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ENVIRONMENTAL AND COST PERFORMANCE OF BUILDING'S ENVELOPE INSULATION MATERIALS TO REDUCE ENERGY DEMAND: THICKNESS OPTIMISATION

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Abstract

Thermal insulation materials play an important role in the challenge of nearly zero-energy buildings thanks to their potential in reducing building's energy demand and carbon emissions. However, increasing the thickness of the insulation material in the building's envelope has implications from the energy, environmental and economic viewpoints. In this context, efforts should be made to optimise insulation thickness to balance all these aspects.

This study presents a methodology to analyse optimum insulation material for the building's envelope (roof, façade and floor) and its thickness to achieve energy demand reductions in the operation phase of the building, which is based on the Life Cycle Assessment and Life Cycle Costing methodologies to integrate both environmental and economic aspects, respectively. The system boundary includes the life cycle stages of product and use defined by recent European standards. A selection of eleven alternative insulation materials, both conventional and emerging ones based on natural products, were chosen to conduct the study. After applying the methodology to a single-family house in Spain and performing a sensitivity analysis, the results revealed that sheep wool and recycled cotton, jointly with traditionally used mineral and glass wool, should be promoted in the construction industry as they offer the highest eco-efficient performance among the analysed insulation materials. Reductions of up to 40% in energy demand compared to regulations standards can be achieved in theeco-efficiency context.

Keywords: optimuminsulation thickness; eco-efficiency; life cycle assessment; life cycle cost; energy demand

Highlights

- Optimising insulation thickness for the building's envelope
- Eco-efficiency analysis of life cycle and cost assessment
- Sensitivity analysis by varying the building's energy demand scenarios
- Emerging naturally-based insulation materials were the most eco-efficient

1. Introduction

With the introduction of the nearly zero-energy building (NZEB) concept, the Energy Performance of Buildings Directive [1] urges designers to include insulation materials in the building's envelope to reduce the amount of energy required in the use stage to maintain the building's envisaged temperature conditions and to acquire indoor thermal comfort for its occupants. In this context, thermal insulation materials play an important role in the NZEB challenge given their potential to reduce the building's energy demand and carbon emissions [2].

This recent tightening of building regulations implies reductions in the overall life cycle energy demand of buildings [3]. For this purpose, insulation materials, as a building's component, are a key aspect to fulfil this aim. As the energy consumption in the building's use stage decreases when the insulation thickness in the building's envelope increases, the environmental impact and cost related to manufacturing insulation materials are supposed to increase considerably due to the larger amount of material needed. Thus efforts should focus on optimising the thickness of insulation material to limit the building energy demand [4,5], and this should be done in the building's early design stages to achieve as many benefits as possible.

The most commonly used insulation materials in the construction industry have been widely analysed in the literature from different points of views. However, their environmental or cost effect on buildings' life cycle energy demand is an emerging research area promoted by recent changes within the regulatory framework of buildings [6–8]. By way of example, [4,5,9–16], they focus on their environmental performance, while [4,5,17] also focusing on their cost performance. However, and in agreement with the conclusions from [18], the insulation thickness calculated by applying energy or environmental optimisation criteria give, in some cases, results that are 10-fold higher than those obtained using economic criteria. Thus environmental and cost aspects cannot be evaluated independently, but together in order to reach holistic conclusions. In addition, the type of insulation materials (material manufacturing and thermal properties) and the conditions of the site where the material is installed (e.g. the climatic zone defined by degree-days) also strongly affect the determination of optimum thicknesses [18,19].

In this context, the present study states a methodology to determine the optimum insulation material thickness for the building's envelope by considering the roof, the façade and the floor to achieve energy demand reductions in the building's operation phase. It combines environmental and cost performance by applying an eco-efficiency analysis [20]. Finally, the methodology is applied to a single-family building as a case study by comparing eleven insulation material alternatives, which are both conventional and the emerging ones that derive from natural products, for six different energy demand scenarios. It allows the identification of the insulation material alternative with better environmental and cost performance (eco-efficiency) and an optimum thickness for each one.

2. Background

A selection of studies in the literature was undertaken to achieve a comprehensive understanding of current knowledge published in the field of environmental and cost performance of insulation materials, as Table 1 reports.

A content analysis of the selected articles was performed to identify the main topics addressed in each one related to the:

- Study purpose of differentiating among energy, environment or cost analysis
- Analysed insulation materials
- LCA methodology aspects: functional unit (FU), life cycle stages considered according to the system boundary proposed by EN 15978 [6] (Table 2), data source for compiling the life cycle inventory (LCI) by differentiating between primary data (directly obtained from companies) and secondary data (obtained from free/commercial LCI databases), and the life cycle impact assessment (LCIA) method

applied for obtaining the environmental indicators by differentiating between the mid-point LCIA methods (and mid-point impact categories) and end-point LCIA methods.

- Existence of an application case to a specific building.

Table 1. LCA research studies of insulation materials

	Purpose			Insulation materials analysed														Life cycle stage						LCIA mid-point category																Mid-point LCIA method			
Reference	Environmental analysis	Cost analysis	Energy analysis	Mineral wool (MW)	Glass wool (GW)	Expanded Polystyrene (EPS)	Extruded Polystyrene (XPS)	Polyurethane (PUR)	Polyisocyanurate n(PIR)	Phenol Formaldehyde (PF)	Foam glass (FG)	Cellulose (Ce)	Eco-fibre (recycled newspapers) (EF)	Cork (C)	Wood fibres (WF)	Aerogel (AG)	FU	Production of insulation materials	Distribution of insulation materials	Installation/use of insulation material	End of life of insulation materials	**Life cycle stage** (according to Table 2)	LCI data source	Abiotic depletion	Global warming	Ozone layer depletion	Photochemical oxidation	Acidification	Eutrophication	Embodied energy	Primary energy consumption	Toxicity	Fuel consumption	Particulate matter	Radiation	Land use	Exergy	Ionizing radiation	Resources depletion	CML	TRACI	**End-point LCIA method** (Ecoindicator'99)	**Application to a building**
[9]	●			●	●	●	●	●		●	●						W: 1 kg*	●				A1-A3	[21]								●												
[4]	●	●		●	●												A: 1 m^2	n/s				n/s	n/s																			●	
[10]	●					●	●	●						●			W: 1 kg*	●				A1-A3	[22,23]	●	●	●	●	●	●											●			
[11]	●			●	●	●					●	●					R: 1 m^{2}K/W	●				A-B?	[22]		●						●									n/s			●
[12]	●			●	●	●	●	●									A: 1 m^2	●				A	[22]	●	●	●	●	●	●	●										●			
[13]	●		●			●									●		A: 1 m^2					A-B?	[24]		●	●	●	●	●		●										●		●
[14]	●		●			●	●		●							●	W: 1 kg*	●	●	●	●	A-B-C-D	[22,25,26]		●						●												●
[17,27]	●	●		●		●		●					●				V: 1 m^3	●	●	●	●	A1-A3,B?	n/s																			●	●
[5]	●	●		●	●												A: 1 m^2					?	n/s		●								●				●			n/s		●	
[15]	●			●		●			●	●					●		A: 1 m^{2**}	●	●			A1-A3	[22]		●	●	●	●	●			●		●		●		●	●	n/s			
[16]	●																W: 1 kg*	●	●	●	●	A-C-D?	n/s																			●	●

F.U.: functional unit; W: weight; A: area; R: thermal resistance; n/s: not specified; ?: not clear
*To provide thermal resistance R= 1 m^2·K/W; ** To provide thermal resistance R= 3 m^2·K/W

Table 2. Life-cycle stages of building materials based on European standards (EN 15978 [6])

LCA Module	Description
Product stage (A1-A3)	A1 Raw material extraction and processing, processing of secondary material input A2 Transport to the manufacturer A3 Manufacturing
Construction process stage (A4–A5)	A4 Transport to the building site A5 Installation in the building
Use stage—information modules related to the building fabric (B1–B5)	B1 Use or application of the installed product B2 Maintenance B3 Repair B4 Replacement B5 Refurbishment
Use stage—information modules related to the operation of the building (B6–B7)	B6 Operational energy use B7 Operational water use
End-of-life stage (C1–C4)	C1 De-construction, demolition C2 Transport to waste processing C3 Waste processing for reuse, recovery and/or recycling (3R) C4 Disposal
Reuse, recovery and/or recycling potential (D)	D Benefits and loads beyond the system boundary

Taking into account the purpose of each study, it was observed that they strongly focused on analysing the environmental performance of insulation materials since only three of them [4,5,17] included a cost analysis and two of them [13,14] an energy assessment. Therefore, none of them jointly analysed all these aspects.

From Table 1, it can be concludedthat the most commonly used materials in the construction industry are widely analysed in the literature, namely mineral wool (MW) [4,5,9,11,12,15,17], glass wool (GW) [4,5,9,11,12], expanded polystyrene(EPS) and extruded polystyrene (XPS) ([9–15,17] and [9,10,12,14], respectively) and polyurethane (PUR) [9,10,12,17]. Some other materials have also been addressed, but only slightly, such as polysocyanurate (PIR) [14,15], phenol formaldehyde (PF) [9,15], foam glass (FG) [9,11], cellulose (Ce) [11], eco-fibre (EF) [17], cork (C) [10], wood fibres (WF) [13,15] or aerogel (AG) [14]. Among the unconventional insulation materials, it was noted that those which derive from natural products have not been widely analysed, along with some emerging materials in the construction industry, such as sheep wool or recycled cotton, which have been generally overlooked. In line with this, and as concluded from [28], the use of natural insulation materials does not necessarily imply reduced environmental impacts and, for this reason, they deserve special attention in the building's overall life cycle assessment.

When we focused on the studies that have analysed the environmental performance of insulation materials, they had all applied the Life Cycle Assessment (LCA) [29,30] methodology to obtain the environmental indicators. However, the way in which they applied each LCA methodology stage varied. In relation to the functional unit (FU), most of these studies defined the mass (kg) of insulation material that provides a thermal resistance R of 1 ($m^2 \cdot K/W$). Regarding the system boundary, the product stage (from raw material extraction and processing, A1, to installing the building, A5) was addressed in most of the reviewed studies, while the use stage (B) was considered only in a few of them [11,13,14,17]. The end-of-life stage (C) was sistematicalyignored and only [14] considered all the stages (from A to D), as defined in recent European standards by EN 15978 [6]. However, this information was not clearly reported and was even confusing in some cases to identify the modules considered in each life cycle stage. Regarding the life cycle inventory (LCI) data source, Ecoinvent[22] was the most commonly used database [10–12,14], while BESLCI [21] was used in [9] and Athena IE [24] in [13]. It is worth noting that a considerable number of studies [4,5,16,17] did not specify the source for the LCI model. As for the life cycle impact assessment (LCIA) stage, almost all the reviewed studies considered mid-point LCIA methods to present the environmental results. The mostly considered environmental impact categories were abiotic depletion potential (ADP), global warming , ozone layer depletion , photochemical oxidation, acidification and eutrophication , in agreement with EN 15978 (Part 2) [6]. The other impact categories addressed in the reviewed literature were embodied energy in [12], primary energy consumption in [9,11,13,14], toxicity, particulate matter, land use, ionising radiation and resource depletion in [15], and fuel consumption and energy in [5]. Not all the studies reported the method applied for the characterisation factors, beingCML [31] and TRACI [32]themost commonly applied ones. Finally, it should be noted that some studies [4,5,16,17] applied Ecoindicator'99 [33] as the end-point LCIA method, which is not consistent with EN 15978 requirements [6].

As pointed out, only three studies included the cost aspect. [4]analysed variations in the insulation cost and fuel cost depending on the insulation thickness for GW and MW. The authors concluded that the insulation cost increases linearly because of insulation geometry, and the fuel cost decreases with insulation thickness. They also mentioned that the fuel cost initially decreases with higher values, and that this decrease continues with lower values. [17]explored the most favourable values of ecological cost-effectiveness for eco-fibre (EF), the building's heating with electricity (the highest environmental impact option) and the coldest climate in Poland. They concluded that the ecological payback period of thermal insulation investment can be obtained within the 0-6 years range. [5]performed a life cycle cost and environmental impact analysis by taking into account two kinds of insulation materials (also MW and GW) and fuel for cost minimisation. The authors determined optimal thicknesses for a minimum environmental impact and for maximum annual cost saving. Their study also revealed that changing the heating degree days had the strongest effect on the environmental impact.

Finally, considering the application of the work in the reviewed studies, some of them applied their methodologies to specific buildings as a case study. For instance, [11] applied their workto a building according to two standards, namely the Swedish building code of 2012 and the Swedish Passivhaus 2012 criteria. The authors in [13] applied their methodology to a low-rise office building in the USA, [17] to two single-family houses in Poland, and [16] to a single low-energy building that contained 19 flats in Belgium.

As derived from this background, it can be concluded that there is need to develop a methodology that combines both environmental and economic aspects when analysing the energy implications of insulation materials in buildings in agreement with EN 15643-1 [34]. It would also be interesting to expand the boundaries of the study to consider other non-conventional alternatives of insulation materials, such as emerging materials based on natural resources and different energy demand scenarios.

3. Methodology

This work analyses the influence of the thickness of the insulation material installed in the building's envelope to achieve energy demand reductions in its use stage. To this end, a baseline scenario (scenario 1) is defined as a reference scenario. It considers the minimum thickness of the insulation required in the roof, the façade and the floor of the building to meet the energy demand standard limit value required by energy-efficiency legislation [1]. Then the baseline scenario is compared with alternative scenarios (scenario 2, scenario 3, …, scenario n) which consider a progressive reduction in energy demand by increasing the thickness of the insulation material in the building's envelope to fulfil it. For each scenario, the environmental and cost performance are analysed and compared through eco-efficiency graphs in order to find those insulation materials and energy demand scenarios that best combine both criteria.

