the results are reflecting the performance of specific products and cannot be extrapolated to all insulation products produced by the manufacturers concerned or, more generally, made from the same material.

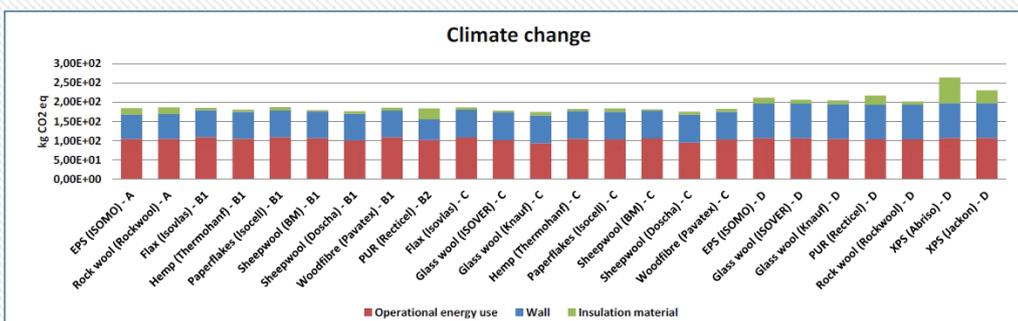


Figure 3: Comparison of the impact of the total wall in the category climate change

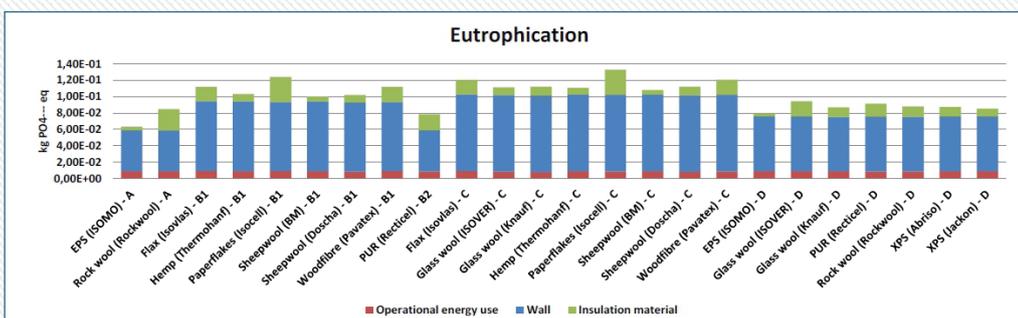


Figure 4: Comparison of the impact of the total wall in the category eutrophication

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## 4. Goals of the studies and model buildings

### Goals of the studies

The overall objective of the studies was to quantify the contribution of PU insulation to the environmental and economic performance of low energy buildings (building elements) and compare it to the use of alternative insulation materials used in the same applications. The environmental impacts from different insulation solutions were then compared to the use phase benefits, i.e. the energy consumption of the building over its life cycle.

Evidence was sought that setting environmental criteria at the product level or comparing insulation materials without knowing the exact building design requirements, does not lead to meaningful results.

The innovative element of the studies consisted in the fact that they went beyond comparisons of environmental impacts per weight unit or R-value. For the first time, a study also looked at the knock-on effects of material choices on the building itself (additional rafters, larger foundations and roofs, ancillary requirements, etc.). This is the reason why the impacts from construction materials differ for the various insulation solutions investigated per building element.

### Model buildings

The BRE designed the model building and the building components, determined the insulation solutions and construction material choices from its own data bases. PU Europe only defined the U-values for the building components based on typical low energy house levels.

The model building was a small detached house from the BRE Client Report *Standard Dwellings for Energy Modelling* (CR444/98) by Peter Iles. The total floor area of the two storey house was 104 m<sup>2</sup> with the heating system, lighting, etc. fixed, with only the insulation of the building fabric varying. This model building was also used for the second part of the PWC study.

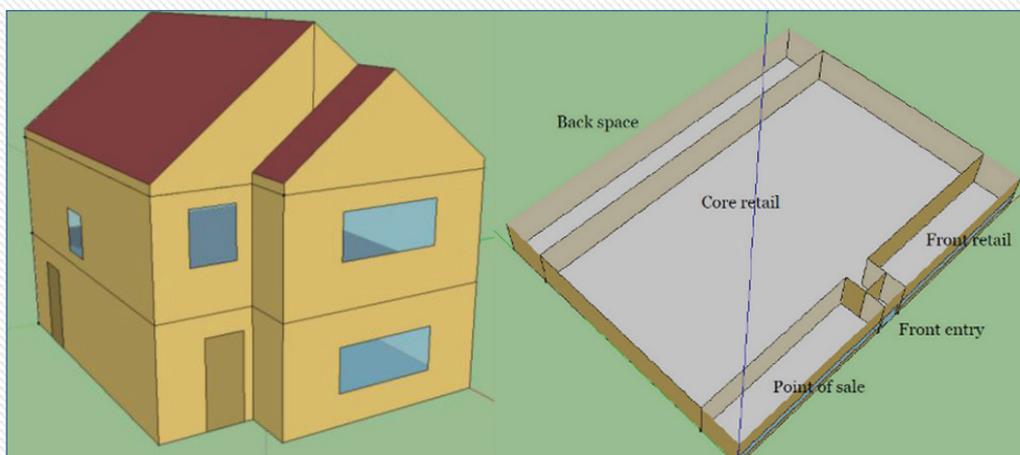


Figure 5: Residential and commercial reference buildings

In addition, PWC modelled a large stand-alone commercial building (retail). Due to the lack of reference commercial building models in Europe, the definition of the reference building is based on the work carried out by the U.S. Department of Energy.

Three climatic zones were covered: Mediterranean, Temperate Oceanic and Cool Continental. The modelled constructions were common and relevant for all climatic zones in the study. Whilst the BRE study used similar U-values for all climatic zones, PWC applied U-values depending on the climatic conditions of each region.

### Calculation of energy emissions for space heating and cooling

The energy used for space heating was calculated using a version of BRESAP amended for the different external climatic zones. The energy source was natural gas.

In the case of the BRE study, there was of course a clear difference in energy consumption for space heating between each of the three external climates. For example, using the Temperate Oceanic zone as the base consumption, the consumption for heating in Cool Continental new builds was 140% higher.

The heating and cooling demand of the large commercial building investigated by PWC was using data from the U.S. Department of Energy with some minor adjustments.

The BRE study consisted of three parts:

- Part 1: impact of insulation in new build from a total building perspective
- Part 2: impact of insulation in renovation when thickness is restricted
- Part 3: impact of insulation in new build warm deck flat roofs

The PWC study consisted of two parts:

- Part A: impact of insulation in a new large commercial building
- Part B: impact of insulation in the renovation of a typical pitched roof in a dwelling

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## 5. Results of the studies

### 5.1 Case study 1: Residential building – Whole new construction

#### **BRE Part 1: Impact of insulation in new build from a total building perspective – impact of thermal conductivity**

In the first case study, the whole new building – a three-bedroom double-storey detached house – was analysed. The U-values for the different building components were fixed as follows:

- Pitched roof: 0.13 W/m<sup>2</sup>·K
- Cavity wall: 0.15 W/m<sup>2</sup>·K
- Ground floor: 0.18 W/m<sup>2</sup>·K
- Windows: 2.10 W/m<sup>2</sup>·K

Heat loss associated with the thermal bridging:  $\gamma$ -value = 0.08 W/m<sup>2</sup>·K.

The objective was to assess the performance of each design, using different insulation solutions based on PU, stone wool and glass wool. Because of their different thermal conductivity levels, they have been used at different thicknesses to achieve the same U-values. In fact, to achieve a U-value of 0.15 W/m<sup>2</sup>·K for the cavity wall, 180 mm of PU insulation were sufficient, whereas the glass wool and stone wool solutions required a 270 mm insulation layer. The pitched roof solutions used 190 mm of PU, 300 mm of glass wool and 310 mm of stone wool.