The proposed methodology is presented in Figure 1, whose stages are described below.

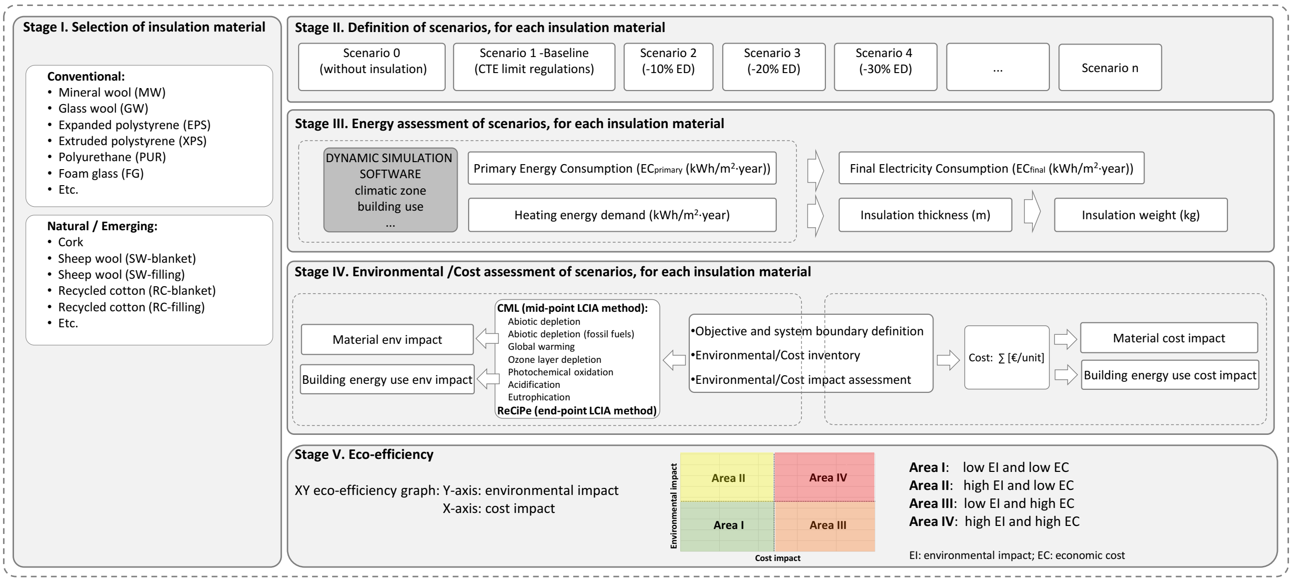


Figure 1. Methodological framework

Stage I. Selection of insulation materials

Depending on the building's characteristics and the typical envelope assemblies of the geographical location, a set of insulation materials applicable to the building's envelope is selected. Some can be the commonest materials used in the construction industry, such as glass wool (GW), mineral wool (MW), expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PUR), foam glass (FG), etc., while others can be emerging insulation materials that derive from natural products such as cork (C), sheep wool (SW) or recycled cotton (RC), among others.

The physical characteristics of insulation materials need to be defined as they are necessary data for energy assessment simulations. Density (kg/m^3) is used to calculate the volume and the weight of required the insulation material. Further physical properties, such as thermal conductivity (W/m·K), specific heat capacity (kJ/kg·K) and water vapour diffusion resistance (μ), are needed to calculate the operational energy demand by thermal dynamic simulation.

Stage II. Definition of scenarios for each insulation material

In order to identify the influence of increasing insulation thickness to achieve building's energy demand reductions from the environmental and economic viewpoints it is necessary to define several energy efficiency scenarios:

- Scenario 0: points out the building with no thermal insulation in its envelope.
- Scenario 1 (baseline scenario): the reference scenario that considers the minimum thickness of the insulation required in the building's roof, the façade and the floor to fulfil the energy demand required by legislation. That is to say, it considers the required heating energy demand in kWh/m^2·year according to specific legislation on the energy efficiency of buildings (i.e., EPDB [1] in European countries) applicable to the case study that determines the minimum thickness of the insulation material required to fulfil it.
- Scenarios 2 to Scenario n (additional scenarios) that progressively reduce the heating energy demand required by the specific legislation applicable to the case study by increasing insulation material thickness.

Stage III. Energy assessment of scenarios for each insulation material

Building energy assessment is analysed by considering the annual primary energy consumption ($EC_{primary}$ (kWh/m^2·year)) of the building's use stage, considering the energy demand both for heating and cooling and the domestic hot water (DHW) system. All of them can be obtained by means of dynamic simulation software, by considering aspects such as the building use or the climatic zone, among others.

The annual primary energy consumption and the annual final energy consumption (EC_{final}) has a relationship by applying the conversion factor ($k_{primaryenergy}$) according to the following equation:

$$EC_{primary}\ (kWh) = EC_{final}(kWh) \cdot k_{primaryenergy} \quad \text{[eq. 1]}$$

The conversion factor $k_{primaryenergy}$ is always greater than 1 and its value depends on the energy system of the country and on the type of final energy consumed. The lower the coefficient, the more efficient the energy system (energy mix) of the country.

Heating energy demand has been also considered for calculating the insulation thickness for each insulation material and for each scenario. It measures the amount of energy that the building's thermal installations have to provide to ensure inner comfort conditions. The building's energy demand for heating is established as an objective to be reached in each defined scenario, depending on specific legislation on the energy efficiency of buildings applicable to the case study. Then the thermal resistance (R-value, m^2K/W) of the building's envelope elements (roof, façade and floor) required to fulfil each scenario can be determined. The R of the roof, the façade and the floor is calculated by the sum of thermal resistances of each layer that compounds the envelope assembly. However, the insulation layer represents a variable in the study, since its R can be obtained by different ways: varying the thickness or the thermal conductivity, λ (W/m·k) (when considering different insulation products). Therefore, the R of the insulation layer required to fulfil each scenario is calculated, and considering different λ depending on the insulation product used, the minimum thickness of the insulation material (m) can be obtained, and then weight (kg). This process is followed for each scenario and for each considered insulation material type. This process is graphically described in Figure 2.

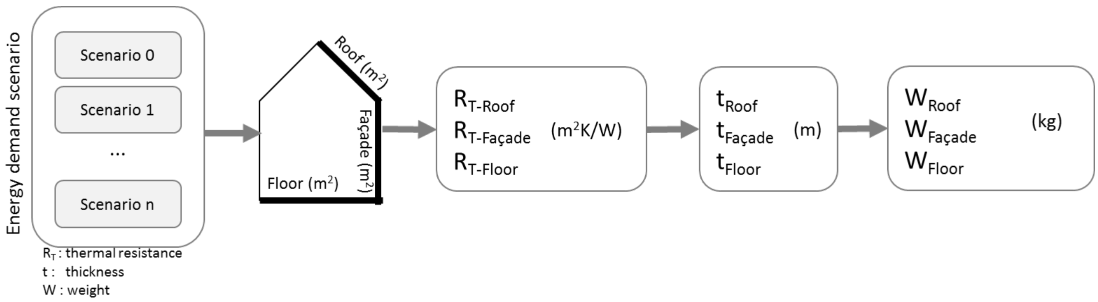


Figure 2. Scheme to determine the insulation material's weight

Stage IV. Environmental/Cost assessment of scenarios, for each insulation material

From the insulation material's weight and the final energy consumption calculated for each scenario and for each insulation material type in the Stage III of the methodology, the environmental and cost performance can be assessed. For this purpose, the Life Cycle Assessment [29,30] and the Life Cycle Costing (LCC) [35] methodologies can be applied by considering the following stages:

- **Objective and boundary definition.** The aim of the study is to compare the environmental and cost performance of a set of alternative insulation materials applicable for the building's envelope (roof, façade and floor) by considering the appropriate thickness to achieve a set of energy efficiency scenarios. The functional unit (FU) considered is the amount of insulation material (kg) needed to provide the R (m^2K/W) required to fulfil each energy efficiency scenario for 50 years [12].
- **Environmental/Cost inventory.** The inventory data needed to evaluate each scenario from an environmental and cost perspective were selected by taking into account:

- For the environmental inventory and according to EN 15978 [6], the used environmental data need to be in coherence with EN 15804 requirements [36]. To this end, the primary data directly collected from material insulation manufacturers and/or the secondary data extracted from comprehensive, transparent and internationally recognised databases, such as the Ecoinvent database [22], can be applied.
- For the cost inventory and following the EN 15643-4 guidelines [37], the unitary cost of each stage considered in the boundary of the study need to be calculated.

- **Environmental/Cost impact assessment.** To obtain the environmental and cost indicators, the following considerations need to be implemented:
  - Environmental indicators describe the environmental behaviour of each scenario. For this purpose, it needs to be expressed mandatorily by an impact category using mid-point LCIA methods, and optionally using end-point LCIA methods, in agreement with the ISO 14040 [29] and ISO 14044 [30] guidelines. To do so, EN 15804 [36] proposes using the impact category and the indicators reported in Table 3.

Table 3. Impact categories and units that measure them according to EN 15804 [36]

Environmental impact category	Environmental indicator unit
Abiotic Depletion Resources – elements (AD)	kg Sb eq.
Abiotic DepletionResources – fossil fuels (AD ff)	MJ, net calorific value
Global Warming (GlobalW)	kg CO_2 eq.
Ozone Depletion (OD)	kg CFC-11 eq.
Photochemical Ozone Oxidation (PO)	kg C_2H_4 eq.
Acidification (AC)	kg SO_2 eq.
Eutrophication (EU)	kg PO_4^{3-} eq.

  - The cost indicators describe the economic behaviour of each scenario expressed in terms of costs throughout the life cycle in economic units (i.e., €, $, etc.).

Stage V. Eco-efficiency analysis

According to ISO 14045[38] eco-efficiency can be defined as a quantitative management tool that enables the consideration of life cycle environmental impacts of a system alongside its cost. In this study, it is applied to identify the best economic and environmental optimal alternative [20]. Once the environmental and cost indicators have been obtained for each scenario and for each insulation material type, the eco-efficiency analysis for each scenario can be graphically represented using an XY eco-efficiency graph, as shown in Figure 3. The Y-axis represents the environmental impact, while the X-axis shows the economic cost. For each impact category and impact assessment method, the maximum and minimum values of the X and Y axis correspond to the maximum and minimum values of cost and environmental indicator, respectively, which are reached for all the analysed scenarios.

The eco-efficiency graphs are divided into four equal areas, limited by that maximum and minimum values [39]. The four resulting areas represent a different level of environmental and cost efficiency. For each scenario, the bottom left-hand area (area I) represents the maximum eco-efficiency as the contained insulation materials that offer the lowest environmental indicator with the lowest cost indicator. These can thus be considered the best options. Meanwhile, the top right-hand area corresponds to minimum eco-efficiency (area IV). The remaining areas, area II and area III, correspond to combinations of high environmental impact with low economic cost and low environmental impact with high economic cost, respectively.

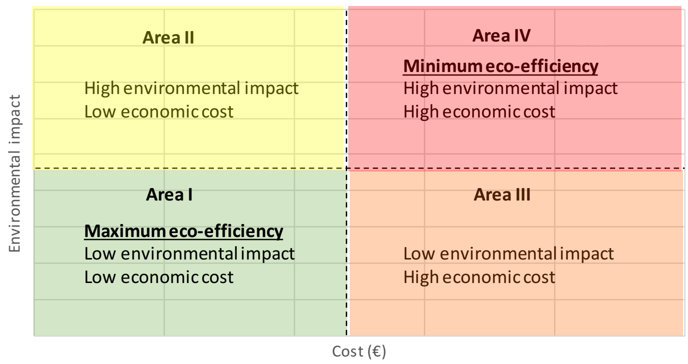


Figure 3. Eco-efficiency analysis graph for each scenario, adapted from [20]

4. Description of the case study

The previously described methodology is applied to a single-family house as a case study. The building is located in Castellón de la Plana (east coast of Spain at 39˚ 59’ 11’’ north latitude and 0˚ 2’ 12” east longitude) and consists of 278.40 m^2 of built area split into one level. The 3D geometry of the building model is presented in Figure 4.

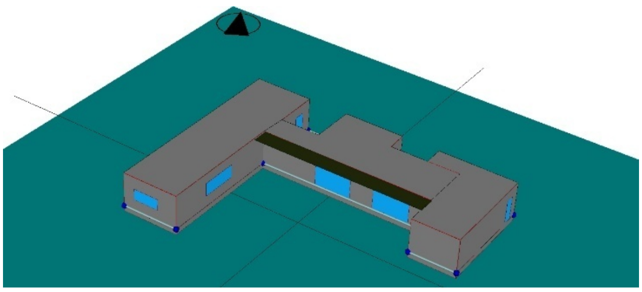
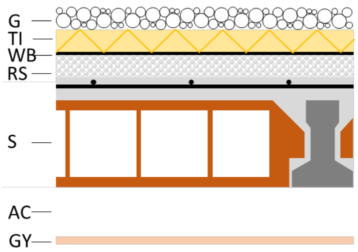
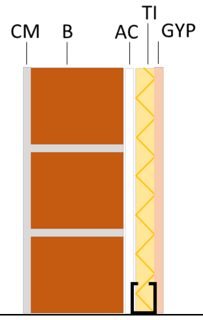
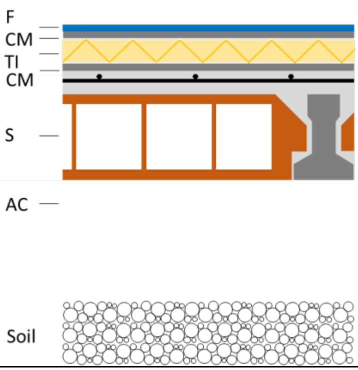


Figure 4. 3D building model in HULC [40]

The characteristics of the building’s envelope are described in Table 4. The roof consists of a flat inverted roof that is non-trafficable with an R of 0.943 m^2·K/W. The façade is a double-layer wall of ceramic brick and inner gypsum panels with an R of 1.265 m^2·K/W. The ground floor is separated from soil with a ventilated air chamber in order to prevent moisture and condensation, and has an R of 0.487 m^2·K/W. The effect of the insulation material was not considered for the R-values calculations, since it represents a variable in the study. Nonetheless, its position is presented in the schemes of Table 4. Neither its thickness is provided in Table 4 as it depends on the energy demand scenario requirements and the type of insulation material considered, which imply different λ-values.

Table 4. Building's envelope description and thermal resistance R ($m^2·K/W$)

Graphical description	Layer	Thickness (m)	λ (W/m·K)	R (m^2·K/W)
Roof 	External surface R		-	0.040
	G: Gravel	0.050	2.000	
	TI: Thermal insulation	-	-	
	WB: Waterproof bitumen	0.002	0.230	
	RS: Aerated concrete for roof slope	0.060	0.180	
	S: Reinforced concrete one-way slab	0.300	2.000	
	AC: Air chamber	0.100	-	0.180
	GY: Gypsum plastering	0.012	0.250	
	Internal surface R		-	0.100
	Total			**0.943**
Façade 	External surface R		-	0.040
	CM: Cement mortar	0.020	0.550	
	B: Ceramic brick	0.240	0.296	
	AC: Air chamber	0.010	-	0.150
	TI: Thermal insulation	-	-	
	GYP: Gypsum panel	0.024	0.250	
	Internal surface R		-	0.130
	Total			**1.265**
Floor 	Internal surface R		-	0.170
	F: Flooring	0.008	1.900	
	CM: Cement mortar	0.020	0.550	
	TI: Thermal insulation	-	-	
	CM: Cement mortar	0.020	0.550	
	S: Reinforced concrete one-way slab	0.300	2.000	
	AC: Ventilated air chamber	0.500	-	0.090
	External surface R		-	0.040
	Total			**0.487**

The transposition of the Energy Performance of Buildings Directive (EPBD [1]) into Spanish legislation has materialised as the Technical Code of Building (CTE), Sections DB HE 0 and 1 [41]). This legislation limits buildings' heating energy demand depending on their use and the climatic zone where they are located. Castellón de la Plana corresponds to climatic zone B3.

5. Applying the methodology to the case study

5.1 Stage I. Selecting insulation materials

The literature review indicated that the environmental performance of insulation materials has been analysed mainly for materials such as GW, MW, EPS, XPS, PUR, FG and C. These products are also the most commonly used insulation materials applied in the building industry in the region of the building under study. As seen, some derive from natural products, which are MW and C, and have been used for decades. Nevertheless, emerging materials, also based on natural products, have recently appeared on the market. These are SW and RC, both in blanket and filling forms. By taking into account this context, the selected insulation materials considered in this case study and the characteristics of each one are reported in Table 5.

Table 5. Selected insulation materials for the case study, and their characteristics and common applications

Insulation material	Source	Density (kg/m^3)	λ (W/mK)	Specific heat (kJ/kgK)	Water vapour diffusion resistance factor (μ)	Commonest applications: Roof – Sloping	Roof – Flat	Façade – ETICS	Façade – Ventilated	Façade – Internal insulated	Floor
Conventional materials											
Glass wool (GW)	Ecoinvent 3 [22] Schiavoni et al. [19]	40	0.04	0.9-1.0	1-1.1	●	●		●	●	●
Mineral wool (MW)	Ecoinvent 3 [22] Schiavoni et al. [19]	45	0.035	0.8-1.0	1-1.3	●	●		●	●	●
Expanded Polystyrene (EPS)	Schiavoni et al. [19]	25	0.034	1.25	20-70	●	●	●	●	●	●
Extruded Polystyrene (XPS)	Ecoinvent 3 [22] Schiavoni et al. [19]	30	0.035	1.45-1.7	80-150	●	●	●	●	●	●
Polyurethane (PUR)	Schiavoni et al. [19]	45	0.032	1.3-1.45	30-170	●	●		●	●	●
Foam glass (FG)	Ecoinvent 3 [22] CTE HULC [40]	110	0.04	1	$1 \cdot 10^{10}$		●			●	●
Cork (C)	Schiavoni et al. [19]	170	0.04	1.5-1.7	5-30	●	●	●		●	●
Emerging materials (natural)											
Sheep wool (SW-blanket)	RMT-NITA [42]	15	0.043	1.3-1.7	1.0-3.0	●	●		●	●	●
Sheep wool (SW-filling)	RMT-NITA [42]	15	0.043	1.3-1.7	1.0-3.0	●	●			●	●
Recycled cotton (RC-blanket)	RMT-NITA [42]	30	0.036	1.6	1-2	●	●		●	●	●
Recycled cotton (RC-filling)	RMT-NITA [42]	15	0.044	1.6	1-2	●	●			●	●

5.2 Stage II. Defining scenarios for each insulation material

Seven scenarios for the building described in Section 3 were set down to conduct this study (Table 6). The first one (scenario 0) pointed out the building without insulation in its envelope. The second one (scenario 1) considered the minimum insulation thickness required to fulfil Spanish legislation on the energy efficiency of buildings (CTE [41]). The following scenarios (2 to 6) considered a progressive heating energy demand reduction of 10% compared to the previous scenario, until a 50% reduction was reached compared to the baseline scenario (scenario 1).

The energy demand for heating legally required by CTE [41] was taken as a reference, which in climatic zone B3, is limited to 15 $kWh/m^2 \cdot year$. This corresponds to the energy demand fixed to model scenario 1. The remaining scenarios 2 to 6 considered a progressive heating energy demand reduction of 10% compared to the previous one, as reported in Table 6.

Table 6. Energy efficiency scenarios description

Energy efficiency scenario	Scenario description: Building energy demand for heating…	Energy demand ($kWh/m^2 \cdot year$)
Scenario 0 (without insulation)	without thermal insulation	
Scenario 1	considering minimal insulation thickness to fulfil CTE requirements	15,00
Scenario 2	10% reduction compared to CTE requirements	13,50
Scenario 3	20% reduction compared to CTE requirements	12,00
Scenario 4	30% reduction compared to CTE requirements	10,50
Scenario 5	40% reduction compared to CTE requirements	9,00
Scenario 6	50% reduction compared to CTE requirements	7,50

These reductions have been reached by increasing the insulation material thickness of the roof, the façade and the floor of the building, proportionally in accordance to their influence in the building's energy demand for heating. From a previous energy assessment analysis we can observe that building's envelope elements (roof, floor or façade) strongly influences energy demand. As observed in Figure 5, which relates insulation thickness with the building's heating energy demand reduction, roof require, *a priori* in scenario 1, a higher insulation thickness value than façade and floor to reduce energy demand. However, it is also observed that the façade' insulation thickness should significantly increase to achieve higher energy efficiency levels (scenario 6), which implies a 50% reduction compared to the energy demand required by Spanish CTE [41]. Besides, floors are the least influential element for building energy demand.

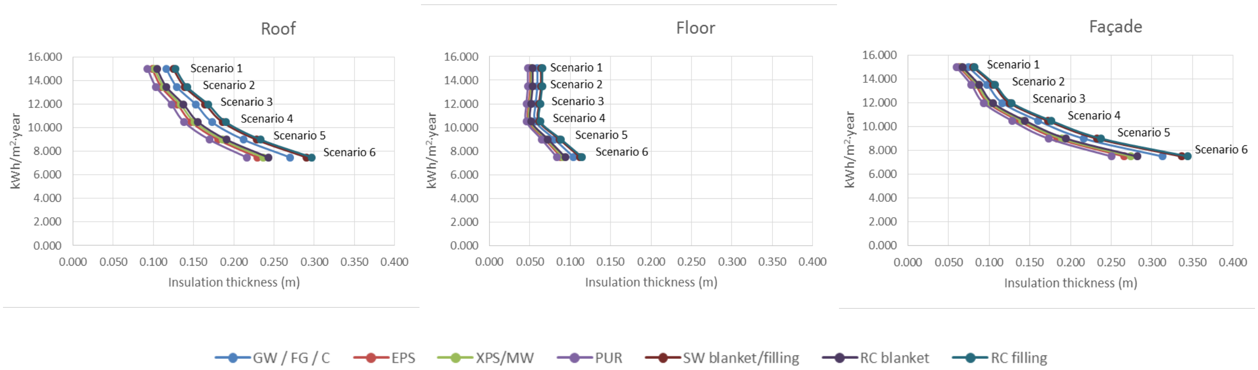


Figure 5. Influence of the insulation thickness of the roof, façade and roof on heating energy demand reduction

5.3 Stage III. Energy assessment of scenarios, for each insulation material

Building energy consumption calculations were carried out using the HULC software [40], which is the official tool to verify the fulfilment of Spanish legislation on energy efficiency of buildings (CTE [41]). This is an energy performance modelling and dynamic simulation software that can estimate the primary energy consumption of the building ($EC_{primary}$ (kWh/m^2·year)) during its use stage, according to the characteristics of the building.

The assumptions for running the energy calculations for this case study are outlined in Table 7. Climatic zone B3 in Spain means moderate winter severity and warm summers. The average maximum daily temperature in summer is 26˚C (August) and the average minimum temperature in winter is 10.6˚C (January). Some other assumptions were considered; e.g., characteristics of windows (double glazing and aluminium frame with thermal bridge breakage) and the domestic hot water system (50% of solar energy contribution, as the minimum required by regulations) supplied by an electric boiler. Also the heating and cooling systems are supplied by electricity.

Table 7. Assumptions for energy calculations

Parameter	Value
Climatic zone	B3 according to CTE (2013) Monthly/annual average maximum daily temperature in August: 26˚C Monthly/annual average minimum daily temperature in January: 10.6˚C
Solar orientation	North/South/East/West (single-family detached house)
Thermal envelope	
Roof	U-value= 1.06 W/m^{2}K; A= 278.40 m^2
Façade	U-value= 0.79 W/m^{2}K; A= 304.80 m^2
Floor	U-value= 2.05 W/m^{2}K; A= 278.40 m^2
Windows	Aluminium frame with thermal bridge breakage: U-value= 4.00 W/m^{2}K; solar absorptivity = 0.70 Double glazing: U-value= 2.50 W/m^{2}K; SHGC= 0.70 Air permeability= 0.27 m^3/hm^2
Ventilation system	Mechanical ventilation
Domestic Hot Water (DHW) system	50% of solar energy contribution DHW demand: 112 litres/day Electric boiler (10 kW; 0.90 of efficiency)
Heating and cooling systems	Electricity supply

SHGC: solar heat gain coefficient; ACH: air changes per hour

Energy simulations run with HULC allowed us to find the R-values required for each envelope solution (roof, façade and floor) to meet all the energy demand scenario requirements. Knowing the R-values without including the insulation material layer (based on Table 4), allows the R-value of the thermal insulation (TI) to be determined for each scenario. These R-values are presented in row 2of Table 8. As seen, the R-values increase as the scenario does for the eleven types of selected insulation materials. Then, by considering the specific λ of each insulation material, the necessary thickness (m) for each one in the six scenarios (1 to 6)can be determined. The theoretical thickness was normalised according to the commercial available thicknesses for each insulation material. These commercial thicknesses are provided in Table 12.

Table 8. Thickness (m) calculation for the insulation materials for each scenario

		Scenario 1 (CTE-Baseline)			Scenario 2 (-10%)			Scenario 3 (-20%)			Scenario 4 (-30%)			Scenario 5 (-40%)			Scenario 6 (-50%)		
Type	**λ (W/mK)**	$R_{TI:roof}$	$R_{TI:façade}$	$R_{TI:floor}$	$R_{TI:roof}$	$R_{TI:façade}$	$R_{TI:floor}$	$R_{TI:roof}$	$R_{TI:façade}$	$R_{TI:floor}$	$R_{TI:roof}$	$R_{TI:façade}$	$R_{TI:floor}$	$R_{TI:roof}$	$R_{TI:façade}$	$R_{TI:floor}$	$R_{TI:roof}$	$R_{TI:façade}$	$R_{TI:floor}$
		2.900	**1.860**	**1.480**	**3.223**	**2.439**	**1.480**	**3.819**	**2.900**	**1.426**	**4.320**	**4.000**	**1.426**	**5.307**	**5.402**	**2.010**	**6.749**	**7.826**	**2.600**
GW	0.040	0.120	0.075	0.060	0.135	0.100	0.060	0.160	0.120	0.060	0.180	0.160	0.060	0.225	0.225	0.080	0.275	0.315	0.110
EPS	0.034	0.100	0.070	0.050	0.110	0.090	0.050	0.130	0.100	0.050	0.150	0.140	0.050	0.180	0.190	0.070	0.230	0.270	0.090
XPS	0.035	0.110	0.070	0.060	0.120	0.090	0.060	0.140	0.110	0.050	0.160	0.140	0.050	0.190	0.190	0.070	0.240	0.280	0.100
PUR	0.032	0.100	0.060	0.050	0.110	0.080	0.050	0.130	0.100	0.050	0.140	0.130	0.050	0.170	0.180	0.070	0.220	0.250	0.090
FG	0.040	0.120	0.080	0.060	0.130	0.100	0.060	0.160	0.120	0.060	0.180	0.160	0.060	0.220	0.220	0.080	0.270	0.320	0.110
MW	0.035	0.110	0.080	0.060	0.120	0.090	0.060	0.140	0.110	0.050	0.160	0.140	0.050	0.190	0.190	0.080	0.240	0.280	0.100
Cork	0.040	0.120	0.080	0.060	0.130	0.100	0.060	0.160	0.120	0.060	0.180	0.160	0.060	0.220	0.220	0.080	0.270	0.320	0.110
SW-blanket	0.043	0.150	0.100	0.100	0.150	0.150	0.100	0.200	0.150	0.100	0.200	0.200	0.100	0.250	0.250	0.100	0.300	0.350	0.150
SW-filling	0.043	0.130	0.080	0.070	0.140	0.110	0.070	0.170	0.130	0.070	0.190	0.180	0.070	0.230	0.240	0.090	0.300	0.340	0.120
RC-blanket	0.036	0.150	0.100	0.100	0.150	0.100	0.100	0.150	0.150	0.100	0.200	0.150	0.100	0.200	0.200	0.100	0.250	0.300	0.100
RC-filling	0.044	0.130	0.090	0.070	0.150	0.110	0.070	0.170	0.130	0.070	0.180	0.180	0.070	0.240	0.240	0.090	0.300	0.350	0.120

Once the thicknesses for each insulation material and each scenario are obtained, the necessary weight can be determined by considering the density of each material. The results, referred to as 1 m^2 of roof (W_{roof}), façade ($W_{façade}$) or floor (W_{floor}), are depicted in Table 9.