Insulation Application	PU		SW Solution		GW Solution	
	Cavity wall	Pitched roof	Cavity wall	Pitched roof	Cavity wall	Pitched roof
Thickness <i>mm</i>	180	90 between rafters 100 on rafters	270	220 between rafters 90 on rafters	270	300 between rafters
Density <i>kg/m<sup>3</sup></i>	32	32	39	45 between rafters 145 on rafters	17	17
Weight <i>kg/m<sup>2</sup></i>	5.76	5.76	10.53	22.95	4.59	4.59
Lambda <i>W/mK</i>	0.022	0.023	0.037	0.038	0.032	0.037
U-value <i>W/m<sup>2</sup>K</i>	0.15	0.13	0.15	0.13	0.15	0.13

Since the internal living surface area and volume had to be maintained constant, the building design had to be adapted to fit the differences in component thickness (**Figure 6**).

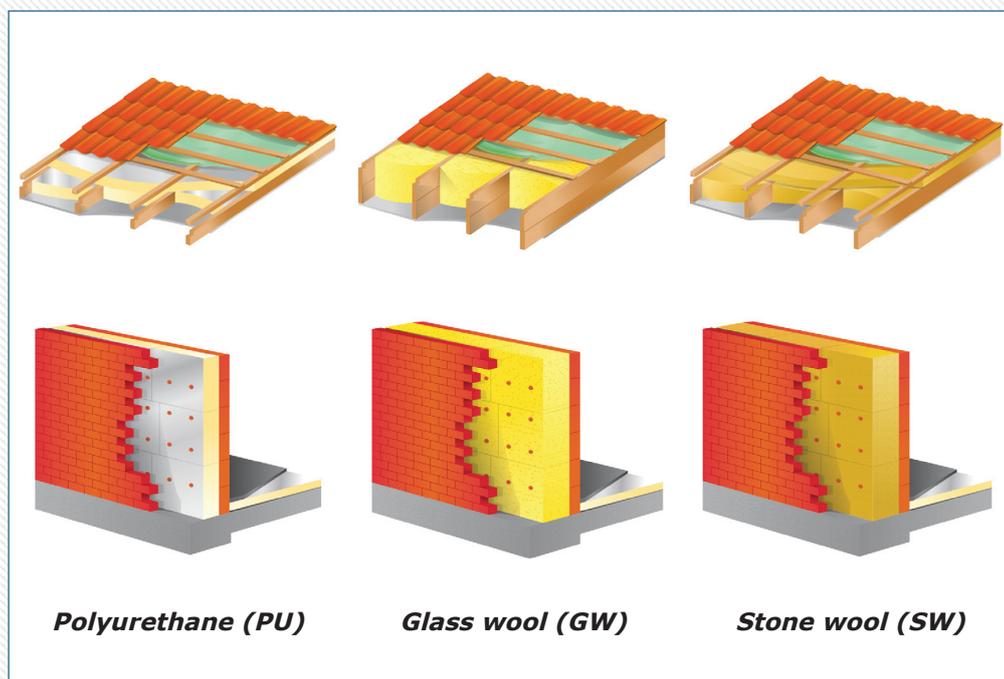


Figure 6: Design solutions for the pitched roof and cavity wall insulation reflecting real thickness ratios of the insulation layer

### Life Cycle Analysis

**Figure 7** shows the normalised environmental impact for the selected five indicators (GWP, AP, POCP, EP and ODP) for the PU, glass wool and stone wool insulation solutions.

Normalised data provide a comparison of the relative size of each environmental impact

category. The results exclude the environmental impact contribution from the energy consumed in the buildings use phase, as it is the same in all three design solutions.

Figure 7: Whole building – Normalised environmental impacts per impact category (temperate oceanic climate)

The spider web clearly shows that, at the building level, there are no significant differences in performance levels. The results were similar for all three climatic zones.

It should be noted that, in all three cases, the ground floor was insulated with PU at a constant U-value of 0.18 W/m<sup>2</sup>·K. A separate chapter looked at EPS as an alternative to PU in the ground floor and the same conclusion could be drawn: there is no noteworthy difference in the environmental performance of the two materials.

The study also allows a comparison of the environmental impacts embodied in the construction and insulation materials with the energy use of the building in the three climatic zones (Figure 8).

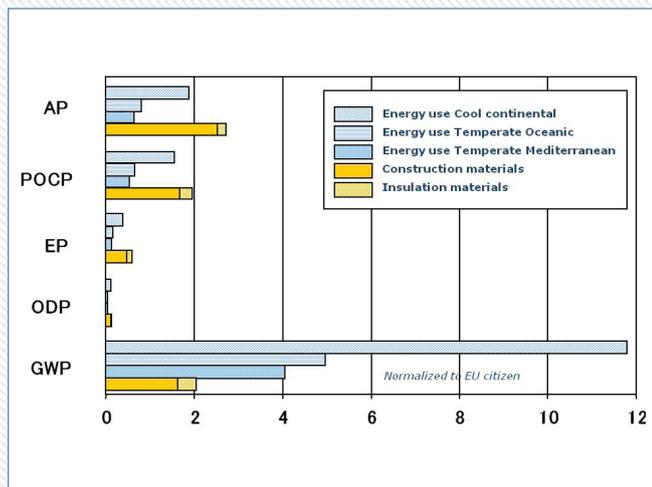
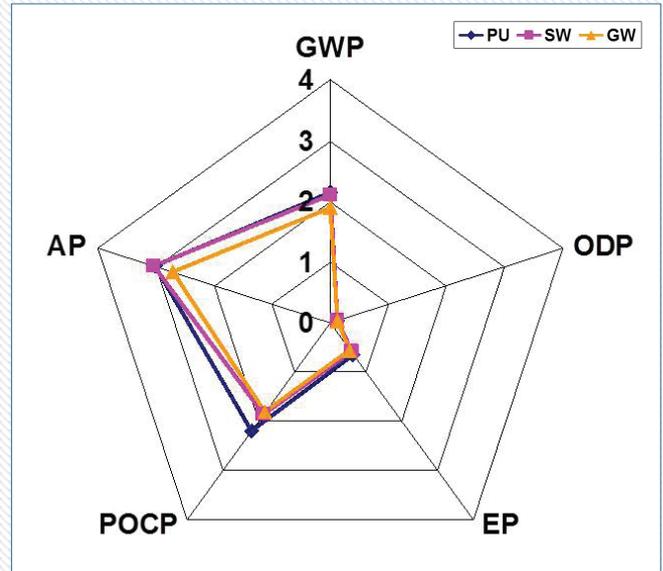


Figure 8: Normalised data – Energy use, construction materials and insulation (the impact of construction and insulation materials is an average of the three design solutions)

Figure 8 shows that the construction and insulation materials of the modelled house accounted for only around one third of the total GWP, with about two thirds stemming from the building’s energy use. This is somewhat contradicting statements that, in low energy designs, the environmental impacts of construction materials would exceed those of the building’s use phase.

On the other hand, the total AP, POCP and EP of the construction and insulation materials were higher than that caused by the energy use of the building.