Table 9. Weight (kg) of the insulation material referred to as 1 m^2 of roof, façade and floor, for each scenario

		Scenario 1 (CTE-Baseline)			Scenario 2 (-10%)			Scenario 3 (-20%)			Scenario 4 (-30%)			Scenario 5 (-40%)			Scenario 6 (-50%)		
Type	**d (kg/m^3)**	W_{roof}	$W_{façade}$	W_{floor}	W_{roof}	$W_{façade}$	W_{floor}	W_{roof}	$W_{façade}$	W_{floor}	W_{roof}	$W_{façade}$	W_{floor}	W_{roof}	$W_{façade}$	W_{floor}	W_{roof}	$W_{façade}$	W_{floor}
GW	40	4.800	3.000	2.400	5.400	4.000	2.400	6.400	4.800	2.400	7.200	6.400	2.400	9.000	9.000	3.200	11.000	12.600	4.400
EPS	25	2.500	1.750	1.250	2.750	2.250	1.250	3.250	2.500	1.250	3.750	3.500	1.250	4.500	4.750	1.750	5.750	6.750	2.250
XPS	30	3.300	2.100	1.800	3.600	2.700	1.800	4.200	3.300	1.500	4.800	4.200	1.500	5.700	5.700	2.100	7.200	8.400	3.000
PUR	45	4.500	2.700	2.250	4.950	3.600	2.250	5.850	4.500	2.250	6.300	5.850	2.250	7.650	8.100	3.150	9.900	11.250	4.050
FG	110	13.200	8.800	6.600	14.300	11.000	6.600	17.600	13.200	6.600	19.800	17.600	6.600	24.200	24.200	8.800	29.700	35.200	12.100
MW	45	4.950	3.600	2.700	5.400	4.050	2.700	6.300	4.950	2.250	7.200	6.300	2.250	8.550	8.550	3.600	10.800	12.600	4.500
Cork	170	20.400	13.600	10.200	22.100	17.000	10.200	27.200	20.400	10.200	30.600	27.200	10.200	37.400	37.400	13.600	45.900	54.400	18.700
SW-blanket	15	2.250	1.500	1.500	2.250	2.250	1.500	3.000	2.250	1.500	3.000	3.000	1.500	3.750	3.750	1.500	4.500	5.250	2.250
SW-filling	15	1.950	1.200	1.050	2.100	1.650	1.050	2.550	1.950	1.050	2.850	2.700	1.050	3.450	3.600	1.350	4.500	5.100	1.800
RC-blanket	30	4.500	3.000	3.000	4.500	3.000	3.000	4.500	4.500	3.000	6.000	4.500	3.000	6.000	6.000	3.000	7.500	9.000	3.000
RC-filling	15	1.950	1.350	1.050	2.250	1.650	1.050	2.550	1.950	1.050	2.700	2.700	1.050	3.600	3.600	1.350	4.500	5.250	1.800

After conducting energy simulations with HULC, the values for the annual primary energy consumption were obtained for each scenario, as reflected in Figure 6. By applying eq [1], the results obtained were converted into final energy consumption by applying the conversion factor $k_{primary\ energy}$ defined from primary energy to final electrical energy for Spain, which is 2.403 [43]. Admittedly, scenario 0 (the building's envelope without insulation material) presents the highest heating energy demand, then also primary and final energy consumption, and clearly reflects the need and energy advantage of incorporating insulation materials into the building's envelope. The reduction in primary and final energy consumption proportionally lowers to heating energy demand, but does so in a notably less pronounced manner. Table 10 shows these energy indicators after considering the building's entire life span. Most European codes propose a 50-year life span for buildings, and the same period is guaranteed by insulate manufacturers[12,18]. In this study, a 50-year life span was considered for the energy assessment and the eco-efficiency analysis.

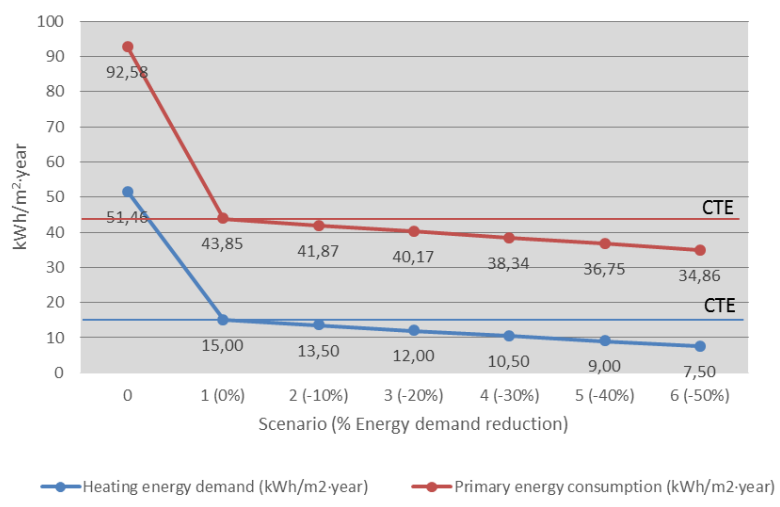


Figure 6. Heating energy demand and primary energy consumption for each energy efficiency scenario

Table 10. Heating energy demand, primary energy consumption and final electricity consumption for a building's 50-year life span

	Heating energy demand		Primary energy consumption	Final energy consumption	Reduction
Scenario	**MWh (50 years)**	**Reduction**	**MWh (50 years)**	**MWh (years)**	**(Primary and final)**
Scenario 0 (without insulation)	716.32	-	1,288.71	536.30	-
Scenario 1 (0%) according to CTE regulations (Baseline)	208.80	0.00%	610.39	254. 01	0.00%
Scenario 2 (-10%) compared to CTE	187.92	-10.00%	582.83	242.54	-4.52%
Scenario 3 (-20%) compared to CTE	167.04	-20.00%	559.17	232.70	-8.39%
Scenario 4 (-30%) compared to CTE	146.16	-30.00%	533.69	222.10	-12.57%
Scenario 5 (-40%) compared to CTE	125.28	-40.00%	511.56	212.88	-16.19%
Scenario 6 (-50%) compared to CTE	104.40	-50.00%	485.25	201.94	-20.50%

5.4 Stage IV. Environmental/Cost assessment of scenarios for each insulation material

5.4.1 Objective and boundary definition

The aim of this study is to compare the environmental and cost performance of a set of alternative insulation materials applied to the building's envelope (roof, façade and floor) by considering the appropriate thickness to achieve a set of energy efficiency scenarios. The insulation materials analysed and the scenarios for each one are defined in Table 5 and Table 10, respectively.

The functional unit (FU) considered herein is the amount of insulation material (kg) needed to provide the R (m^2K/W) required to fulfil each energy efficiency scenario for 50 years [12]. The scope of this study, for each insulation material/scenario, includes the stages of product and construction (A) and use (B) proposed by EN 15804 [36] and shown in detail in Table 2. End-of-life stages (C and D) are beyond the scope of this study since it is the least influential stage when analysing the life cycles of buildings [44].

5.4.2 Environmental/Cost inventory

The inventory data required for the environmental analysis were obtained from Ecoinvent database [22] for GW, EPS, XPS, PUR, FG, MW and C, and in agreement with the conclusions drawn from the literature review (Table 2) and the EN 15978 [6] and EN 15804 [36]Guidelines. The inventory data of those insulation materials not included in this database (SW and RC in blanket and filling form) were obtained from primary sources [42] and were completed with the data from the Ecoinvent database [22].

The inventory data required for the cost analysis (Table 11) were obtained from primary sources, directly from commercial suppliers, and mainly from the official price database BDC IVE [45] for the year 2016. The cost of electricity use in Spain is 0.1182 €/kWh.

Table 11. Commercial insulation material thickness and economic cost

Insulation material	Unit	Commercial thickness (m)	Cost (€/unit)	Source
Glass wool (GW)	m^2	0.030	2.40	[45]
	m^2	0.040	3.20	[45]
	m^2	0.050	3.25	[46]
	m^2	0.060	3.95	[46]
	m^2	0.075	4.15	[46]
Expanded Polystyrene (EPS)	m^2	0.030	6.54	[45]
	m^2	0.040	8.72	[45]
	m^2	0.050	10.90	[45]
	m^2	0.060	13.08	[45]
	m^2	0.070	15.26	[45]
	m^2	0.080	17.44	[45]
	m^2	0.090	16.62	[45]
	m^2	0.100	21.80	[45]
	m^2	0.110	23.98	[45]
	m^2	0.120	26.16	[45]
	m^2	0.130	28.34	[45]
	m^2	0.140	30.52	[45]
	m^2	0.150	32.70	[45]
	m^2	0.160	34.80	[45]
	m^2	0.180	39.24	[45]
	m^2	0.200	43.60	[45]
	m^2	0.220	47.96	[45]
Extruded Polystyrene (XPS)	m^2	0.030	6.59	[45]
	m^2	0.040	8.83	[45]
	m^2	0.050	11.03	[45]
	m^2	0.060	13.24	[45]
	m^2	0.070	15.52	[45]
	m^2	0.080	17.74	[45]
	m^2	0.090	19.96	[45]
	m^2	0.100	22.29	[45]
	m^2	0.120	26.75	[45]
	m^2	0.140	31.20	[45]
	m^2	0.160	35.66	[45]
	m^2	0.180	40.12	[45]
Polyurethane (PUR)	kg	-	3.50	[45]
Foam glass (FG)	m^2	0.020	13.11	[45]
	m^2	0.030	20.79	[45]
	m^2	0.040	26.21	[45]
	m^2	0.050	32.77	[45]
	m^2	0.060	41.58	[45]
	m^2	0.070	45.87	[45]
	m^2	0.080	52.44	[45]
	m^2	0.090	62.37	[45]
	m^2	0.100	65.52	[45]
	m^2	0.110	72.10	[45]
	m^2	0.120	83.16	[45]
	m^2	0.130	85.18	[45]
	m^2	0.140	91.77	[45]
Mineral wool (MW)	m^2	0.040	3.20	[46]
	m^2	0.050	3.75	[46]
	m^2	0.060	4.15	[46]
	m^2	0.080	6.75	[46]
	m^2	0.120	10.10	[46]
Cork (C)	m^2	0.025	7.29	[45]
	m^2	0.030	8.61	[42]
	m^2	0.037	10.83	[45]
	m^2	0.040	11.13	[42]
	m^2	0.050	13.99	[45]
	m^2	0.060	16.70	[42]
	m^2	0.075	21.68	[45]
	m^2	0.080	22.27	[42]
	m^2	0.100	27.89	[42]
Sheep wool (SW-blanket)	m^2	0.050	6.20	[42]
	m^2	0.100	11.70	[42]
Sheep wool (SW-filling)	kg	-	3.80	[42]
Recycled cotton (RC-blanket)	m^2	0.050	3.35	[42]
	m^2	0.100	6.10	[42]
Recycled cotton (RC-filling)	kg	-	2.20	[42]

5.4.3 Environmental/Cost impact assessment

For the environmental impact assessment, each scenario per insulation material was modelled in SimaPro 8.3.2 [47]. By applying CML [31] and ReCiPe[48] as the mid-point and end-point LCIA methods, respectively, environmental impact indicators were obtained for each impact category reported in Table 3 and globally as end-points.

Figure 7 shows the environmental indicators obtained by applying the CML mid-point LCIA method for the global warming impact category, for 1 m^2 of each element of the building's envelope (roof, floor or façade) and per scenario and insulation material. For the remaining impact categories reported in Table 3, the results are included as Supplementary Information A (A2, A5, A8, A11, A14, A17 and A20).