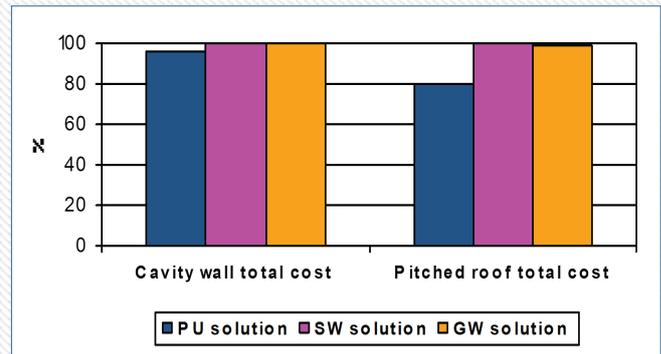
Another important conclusion is that the share of insulation materials in the total environmental impact of a building is very small.

Figure 9: LCC of the cavity wall and pitched roof solutions for temperate oceanic climate (50 years cumulated costs, 3.5% discount rate)

### Life Cycle Costs

The LCC analysis of the wall element and the roof element showed that, for all climatic zones and in each case, the PU solution was more cost-effective over the 50 year life cycle of the building element. Particularly, the PU pitched roof turned out 20% cheaper (**Figure 9**). The ground floor was not investigated as PU was used in all cases.

The higher overall costs for the glass wool and stone wool solutions can be explained by different insulation quantities needed to achieve the required U-values and the knock-on effects of the insulation thickness on the building itself. More external brick wall, longer wall ties and a larger foundation were required in the case of the cavity wall. The pitched roof results were affected by the need for deeper rafters and a larger roof covering surface area.



**Did you know** that one effect of a deeper new wall cavity is the additional footprint area required for roof and floor? On a large building site this may affect the density or number of properties that could be built on the site, e.g. in the worst case, 4.00 m<sup>2</sup> extra on the roof area for each property may mean that only 9 properties could be fitted in an area that may be able to accommodate 10 if the external walls were thinner. The potential cost and environmental impact of this was not taken into account in the current study and could present an area for further research.

### Conclusions for BRE Part 1:

- **LCA**

The analysis showed that, at the building level, all insulation solutions considered show a very similar overall environmental performance. It could also be demonstrated that the contribution of the insulation material to the overall environmental burden of the building is very limited. Even in low energy buildings, the energy consumed in the building's use phase has a far higher global warming contribution than the construction and insulation materials. On the other hand, the AP, EP and POCP of the materials exceed those caused by the energy use of the building.

- **LCC**

For all design solutions covered by the BRE study, PU showed the lowest life cycle cost. Whereas this result cannot be simply extended to all possible building design solutions, it is an indicator of the PU cost competitiveness.

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## 5.2 Case study 2: Residential building – Renovation of a pitched roof

### PWC Part B: Impact of insulation in the renovation of a typical pitched roof of a dwelling

PWC used that same model of a small detached house to simulate the renovation of its pitched roof. The roof was already insulated with 8cm of old stone wool between the rafters. The renovation measure led to a decrease of 14% in heating energy consumption.

All other building elements and equipment remained unchanged. The existing walls and slab were considered as not well insulated causing a high level of air infiltration. This resulted in further heat losses and highlighted the need for a global approach and deep renovation.

- U-value of the existing roof:  
0.52 W/m<sup>2</sup>·K
- U-value of the renovated roof:  
0.16 W/m<sup>2</sup>·K

It is important to note that the PWC study modelled the pitched roof design according to installation solutions promoted by the different insulation materials (see below).

	PU solution	WF Solution	SW Solution	GW Solution
Total thickness <i>mm</i>	100	225	235	200
Density <i>kg/m<sup>3</sup></i>	32	55 between rafters 140 on rafters	70 between rafters 165 on rafters	28
Lambda <i>W/mK</i>	0.023	0.038 between rafters 0.042 on rafters	0.036 between rafters 0.040 on rafters	0.036
U-value <i>W/m<sup>2</sup>K</i>	0.16	0.16	0.16	0.16
Installation	Placed on rafters (existing insulation layer – 80 mm SW – between rafters can stay in place)	Placed between (125 mm) and above the rafters (180 mm): existing insulation layer between rafters removed and fully filled with WF	Placed between (100 mm) and above the rafters (135 mm): existing insulation layer between rafters removed and fully filled with SW	Placed between rafters (100 mm) and under the rafters (100 mm): existing insulation layer between rafters removed and fully filled with GW and aluminium structure added perpendicular to rafters for additional GW layer

### Life Cycle Analysis

As shown in **Figure 10**, the environmental impacts of the different insulation solutions over the building component life cycle are relatively similar with all indicators within a 10% deviation. The choice of the insulation material is therefore of secondary importance when assessing the environmental performance of this pitched roof.

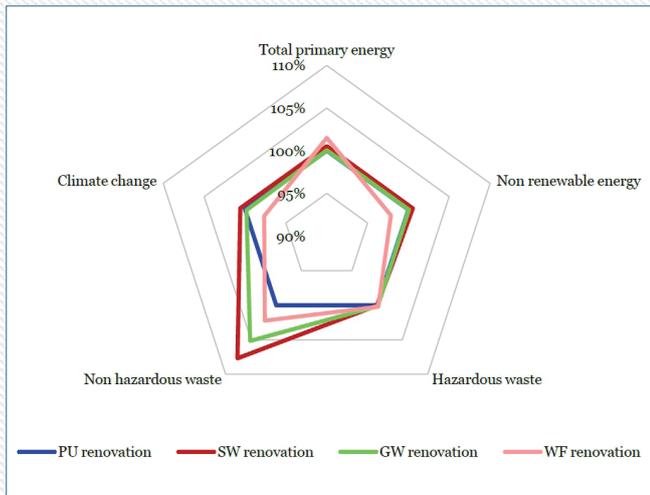
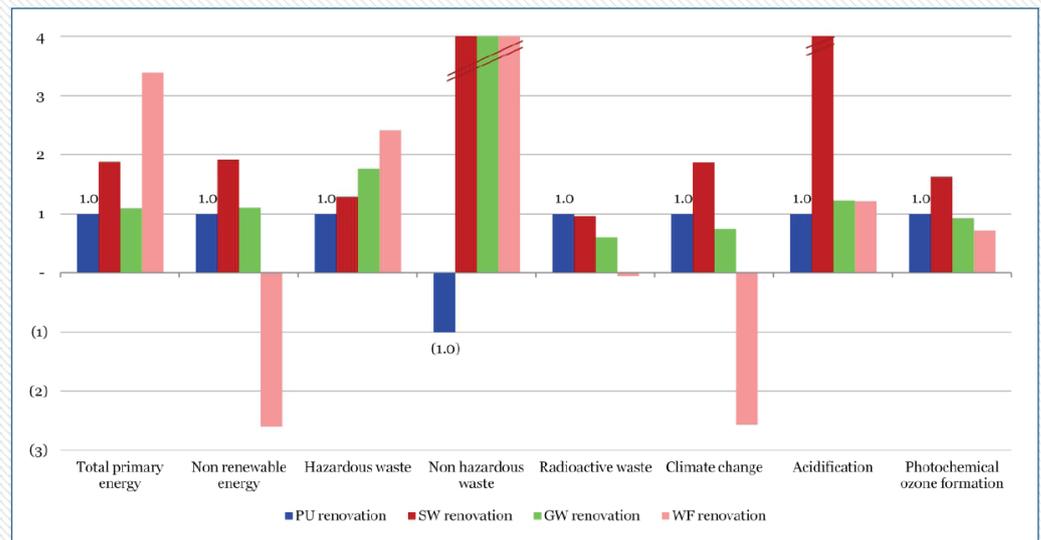


Figure 10: Relative results on the whole study period (PU scenario being 100%)

A look at the direct embodied impacts of the renovated roof shows a good performance of the PU solution in practically all impact categories (see **Figure 11**). This is mainly due to the high thermal performance of PU, the reduced need for ancillary materials and fact that the PU solution allows keeping the existing insulation layer in place. Other solutions need to fill the space between the rafters with new insulation to meet the U-value requirements.