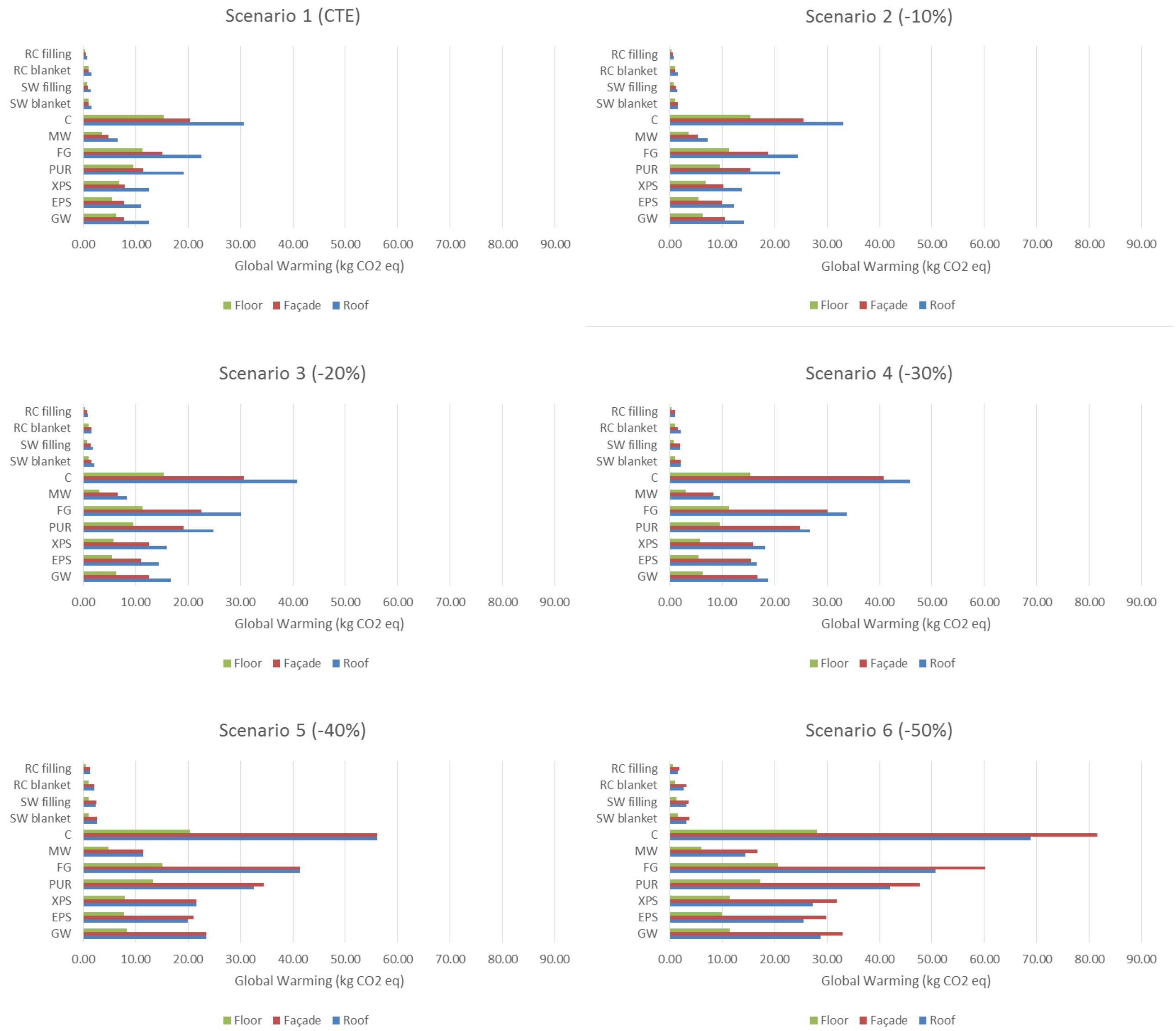


Figure 7. Environmental impact (Global Warming, kg eq. CO_2) per 1 m^2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario

Environmental indicators were also obtained using ReCiPe[48] as the end-point LCIA method (Figure 8).

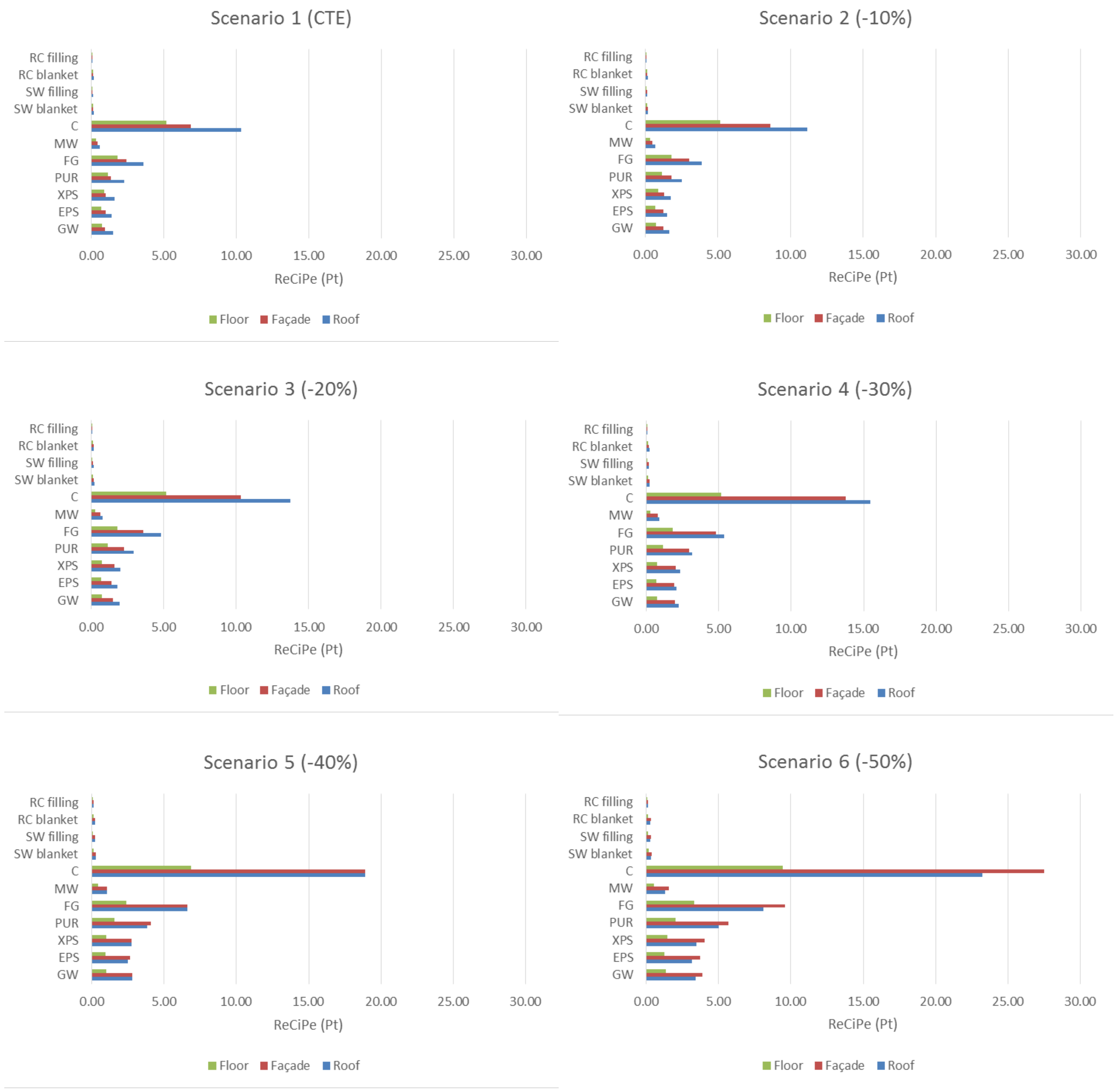


Figure 8. Environmental impact (ReCiPe, Pt) per 1 m^2 of each element of the building's envelope (roof, floor or façade) by type of insulation material and by scenario

Analogously, the cost impact assessment for each scenario per insulation material was made. Figure 9 shows the unitary cost, for 1 m^2 of each element of the building's envelope (roof, floor or façade), for each scenario and per insulation material.

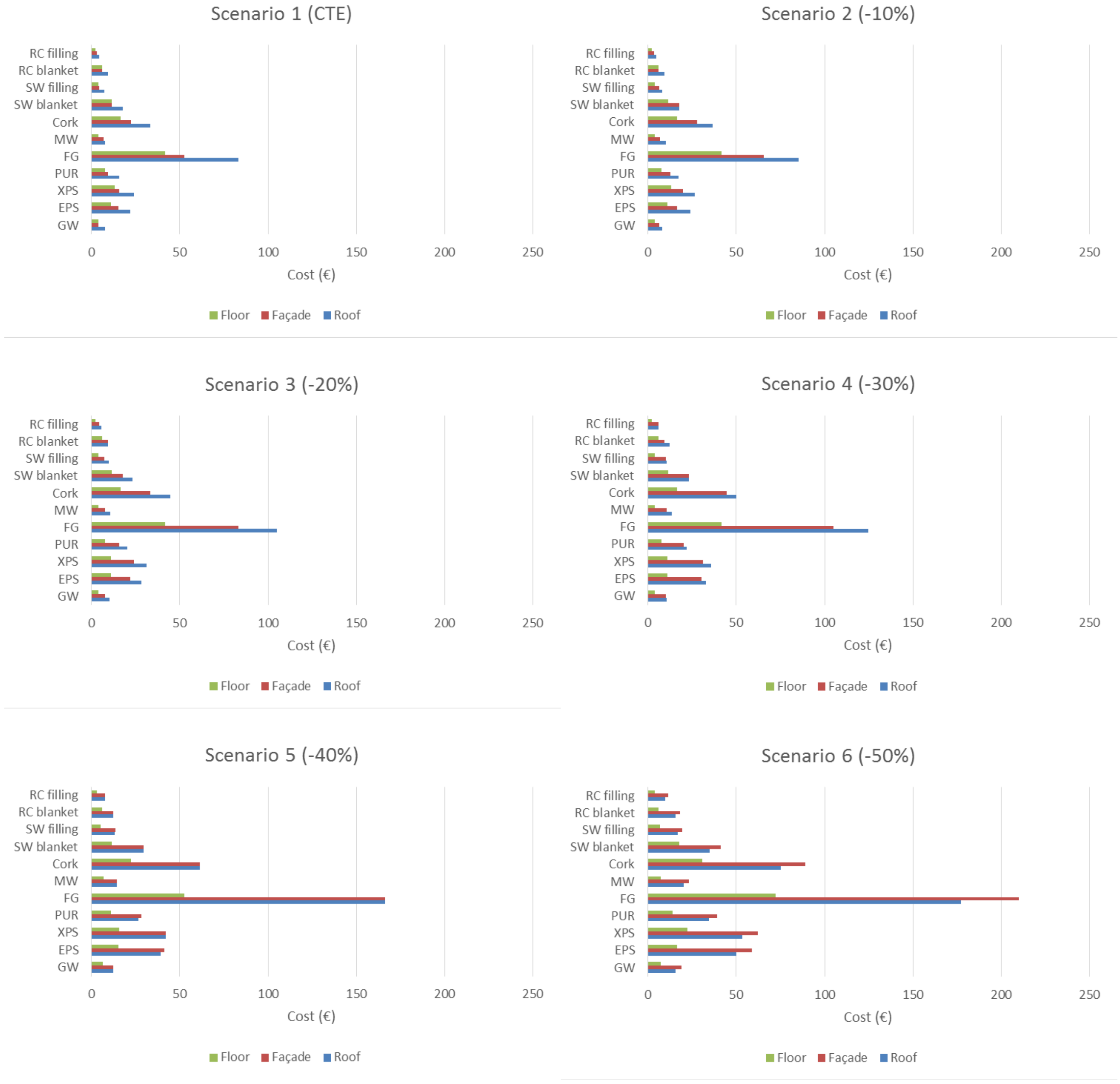
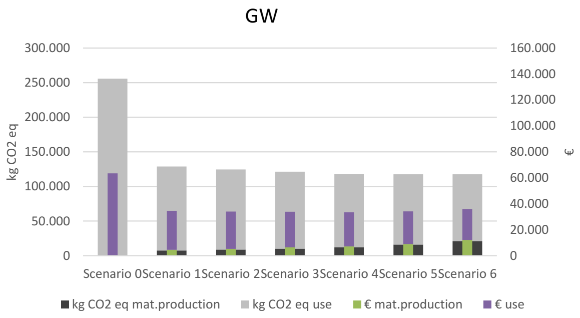
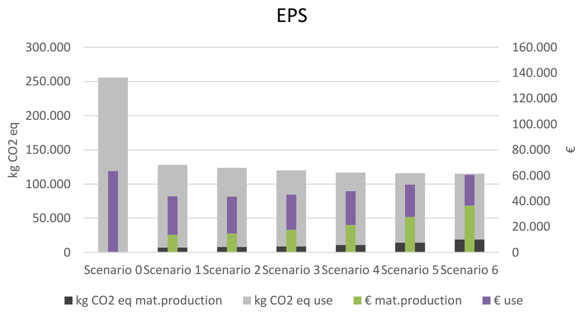


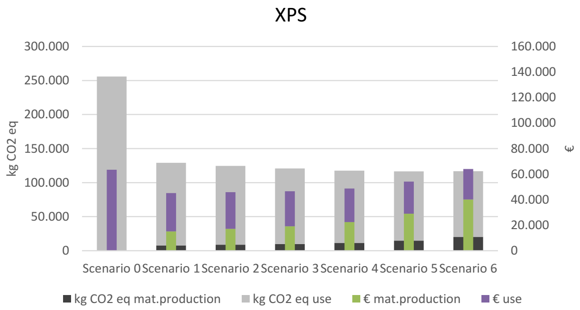
Figure 9. Cost impact (€) per 1 m^2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario

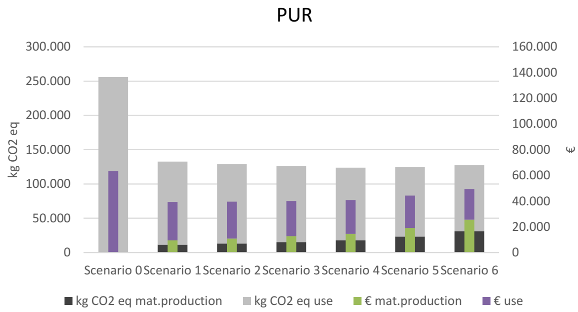
By applying the building's envelope characteristics reported in Table 4 for the roof, façade and floor, and by considering the environmental impact (Figure 7, Figure 8 and Figures A2, A5, A8, A11, A14, A17 and A20 of Supplementary Information A) and the cost impact (Figure 9) per unitary area (1 m^2), the environmental and cost impact assessment for the building under study can be calculated, as Figure 10 and Figure 11 show. Each graph in these figures presents, per insulation material/scenario, the contribution to the environmental (left axis) and cost (right axis) impact during the building's life cycle.

Figure 10 shows the environmental impact calculated for the global warming category according to the CML [31] mid-point LCIA method and the cost (€) for each insulation material considered in the study and for each energy demand scenario. The results for the remaining impact categories are included as Supplementary Information A (Figures A3, A6, A9, A12, A15, A18 and A21). Analogously, Figure 11 presents the environmental impact calculated according to the ReCiPe [48] end-point LCIA method. The cost impact corresponds to the economic cost of the electricity required to supply the building's use stage (for heating, cooling and DHW systems). A 50-year life span of the building and its built area (278.40 m^2) were considered. As referred above, the price of the final electricity in Spain is 0.1182 €/kWh.


GW
300.000
250.000
200.000
150.000
100.000
50.000
0
kg CO2 eq
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production
kg CO2 eq use
€ mat.production
€ use


EPS
300.000
250.000
200.000
150.000
100.000
50.000
0
kg CO2 eq
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production
kg CO2 eq use
€ mat.production
€ use


XPS
300.000
250.000
200.000
150.000
100.000
50.000
0
kg CO2 eq
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production
kg CO2 eq use
€ mat.production
€ use


PUR
300.000
250.000
200.000
150.000
100.000
50.000
0
kg CO2 eq
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
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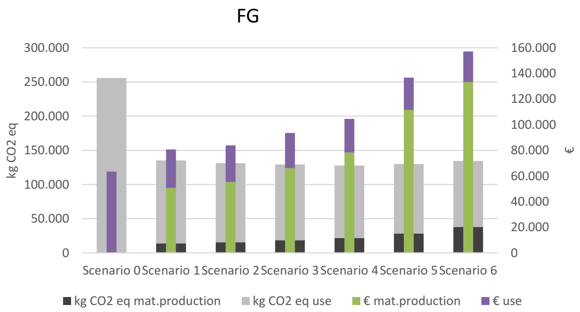
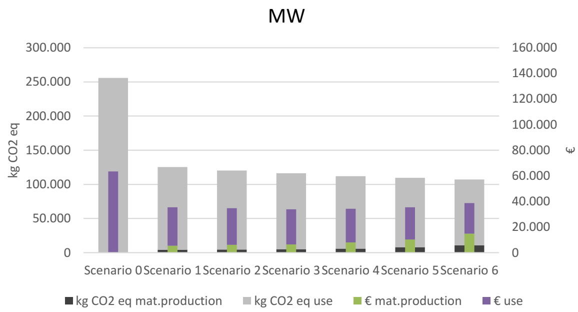
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production
kg CO2 eq use
€ mat.production
€ use


FG
300.000
250.000
200.000
150.000
100.000
50.000
0
kg CO2 eq
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production
kg CO2 eq use
€ mat.production
€ use


MW
300.000
250.000
200.000
150.000
100.000
50.000
0
kg CO2 eq
160.000
140.000
120.000
100.000
80.000
60.000
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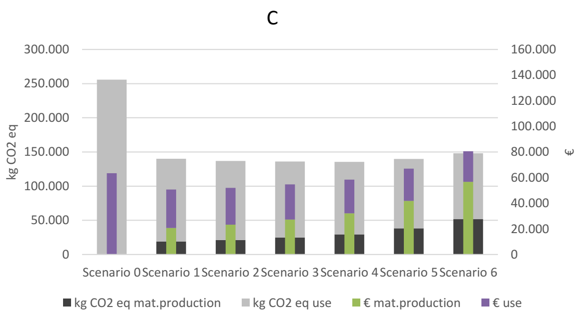
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production
kg CO2 eq use
€ mat.production
€ use


C
300.000
250.000
200.000
150.000
100.000
50.000
0
kg CO2 eq
160.000
140.000
120.000
100.000
80.000
60.000
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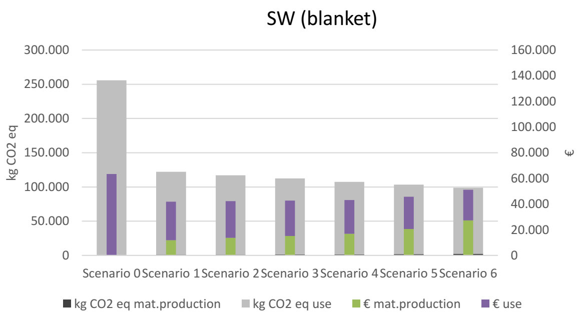
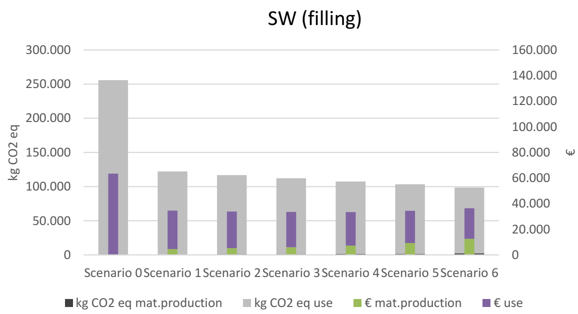
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production
kg CO2 eq use
€ mat.production
€ use


SW (blanket)
300.000
250.000
200.000
150.000
100.000
50.000
0
kg CO2 eq
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production
kg CO2 eq use
€ mat.production
€ use


SW (filling)
300.000
250.000
200.000
150.000
100.000
50.000
0
kg CO2 eq
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production
kg CO2 eq use
€ mat.production
€ use

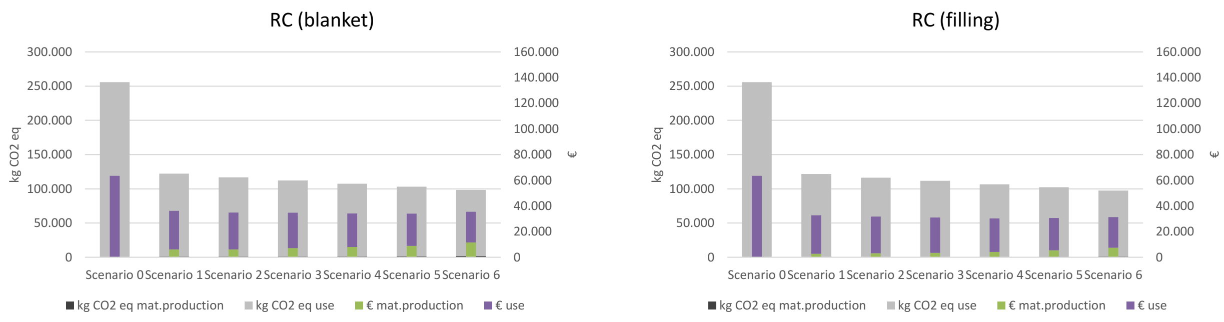
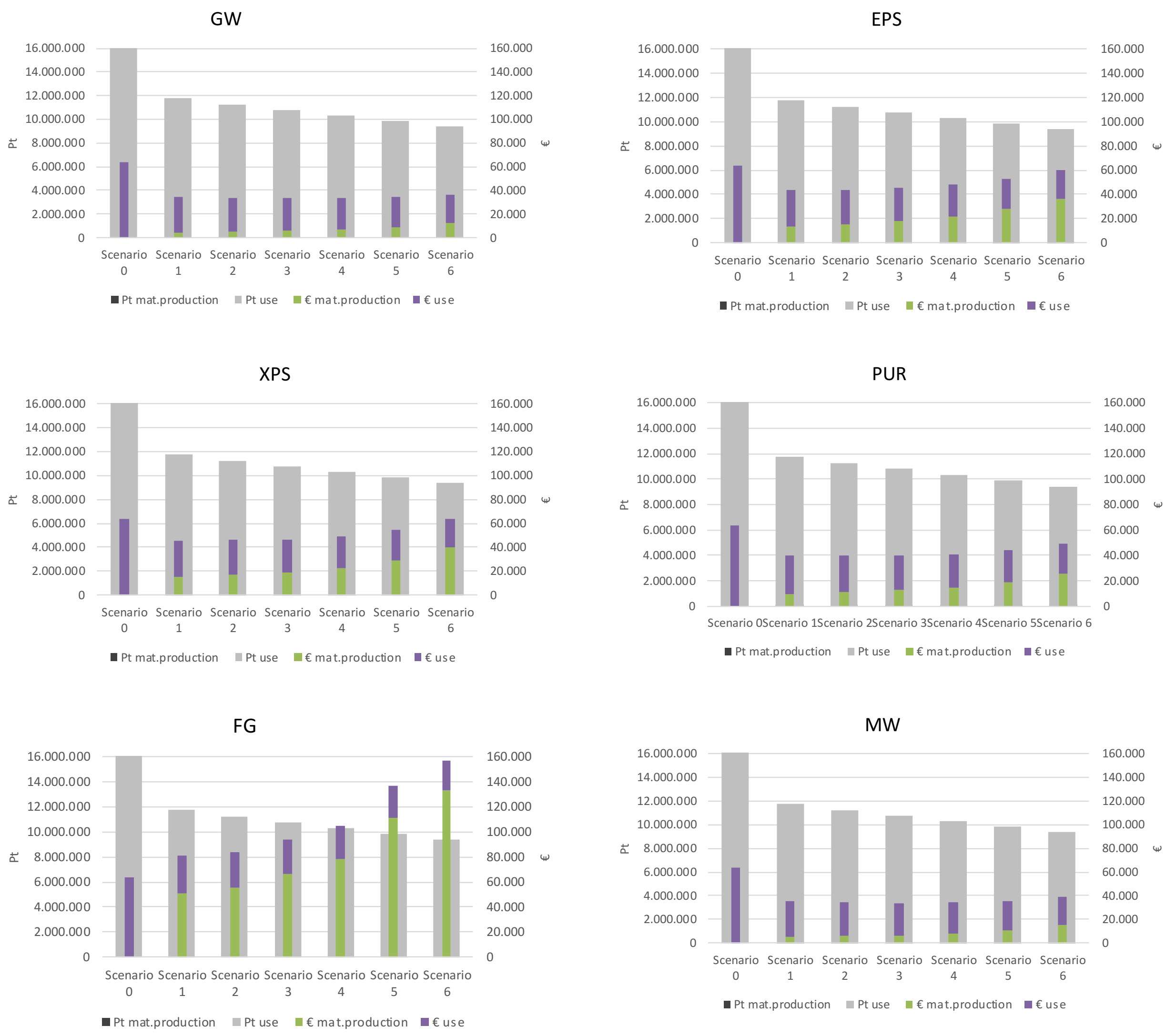


Figure 10. Cost (€) and environmental impact (Global Warming, kg eq. CO_2) for each insulation material and for each scenario



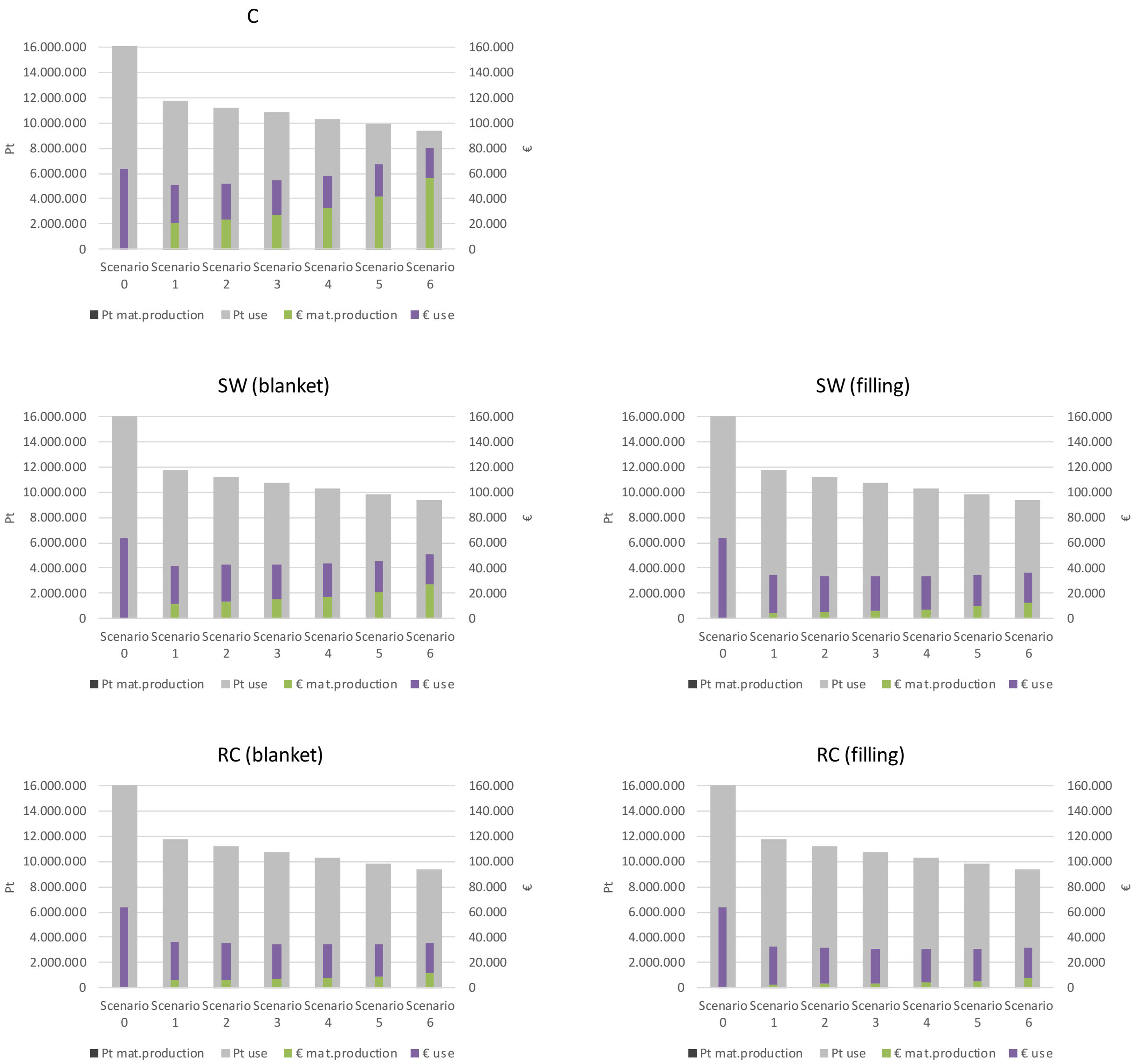


Figure 11. Cost (€) and environmental impact (ReCiPe, Pt) for each insulation material and for each scenario

In Figure 10 we can see that scenario 0 presents only the environmental impact and cost during the building's use stage as there is no insulation material in the building's envelope. As seen, this represents more than twice that of scenario 1 (in accordance with the CTE standard), which confirms the importance of incorporating insulation material in the roof, the façade and the floor of buildings. It is also noted that the material production stage seems negligible compared to the use stage, while the CML method allows this comparison along the seven mid-point categories, as observed in Figure 11 for the ReCiPe.