Another observation is the negative global warming potential of the wood fibre solution. This interpretation of the wood's "carbon sink" function was so far common in Germany and only German EPDs were available for these products. The assumptions are however contested by many scientists and practitioners in other countries [5]. EN 16485, Product category rules for wood and wood-based products for use in construction, specifies that biogenic CO<sub>2</sub> should be considered an intrinsic product property provided the wood harvesting process does not affect the forest carbon pool property (i.e. deforestation). Also, the standard reminds us that biogenic CO<sub>2</sub> is only temporarily "captured in wood" and will be released at end of life, with a net balance of biogenic CO<sub>2</sub> becoming ultimately neutral. When taking into the carbon impact of all related forestry processes and wood treatment, the intrinsic GWP of wood should not show negative values.

Figure 11: Relative results for roof renovation components (PU scenario being 100%)



### Life Cycle Costs

As shown in **Figure 12**, the glass wool solution is about 28%, the stone wool solution 41% and the wood fibre solution 54% more expensive than the PU solution. The reasons for the lower costs are similar to those mentioned under the LCA heading: high thermal performance of PU, reduced need for ancillary materials and existing insulation layer can stay in place.

Figure 12: Refurbishment costs of the pitched roof – components

Looking at the whole life cycle, the additional cost for improving the roof insulation is very low (1% of life cycle costs) whatever the insulant used, whereas savings are significant. The construction costs of the whole building (32%) and the use phase energy costs (26%) dominate overall costs (see **Figure 13**).

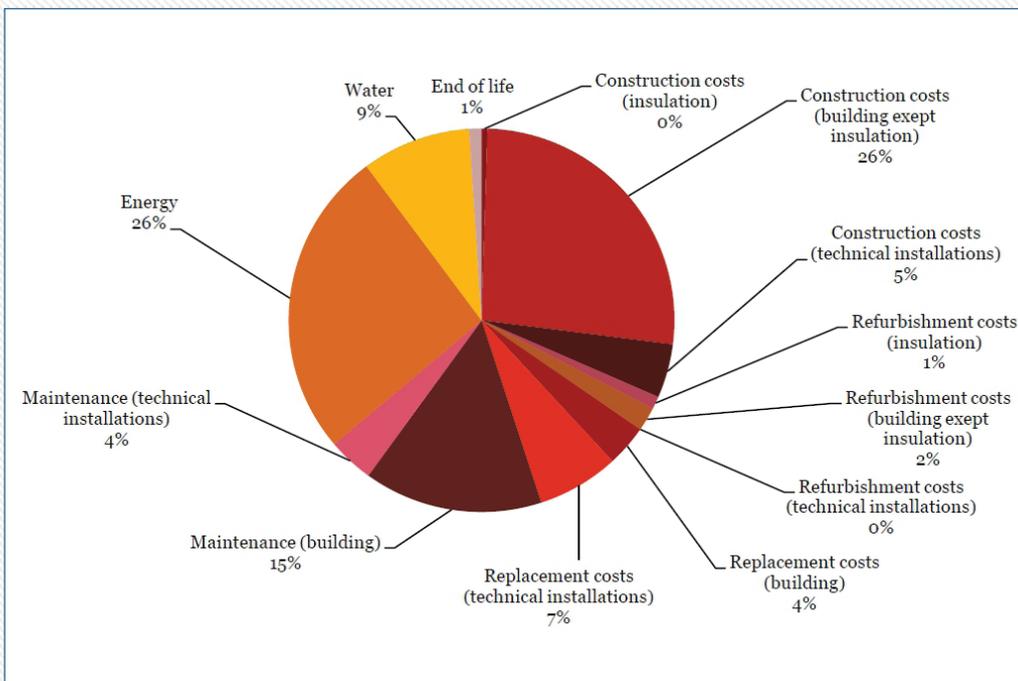
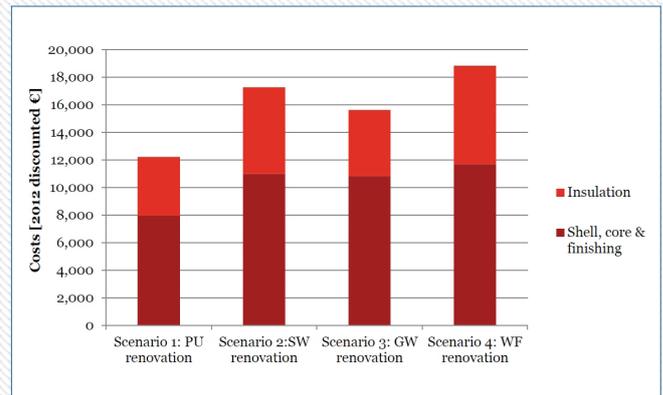


Figure 13: Life cycle cost breakdown for the residential building

**Conclusions for PWC Part B:**

- LCA**  
 Again, the analysis showed that, at the building level, all insulation solutions considered show a very similar overall environmental performance over the component life cycle. Each insulation solution has different “strong” and “weak” impact categories. This emphasises the need to declare all indicators instead of merging them into one overall score.
- LCC**  
 PU showed the lowest life cycle cost for this pitched roof renovation, Again, these conclusions should not be generalised as all producers offer different refurbishment solutions. It is also noteworthy that the additional cost of the insulation forms a negligible part of life cycle costs.

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### 5.3 Case study 3: Residential building – Flat roof

#### BRE Part 3: New build warm deck flat roof – Impact of specific technical requirements

For Part 3 of the BRE study, the roof of the modelled house was replaced with a flat roof with a U-value of  $0.15 \text{ W/m}^2 \cdot \text{K}$  (**Figure 14**). Energy consumption in the building's use phase was not taken into account as it was assumed to be the same for all solutions.

Insulation materials used in flat roofs, and especially in those with foot traffic, must offer additional mechanical properties such as sufficient compressive strength, walkability properties and adequate density. This can affect the overall environmental performance of a particular material.

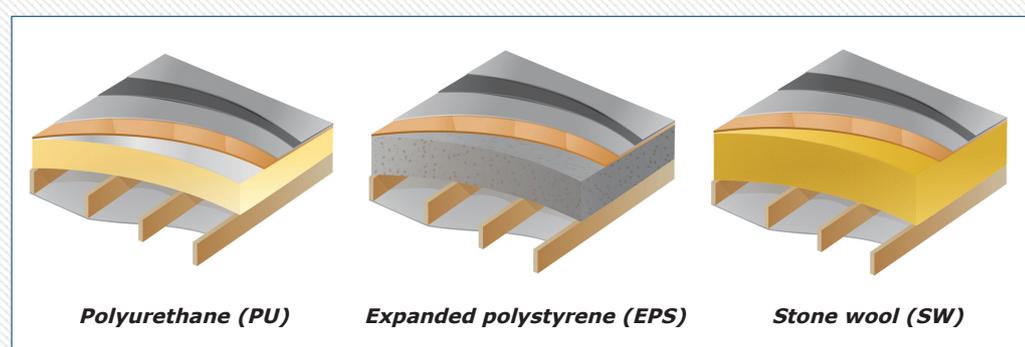


Figure 14: Design solutions for the flat roof insulation reflecting real thickness ratios of the insulation layer

Based on the U-value to be achieved and the thermal conductivity levels of the insulation materials, the BRE proposed the following typical flat roof design solutions:

Insulation	PU	EPS	SW
Density $\text{kg/m}^3$	32	30	130
Thermal conductivity $\text{W/mK}$	0.023	0.034	0.038
Thickness $\text{mm}$	150	220	255
Roof surface $\text{m}^2$	64	64	64
Weight $\text{kg}$	307	422	2121

#### Life Cycle Analysis

Unlike parts 1 and 2, the analysis of the flat roof shows more significant differences between the material solutions (**Figure 15**). The PU solution showed a 26% lower GWP than the stone wool solution. The POCP of the PU solution was 30% lower than that of EPS and the AP 57% lower than that of stone wool.

The significant differences can be explained by the fact that PU can deliver high mechanical performance at low density and low thickness, thus reducing material intensity. Indeed, the  $64 \text{ m}^2$  flat roof analysed in this study required 307kg PU, but 2121kg SW.

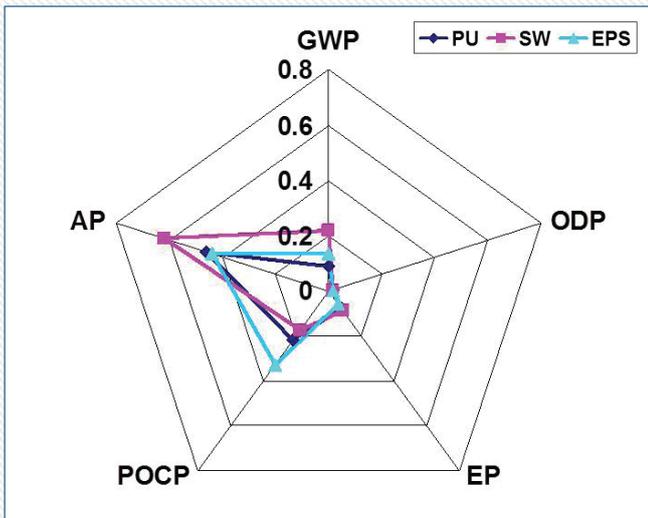
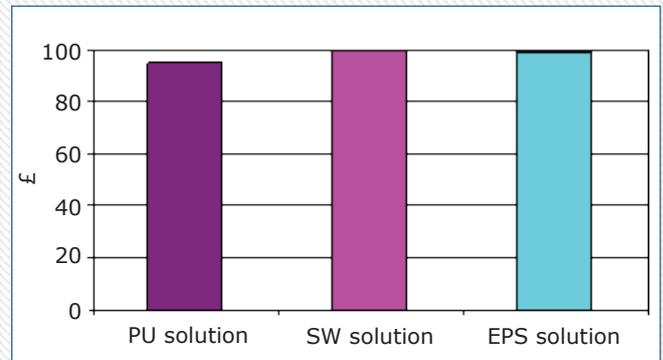


Figure 15: Flat roof – Normalised environmental impacts per impact category (roofing material and insulation)

### Life Cycle Costs

The results for Part 3 indicated that 150 mm polyurethane has the lowest life cycle cost (-5%) when used in all regions, followed by 220mm expanded polystyrene and 255mm stone wool insulation (see Figure 16).

Figure 16: LCC of the cavity wall and pitched roof solutions (50 years cumulated costs, 3.5% discount rate)



### Conclusions for BRE Part 3:

- LCA**  
 Where specific mechanical properties need to be achieved, the use of PU with its low density and low thickness can lead to significant environmental gains.
- LCC**  
 The PU solution showed the lowest life cycle cost. The differences are however too small to be generalised.

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## 5.4 Case study 4: Commercial building – whole new construction

### PWC Part A: Impact of insulation on new build – new large commercial building

This part of the study covered a new retail building of 2300m<sup>2</sup> featuring sandwich panel walls and an insulated steel deck roof. The U-values differ between climatic zones, but are a similar for all insulation solutions per climatic zone (see table). The functional equivalent was defined as the internal surface.

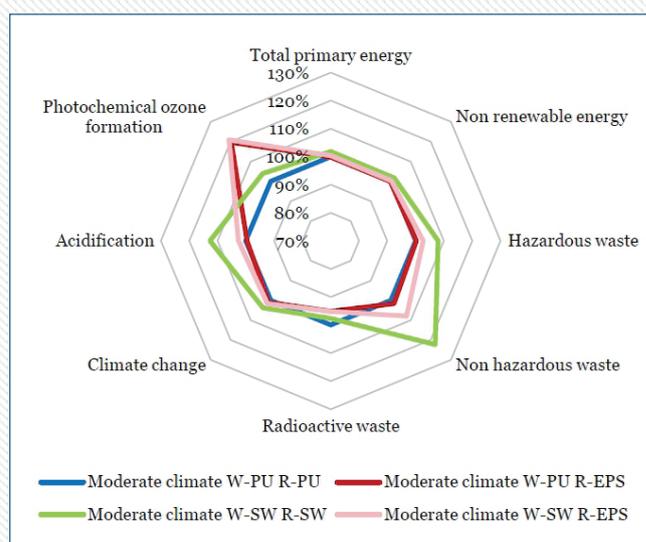
**U-values per climatic zone and building element**

	Insulation material	Density [kg/m <sup>3</sup> ]	Weight of insulation layer (t)	Weight of steel structure (sheet and beams) (t)	Lambda [W/mK]	Real Width [m]	U-value [W/m <sup>2</sup> K]
<b>External walls</b>							
Cold continental	PU	40			0.022	0.130	0.170
	SW	110			0.040	0.240	0.170
Moderate	PU	40			0.022	0.130	0.170
	SW	110			0.040	0.240	0.170
Mediterranean	PU	40			0.022	0.100	0.230
	SW	110			0.040	0.170	0.230
<b>Flat roof</b>							
Cold continental	PU	32	24	172	0.023	0.330	0.069
	SW	150	197	185	0.040	0.570	0.069
	EPS	25			0.035	0.500	0.069
Moderate	PU	32	10.7	126	0.023	0.145	0.155
	SW	150	86.6	141	0.040	0.250	0.156
	EPS	25			0.035	0.220	0.156
Mediterranean	PU	32	9.6	126	0.023	0.130	0.173
	SW	150	76.2	141	0.040	0.220	0.177
	EPS	25			0.035	0.195	0.175

Figure 17: Relative performance on the whole study period for the whole building (W-PU, R-PU scenario being 100%)

**Life Cycle Analysis**

The analysis over the whole building life cycle showed a similar performance of all design options for a number of performance indicators. More significant differences emerged for acidification and even more so for POCP and non-hazardous waste quantities. For the latter two indicators, the burdens from the worst performing option are more than 20% higher than those of the best performer. The PU solution offers favourable performance levels for all categories (see **Figure 17**).



The analysis of the embodied impacts of the individual building elements shows some more visible differences between the insulation solutions. As regards the roof, the PU and EPS solutions have very similar impact levels. Only the POCP is substantially higher for EPS. The stone wool solutions show significantly higher acidification and non-hazardous waste levels.