5.5. Stage V: Eco-efficiency analysis

The results obtained in Stage IV of the methodology can be combined to identify the best economic and environmental optimal insulation material for each scenario, as well as optimal insulation thickness. Eco-efficiency graphs can be used to do so, as described in the Methodology section. Figure 12 and Figure 13 present the eco-efficiency analysis results after considering the Global Warming environmental impact category of the CML mid-point method and the ReCiPe end-point LCIA method, respectively. The total environmental impact is the sum of the environmental impact of the materials and the building energy use stages. The total cost is the sum of the cost of the insulation material and the energy consumed in the building's use stage. Similar graphs were produced for the other mid-point environmental impact categories included in Supplementary Information A (Figures A4, A7, A10, A13, A16, A19 and A22). By analysing these graphs, note that the performance of each insulation material is the same in each energy efficiency scenario.

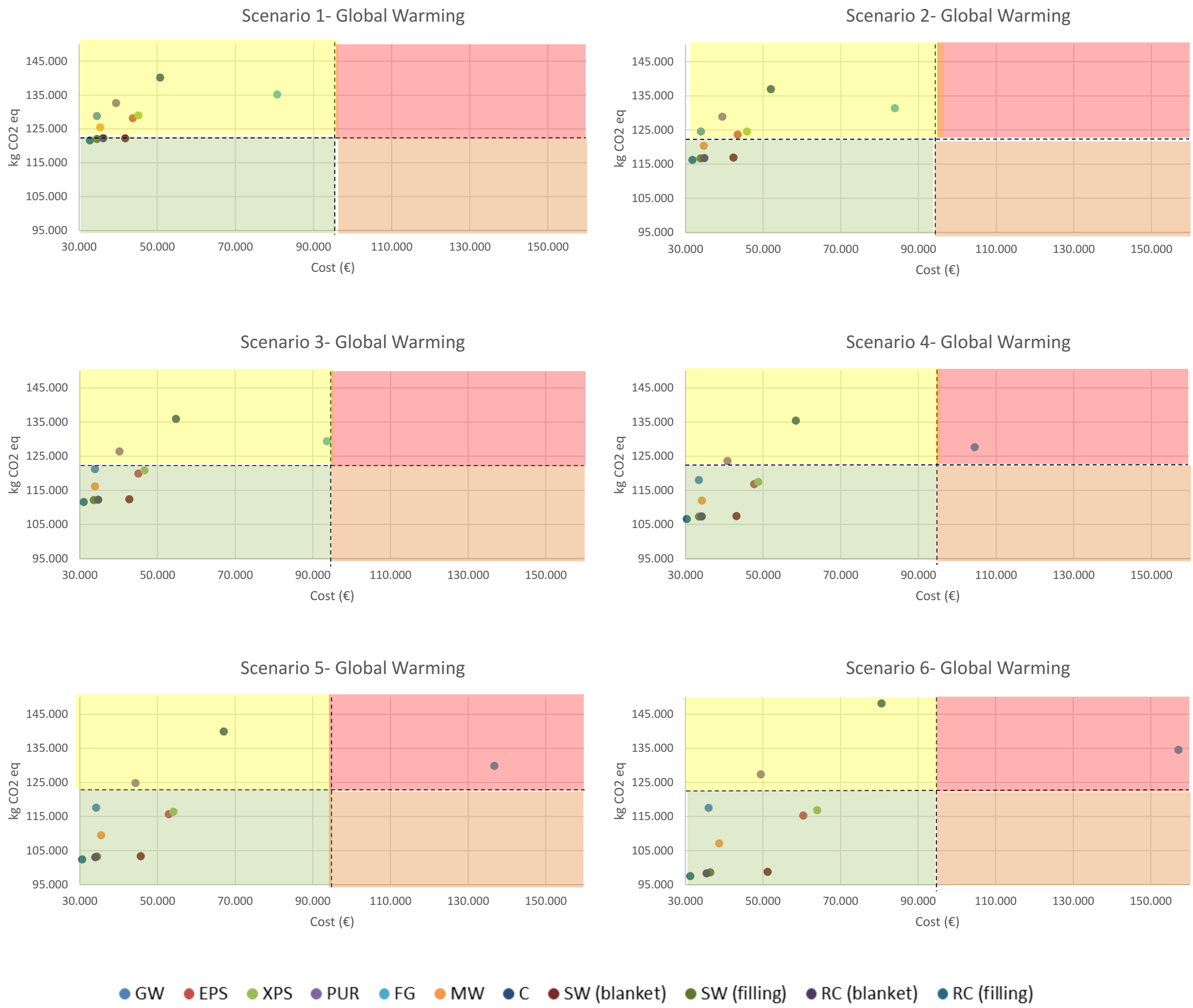


Figure 12. Eco-efficiency analysis: environmental impact (kg eq. CO_2, CML) *vs.* economic cost (€)

Figure 13. Eco-efficiency analysis: environmental impact (Pt, ReCiPe) *vs.* economic cost (€)

Table 12 summarises the results of the eco-efficiency graphs presented in Supplementary Information A. As seen, FG is the lowest eco-efficient material as it remains in areas III and IV (low environmental impact and high cost, and high environmental impact and high cost, respectively) for all the impact categories analysed according to CML method and for ReCiPe. C is the second less efficient insulation material, since it remains in area II for most of the impact categories and ReCiPe. PUR is comprised in area II for all the scenarios for the impact categories depletion of abiotic resources (fossil fuels) and global warming, for the two first scenarios for ozone layer depletion and acidification, and for the three first scenarios for Recipe. For the remaining categories, eco-efficiency is in area I. EPS and XPS perform similarly, and are mainly contained in area I, but obtained their worst results in area II for depletion of abiotic resources (fossil fuels) and photochemical oxidation. The groups formed by GW and MW, and for SW and RC, presents similar results. However, it can be concluded that this last group present the best eco-efficiency results.

Table 12. Eco-efficiency analysis (summary)

	AD		AD (ff)		GlobalW		OLD		PO		AC		EU		ReCiPe	
GW	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
EPS	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
XPS	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
PUR	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
FG	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
MW	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
C	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
SW (blanket)	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
SW (filling)	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
RC (blanket)	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6
RC (filling)	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1	Sc2
	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4	Sc3	Sc4
	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6	Sc5	Sc6

6. Discussion and conclusions

A more detailed study can be conducted for each considered insulation material to identify the optimum energy efficiency scenario for each one by taking into account the results obtained in Figures 10-13 and those included in Supplementary Information A.

The environmental impact trend for the material production stage clearly increases along the scenarios (1 to 6), while the trend for the energy use stage progressively decreases. Concerning cost, the trend is similar for both the material and use stages. However to a certain point, the economic cost of the material stage increases so much that the global cost (the use stages of the material and the building) does not compensate for the reduced global environmental impact (Figure 11). This inflection point was reached differently along the insulation materials, as presented in Table 13, and it determined the optimum energy efficiency scenario for each material and the related optimum insulation material thicknesses.

Table 13. Optimum scenario for each insulation material

		Optimum scenario						Optimum thickness (m)		
		Scenario 1 (CTE-Baseline)	Scenario 2 (-10%)	Scenario 3 (-20%)	Scenario 4 (-30%)	Scenario 5 (-40%)	Scenario 6 (-50%)	Roof	Façade	Floor
Conventional	Glass wool (GW)				•			0.18	0.16	0.06
	Expanded Polystyrene (EPS)		•					0.11	0.09	0.05
	Extruded Polystyrene (XPS)	•						0.11	0.07	0.07
	Polyurethane (PUR)	•						0.10	0.06	0.05
	Foam glass (FG)	•						0.12	0.08	0.06
Natural	Mineral wool (MW)			•				0.14	0.11	0.05
	Cork (C)	•						0.12	0.08	0.06
	Sheep wool (SW-blanket)	•						0.15	0.10	0.10
	Sheep wool (SW-filling)				•			0.19	0.18	0.07
	Recycled cotton (RC-blanket)					•		0.20	0.20	0.10
	Recycled cotton (RC-filling)				•			0.18	0.18	0.07

It can be generally stated that traditionally used insulation materials, such as XPS and PUR, are appropriate to fulfil CTE minimum standards (baseline scenario) but not when higher energy demand reductions are wanted to be accomplished. EPS best performs in scenario 2, which implies a 10% energy demand reduction compared to CTE standards. A 20% reduction is optimum for MW and a 30% reduction for GW, SW and RC, these last two in the filling form. A 40% reduction is appropriate only for RC in blanket form. SW in blanket form shows its optimum in scenario 1, due to its thermal conductivity is higher than in the filing form and then performs worse.

FG and C were the lowest eco-efficient materials and were restricted only to scenario 1. The results reveal that an unlimited increase in insulation thickness does not imply better eco-efficiency in all the types of materials due to the cost factor. So it is not worth using these insulation materials in the global building's envelope and their use should be restricted occasionally to specific purposes; i.e. FG for thermal bridges and certain critical points of the thermal envelope with condensation problems (facilitated by the high μ of FG). In relation to C, similar conclusions were obtained in [28], which revealed that it has greater impact than EPS, XPS, PUR and MW for the majority of impact categories. It is important to remark that the LCI model applied for C from the Ecoinvent database [22] (cork slab), allocates to the raw cork, used as raw material in addition to agglomeration resins, the environmental impact due to the harvesting, thinning, final cutting and under bark processes. The same does not occur for the LCI model of the other natural insulation materials (SW and RC), since they are secondary materials produced from waste.

In agreement with [28], these conclusions support the idea that not all natural insulation materials are related to low environmental impacts. Nevertheless, this is not the case of the emerging natural materials analysed herein, which found that recycled cotton and sheep wool offered excellent eco-efficiency. This means that they combine good environmental performance, good energy performance for the building, together with a low economic cost.

The optimum energy efficiency scenario reveals the optimum thickness to be employed for each insulation material. The findings of this study show that the emerging materials based on natural products (SW and RC), together with conventional GW and MW, are the most eco-efficient as their increased thickness implies significant energy demand reductions at low-cost and low-environmental impact; e.g., as depicted in Table 13, for RC a thickness of 0.20m in the building's roof, 0.20m in the façade and 0.10 m in the floor produce a 40% heating demand reduction compared to the CTE standards (scenario 5). Clearance of thickness depends on the form in which RC is used because the filling form allows thickness to be adjusted to the minimum required to fulfil the specific scenario, while the blanket form has still a narrow range of commercial thicknesses (5 and 10 cm), which leads to oversizing insulation thickness. In line with this, the use of these kinds of insulation materials should be promoted and generalised so that manufacturing companies can provide the market with a wider range of commercial formats in a cost-effective way. Thermal conductivity (λ) differs between the blanket and filling forms, with 0.036 and 0.044, respectively, due to the difference in density. This is also the reason why the RC blanket requires a slight thickness than the RC filling to acquire the same energy efficiency level.

With SW, optimum thickness lies in scenario 4 with a 30% heating demand reduction compared to CTE when considering the filling form. This means a thickness of 0.19m in the building's roof, 0.18m in the façade and 0.07m in the floor. Thermal conductivity is the same for the filling and blanket forms, so the filling form allows to better adjust thickness to the minimum required, and then performs better. Intermediate thicknesses are optimum for GW, with 0.18m in the building's roof, 0.16m in the façade and 0.06m in the floor, which lead to scenario 4.

As seen in the case of SW and RC, different values for thermal conductivity of the blanket and filling forms cause results to vary. This also applies to the rest of the insulation materials, whose thermal conductivity (λ-value) would affect the conclusions drawn. This work has been developed with mean λ-values, which have been extracted from official databases, manufacturers and research literature, as reflected in Table 5. However, it should be kept in mind that this may represent a limitation of the study, since different λ-values for the same insulation material can be found in the market of the construction industry.