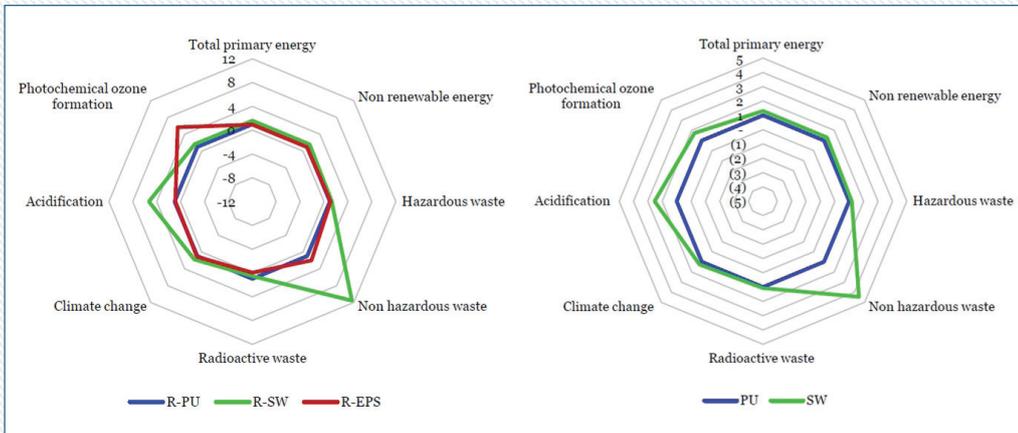


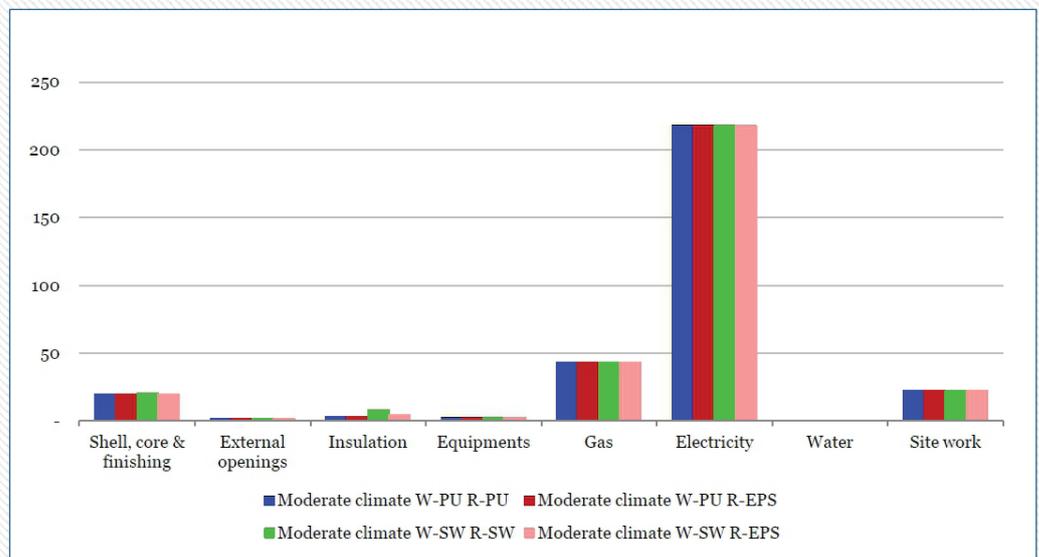
Figure 18: Relative results for the flat roof and the wall (moderate climate, PU solution being 1.00)

Finally, it is interesting to look at the impact of the different insulation solutions on the overall building throughout its life cycle. **Figure 19** shows that impacts from the building construction are about eight times lower than those due to the energy consumption in the use phase. The impact of the insulation is at least 30 times lower than that from the energy consumption, and this independently from the insulant used. The consumption of primary energy due to the insulation ranges from only 1% to 2.7% of the impact of the building on the whole study period. The ratio does not differ much from one climatic zone to the other.

Equally, the impacts on climate change due to the insulation vary between only 1.5% and 4.1% of the building’s impacts and are at least 20 times lower than the impacts due to the use phase energy consumption.

This clearly proves that even in low energy commercial buildings, use phase impacts by far outweigh impacts embodied in construction/insulation products.

Figure 19: Breakdown of total primary energy for the whole building life cycle (construction, use, demolition)

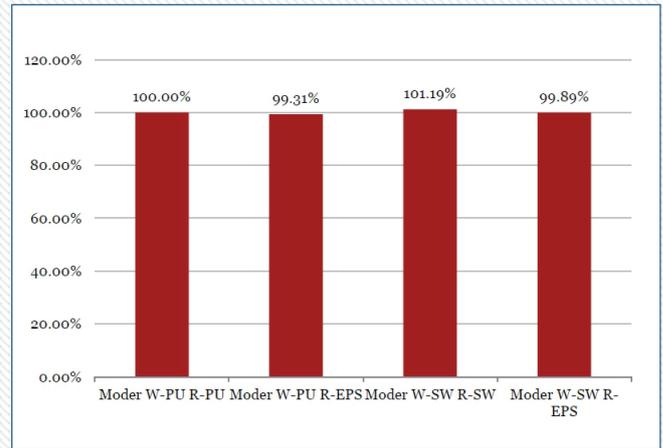


**Did you know** that the choice of the insulation material can have a substantial impact on the overall building footprint or the available internal floor area? In particular the latter affects the life cycle costs through income from rent. The impact can be shown when changing the functional equivalent from the internal surface to the external building footprint. In the case of the commercial building of 2 300 m<sup>2</sup>, the PU wall solution would have offered 24m<sup>2</sup> of additional surface area and 674m<sup>3</sup> of additional volume when compared to the other solutions. If an annual rent of € 300 per year and m<sup>2</sup> is assumed, the additional income thanks to the PU insulation over a 50 year life cycle would sum up to € 360 000.

Figure 20: Relative life cycle costs for the whole building (PU/PU solution being 100%)

**Life Cycle Costs**

Total life cycle costs for the whole building are very similar for all scenarios (see **Figure 20**). This is mainly due to the fact that the cost of insulation accounts for only 5% of life cycle cost, while 31% of LCC can be attributed to use stage energy consumption.



The analysis of the initial construction costs shows that the solution using stone wool in the flat roof and the sandwich panels would be most expensive whereas the combination of PU sandwich panels and an EPS flat roof would be least expensive. Apart from the stone wool solution, the differences are however small and do not allow a clear ranking. The graph in **Figure 21** also shows higher costs for the steel frame if a high density insulant is used for the roof.

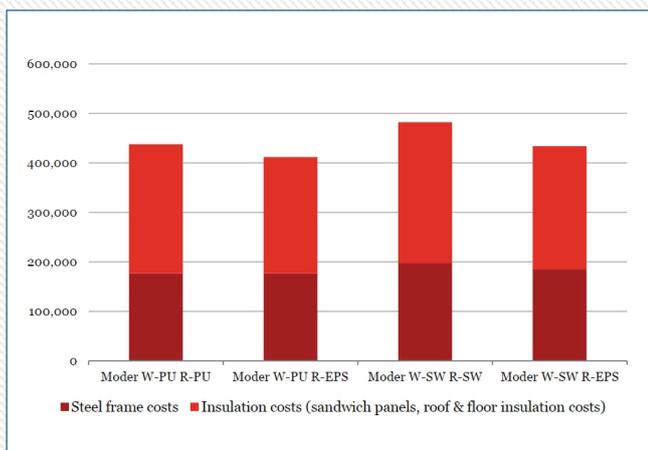


Figure 21: Construction costs (steel frame, sandwich panels and roof insulation)

**Did you know** that the choice of the insulation material can have knock-on effects on the whole building structure? Taking the same building as an example, the steel structure of the steel deck flat roof can be about 15t lighter in moderate and Mediterranean climates when the PU solution is used rather than the heaviest solution. The difference is 13t for the cold climate. This gain of about 10% is due to the fact that the insulation layer of the PU roof weighs only 10.7t compared to 86.7t for the heaviest insulation layer (moderate climate).

**Conclusions for PWC Part A:**

- **LCA**

As in the previous chapter, this example emphasises the impact of insulation product density on the environmental performance of flat roofs and sandwich panels. The low density and high thermal performance of PU allow for the use of a lighter flat roof steel structure.

- **LCC**

The life cycle costs are more or less similar for all design solutions. The stone wool solution is most expensive which can be partially explained by the stronger steel frame required to support the weight of the insulant.

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## 5.5 Case study 5: Residential building – Renovation of external wall with internal lining

### BRE Part 2: Impact of insulation on existing build – Impact of thickness restriction

For this part, a typical renovation case was examined. The way considered to insulate the existing wall, was to add insulation to the internal face of external walls (internal lining) and it was assumed that the building owners/users did not want to lose valuable internal space. Therefore, the thickness of the insulation layer was restricted to 50 mm. In total, a wall surface of 134m<sup>2</sup> had to be insulated for the modelled house.

The thickness restriction resulted in different U-values for the different design solutions based on the insulation materials covered. This in turn led to different energy consumption levels in the building use phase with the PU solution offering the highest energy savings.

	PU solution	EPS Solution	SW Solution	GW Solution
Thickness <i>mm</i>	50	50	50	50
Density <i>kg/m<sup>3</sup></i>	32	30	39	24
Lambda <i>W/mK</i>	0.023	0.034	0.037	0.036
U-value <i>W/m<sup>2</sup>K</i>	0.36	0.47	0.54	0.54
Wall surface <i>m<sup>2</sup></i>	134	134	134	134

The overall efficiency of the model building was lower than the new building considered in part 1 with the following U-values used:

- Pitched roof: 0.40 W/m<sup>2</sup>·K
- Ground floor 0.67 W/m<sup>2</sup>·K
- Windows: 2.7 W/m<sup>2</sup>·K

Heat loss associated with the thermal bridging:  $\gamma$ -value = 0.15 W/m<sup>2</sup>·K.

The BRE proposed two different installation techniques in the modelling, representative of the common practice when using the different insulation materials. The installation materials used are adhesive plaster for PU and EPS, and a timber structure for glass wool and stone wool (see **Figure 22**).

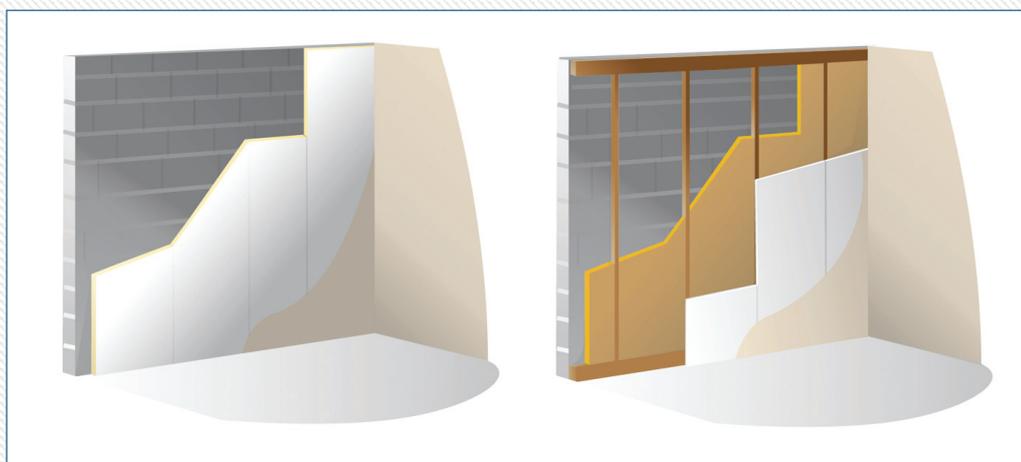


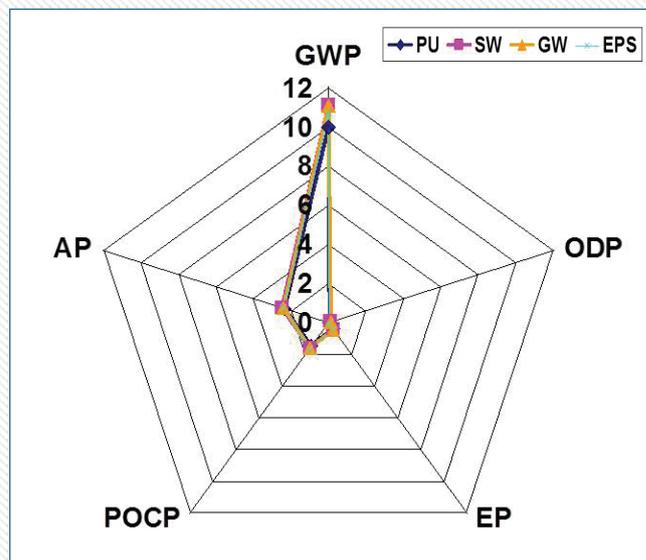
Figure 22: Installation techniques used for PU and EPS (left) and glass wool and stone wool (right)

Figure 23: Internal lining – Normalised environmental impacts per impact category (temperate oceanic climate)

**Life Cycle Analysis**

The LCA looked not only at the environmental impacts of the construction/insulation materials but also at the impacts caused by the energy consumption during the building’s use phase. This was necessary, as different insulation solutions resulted in different U-values and, hence, different energy use levels.

For all three climatic zones, the analysis again showed a similar overall environmental impact for all design solutions covered (see **Figure 23**).



The study also looked into the contribution of the energy use, the internal lining materials and the insulation separately, measured them against each environmental indicator and expressed the results as characterised data, i.e. as a percentage of the maximum value in each impact category (**Figure 24**). The following conclusions can be drawn:

- Looking at the overall results, the differences between the various solutions in any of the impact categories are not relevant. The most important variation can be found in the global warming contributions, which is about 9 % lower for the PU solution when compared to the worst performer. From an LCA point of view, this variation is however not significant.
- With the exception of the acidification potential (AP), the internal lining installation materials have a low to negligible contribution to the total impact of the building component. The environmental impact of the insulation materials is negligible in all impact categories.
- The enlarged part of **Figure 24** demonstrates that, while the PU solution has a high environmental impact for some indicators, the overall PU solution turns out to have a similar or slightly lower impact than the other solutions. In fact, this is because the greater energy saving achieved by PU offsets its higher environmental impact. This is a good example showing as to why the insulation material selection cannot be disconnected from the building life cycle context.

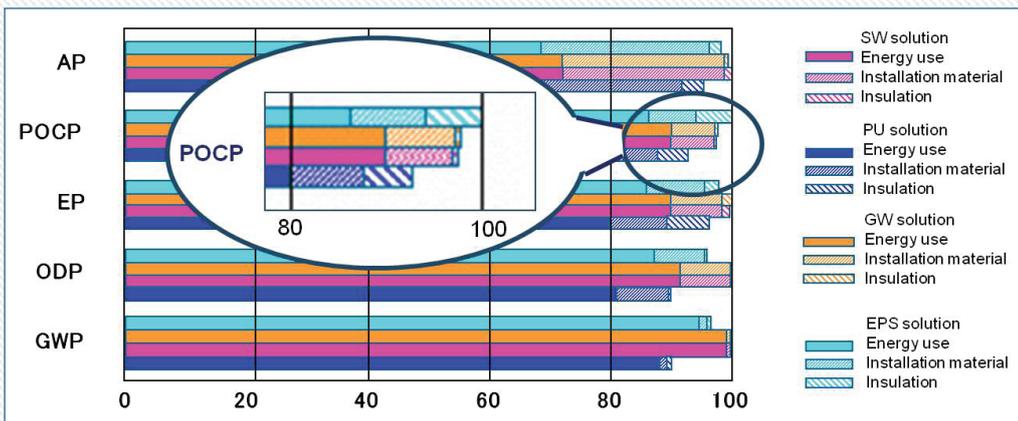
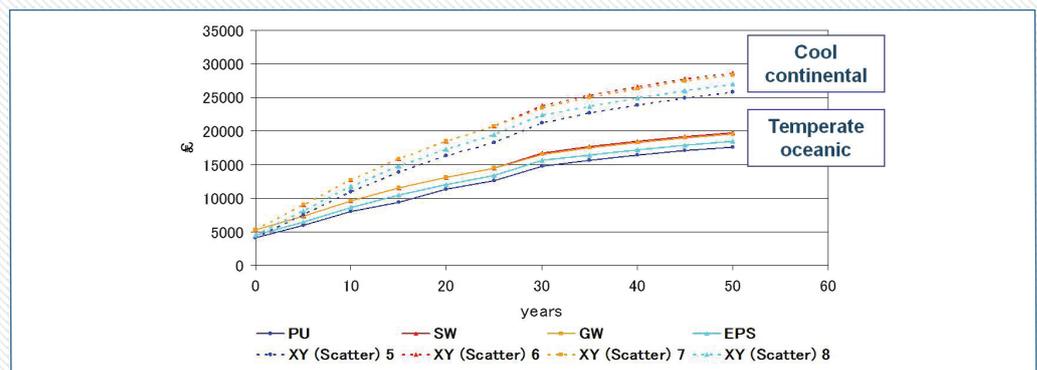


Figure 24: LCA results expressed as characterised data (relative to maximum value in each impact category) – Analysis of energy and material contribution (temperate oceanic climate)

### Life Cycle Costs

The LCC analysis of the internal wall insulation showed similar results for all three climatic zones. On average, over the 50 year life cycle, the EPS solution was 8% and the mineral wool solution 11% more expensive than the PU solution (**Figure 25**). The higher PU cost effectiveness can be explained by the higher energy savings achieved throughout the building’s use phase.

Figure 25: LCC of the internal lining solutions for two climatic zones (50 years cumulated costs, 3.5% discount rate)



**Conclusions for BRE Part 2:**• **LCA**

The analysis showed that, at the building level, all insulation solutions considered show a very similar overall environmental performance. The greater energy savings achieved with the PU solution more than offset the higher impact of the PU material itself for all impact indicators.

• **LCC**

For all design solutions covered by this chapter, PU showed slightly lower life cycle costs. The differences are too small to be generalised.

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**6. Conclusions**

Although defined by independent third parties and based on commonly used design solutions, these studies cannot reflect all possible architectural and material choices. The results can therefore not be automatically extended to all buildings. However, the studies do provide some very valuable conclusions which could be used in further research work:

- Insulation is a key contributor to sustainable construction.
- The selection of the insulation material cannot be disconnected from the specific building context.
- Insulation materials contribute only little to the building's overall environmental impacts – even in the case of low energy buildings. When compared to one another, the most common insulation materials show a very similar environmental performance when assessed at the building level over the whole life cycle.
- The choice of insulation materials should therefore first and foremost be based on their ability to provide highest energy performance at the building level and maintain specified performance levels over their whole life cycle.
- Wood fibre was intended to be included in both studies. In the BRE study, this material had to be omitted as no suitable LCI data were available in the public domain. For the PWC study, EPDs were taken from the German EPD scheme. However, these EPDs show a negative global warming potential for wood fibre insulation. This interpretation of the "carbon sink" function of wood-based products is not shared by many scientists and practices in other countries. The issue needs to be addressed in the revision of the TC350 standards.
- Thermal conductivity and, in some cases, insulation density are critical properties to consider in LCA and LCC assessments as they define the material intensity and knock-on effects on the building structure and, hence, its overall environmental and cost performance.
- Where specific mechanical properties need to be achieved, such as in a flat roof, the use of polyurethane can lead to a significantly better environmental performance.

- PU insulation solutions in low energy buildings offer low life cycle costs and can be more cost-effective than other insulation solutions.
- Future research work should quantify the impact of larger building footprints due to thicker walls in terms of both environmental and cost performance.

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## 7. Glossary

<b>AP</b>	Acidification potential		potential
<b>EP</b>	Eutrophication potential	<b>R-EPS</b>	Flat roof with EPS insulation
<b>EPD</b>	Environmental product declaration	<b>R-PU</b>	Flat roof with PU insulation
<b>EPS</b>	Expanded polystyrene	<b>R-SW</b>	Flat roof with SW insulation
<b>GW</b>	Glass wool/fibre	<b>R-value</b>	Thermal resistance of an insulation product ( $m^2 \cdot K/W$ )
<b>GWP</b>	Global warming potential	<b>SW</b>	Stone wool/fibre
<b>LCA</b>	Life cycle assessment (analysis)	<b>U-value</b>	Heat loss rate of a building (element) ( $m^2 \cdot K/W$ )
<b>LCC</b>	Life cycle costs	<b>WF</b>	Wood fibre
<b>LCI</b>	Life cycle inventory	<b>W-PU</b>	Sandwich panel wall with PU insulation core
<b>ODP</b>	Ozone depletion potential	<b>W-SW</b>	Sandwich panel wall with SW insulation core
<b>PU</b>	Polyurethane (PUR/PIR)	<b>XPS</b>	Extruded polystyrene
<b>POCP</b>	Photochemical ozone creation		

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## 8. References

- BRE Global: *Life cycle environmental and economic analysis of polyurethane insulation in low energy buildings* (client report number 254-665), 2010 ([http://www.pu-europe.eu/site/fileadmin/Reports\\_public/LCA\\_LCC\\_PU\\_Europe.pdf](http://www.pu-europe.eu/site/fileadmin/Reports_public/LCA_LCC_PU_Europe.pdf))
- PWC: *Environmental and economic analysis of insulation products in low energy buildings*, 2013 ([http://www.pu-europe.eu/site/fileadmin/PU\\_Europe\\_files\\_2013/PU\\_13-136\\_PWC\\_for\\_PU\\_Europe\\_-\\_Environmental\\_and\\_economic\\_analysis\\_of\\_insulation\\_products\\_in\\_low\\_energy\\_buildings\\_\\_May\\_2013\\_.pdf](http://www.pu-europe.eu/site/fileadmin/PU_Europe_files_2013/PU_13-136_PWC_for_PU_Europe_-_Environmental_and_economic_analysis_of_insulation_products_in_low_energy_buildings__May_2013_.pdf))
- VITO for Belgian government: Study commissioned by the Federal Public Service of Health, Food Chain Safety and Environment ([www.health.fgov.be](http://www.health.fgov.be)). Final LCA background report – LCA:TIM project – *Het opstellen van regels, het uitvoeren van levenscyclusanalyses inclusief dataverzameling en het geven van beleidsaanbevelingen m.b.t. vijf niet-hernieuwbare (glaswol, rotswol, PUR, EPS, XPS) en vijf hernieuwbare (schapenwol, papiervlokken, vlasisolatie, houtvezelisolatie, hennepisolatie) thermische isolatiematerialen voor spouwmuren* (Bestek met nummer: DG5/PP/DD1/11032) Task 2 – Life cycle assessment of thermal insulation materials for walls in the Belgian building context

**Footnotes:**

- [1] EN 15643-1:2008 *Sustainability of construction works – Sustainability assessment of buildings* – Part 1: General framework
- [2] X=input value, r= rate of interest or discount rate, n= number of years
- [3] BS/ISO 15686-5:2008 *Buildings and constructed assets – Service-life planning* – Part 5: Life-cycle costing
- [4] Source: Study commissioned by the Federal Public Service of Health, Food Chain Safety and Environment ([www.health.fgov.be](http://www.health.fgov.be)). Final LCA background report – LCA:TIM project – *Het opstellen van regels, het uitvoeren van levenscyclusanalyses inclusief dataverzameling en het geven van beleidsaanbevelingen m.b.t. vijf niet-hernieuwbare (glaswol, rotswol, PUR, EPS, XPS) en vijf hernieuwbare (schapenwol, papiervlokken, vlasisolatie, houtvezelisolatie, hennepisolatie) thermische isolatiematerialen voor spouwmuren* (Bestek met nummer: DG5/PP/DDL/11032) Task 2 – Life cycle assessment of thermal insulation materials for walls in the Belgian building context
- [5] See footnote 4

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