The life span selected for the building may also be susceptible to affect the results of the study. To deal with this issue, different durations (30 and 70-years life span) were explored and the results concluded that, generally, the optimum thickness for each insulation material is maintained along the time, it means for the same scenarios found in the case of 50-years building life span. Thus, the trend is similar for every environmental impact category and for every energy demand scenario: RC in filling and blanket forms, SW (filling) and MW are presented as the most eco-efficient materials; while C and FG as the least. Slight and minor variations are found regarding SW (blanket), EPS, XPS, PUR and GW, depending on the impact category. Analogous graphs to Figure 11, for 30-years and 50-years life span of the building, are presented in Supplementary information A, in Figures A26 and A27, respectively.

All things considered, this study provides a content analysis of some conventional and naturally-based emerging insulation materials, which include not only the life cycle stages of product and construction (A) and use (B) stated by EN 15804 [36], but also the environmental, energy and cost aspects. From these findings, it can be concluded that using some specific natural insulation materials, such as sheep wool and recycled cotton, along with traditionally-used mineral and glass wool, should be promoted in the construction industry as they provide high eco-efficient performance according to current European standards. These findings can help different stakeholders, e.g., architects, building engineers, manufacturing companies of insulation materials and legislators, in the challenging way to reach the NZEB buildings target.

This study was applied herein to a single-family house, but the same methodology can be replicated to other kinds of buildings, such as multi-family buildings, and to other climatic zones or country regulations. The results can be compared to explore foreseeable variations among different case studies. Finally, it is noteworthy that the social argument is also encouraged by EN 15804 [36],so future efforts should be made to integrate it into sustainability assessments of building components.

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Supplementary Information A

Figures A2 to A22 show the remaining results of the impact categories and insulation materials, considering 50-year lifespan of the building. Firstly, Figures A2, A5, A8, A11, A14, A17, A20 and A23 present the environmental impact per 1 m^2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario, per impact category. Figures A3, A6, A9, A12, A15, A18, A21 and A24 the cost and environmental impact of each insulation material per impact category. Figures A4, A7, A10, A13, A16, A19, A22 and A25 present the eco-efficiency analysis, it means, environmental impact vs. economic cost.

Figures 26 and 27 present the cost and environmental impact of each insulation material for ReCiPe, considering 30-year and 70-year lifespan of the building, respectively.

Finally, figure A1 presents the legend for insulation materials used.

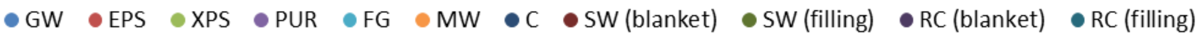


Figure A1. Legend of insulation materials in Figures A4, A7, A10, A13, A16, A19 and A22 (eco-efficiency analysis)

Abiotic depletion

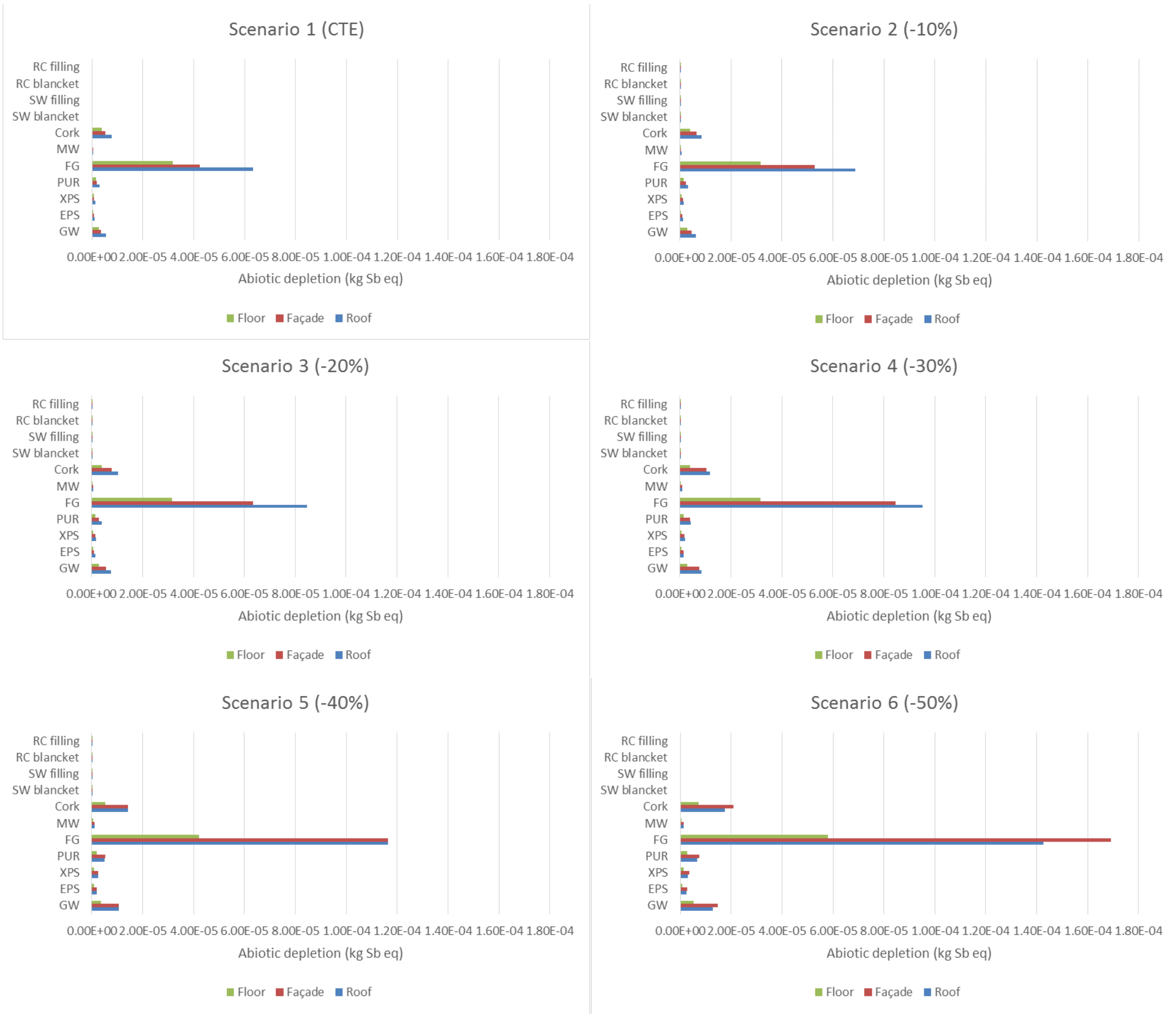
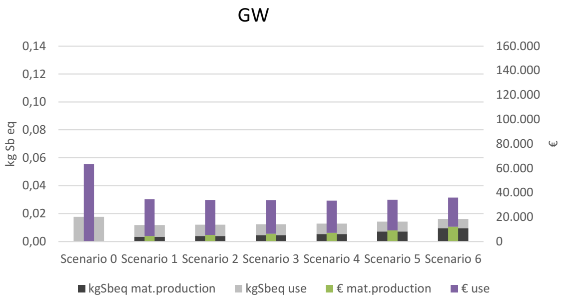


Figure A2. Environmental impact (Abiotic depletion, kg Sb eq) per 1 m2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario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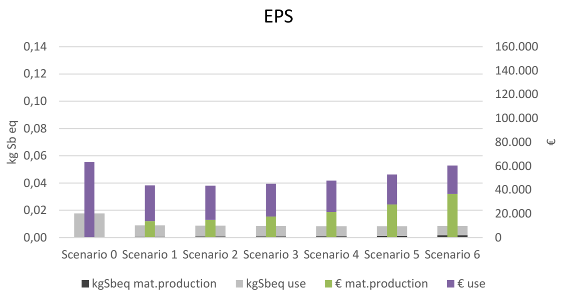
kgSbeq use
€ mat.production
€ use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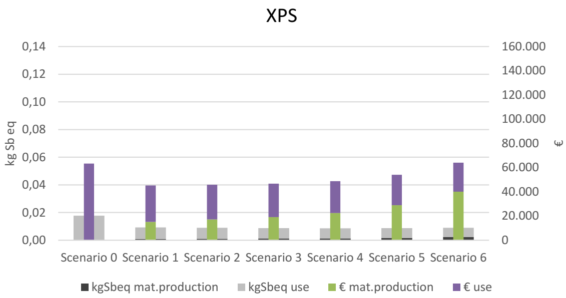
kgSbeq mat.production
kgSbeq use
€ mat.production
€ use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kgSbeq use
€ mat.production
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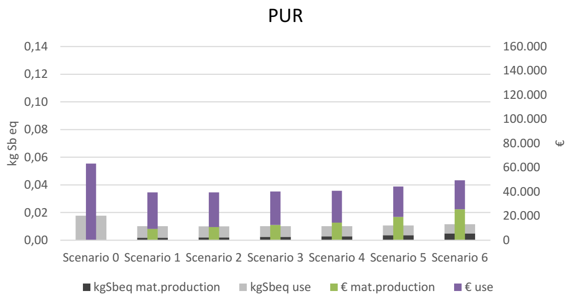
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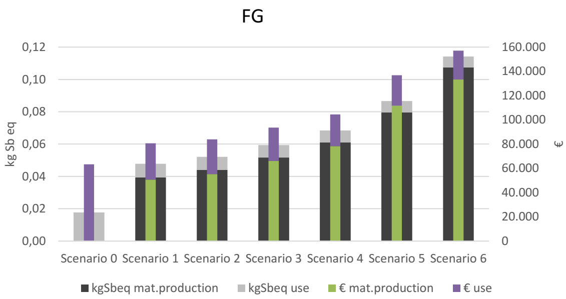
kgSbeq mat.production
kgSbeq use
€ mat.production
€ use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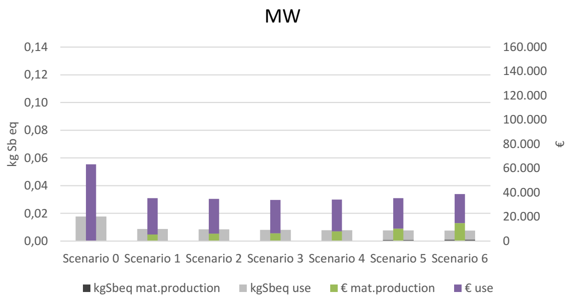
kgSbeq mat.production
kgSbeq use
€ mat.production
€ use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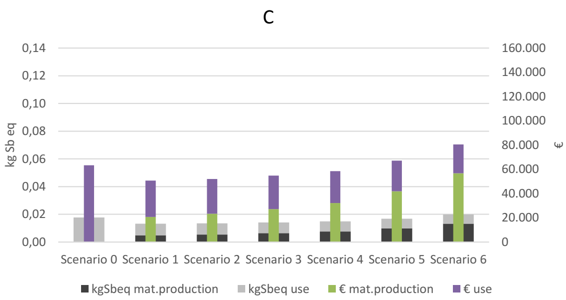
kgSbeq use
€ mat.production
€ use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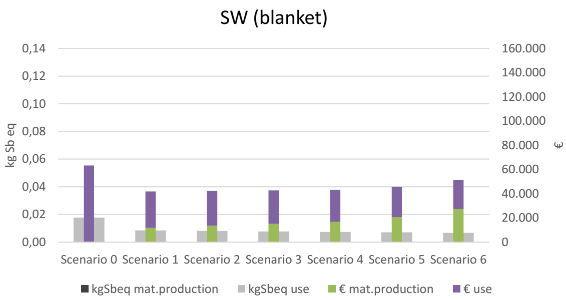
kgSbeq mat.production
kgSbeq use
€ mat.production
€ use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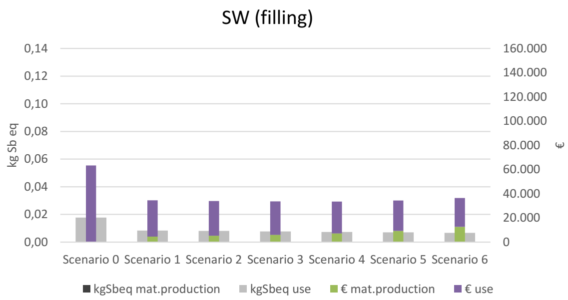
kgSbeq mat.production
kgSbeq use
€ mat.production
€ use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kgSbeq mat.production
kgSbeq use
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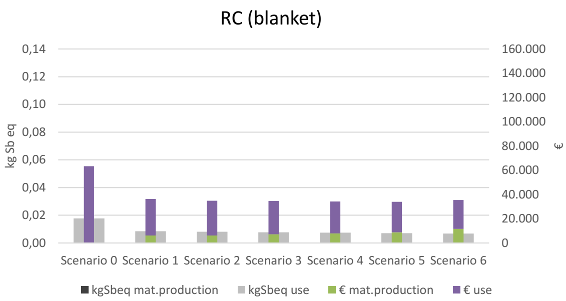
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kgSbeq mat.production
kgSbeq use
€ mat.production
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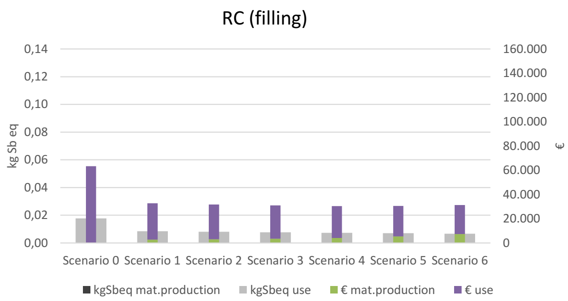
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Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSbeq mat.production
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Figure A3. Cost and environmental impact of insulation material: Abiotic depletion, kg Sb eq

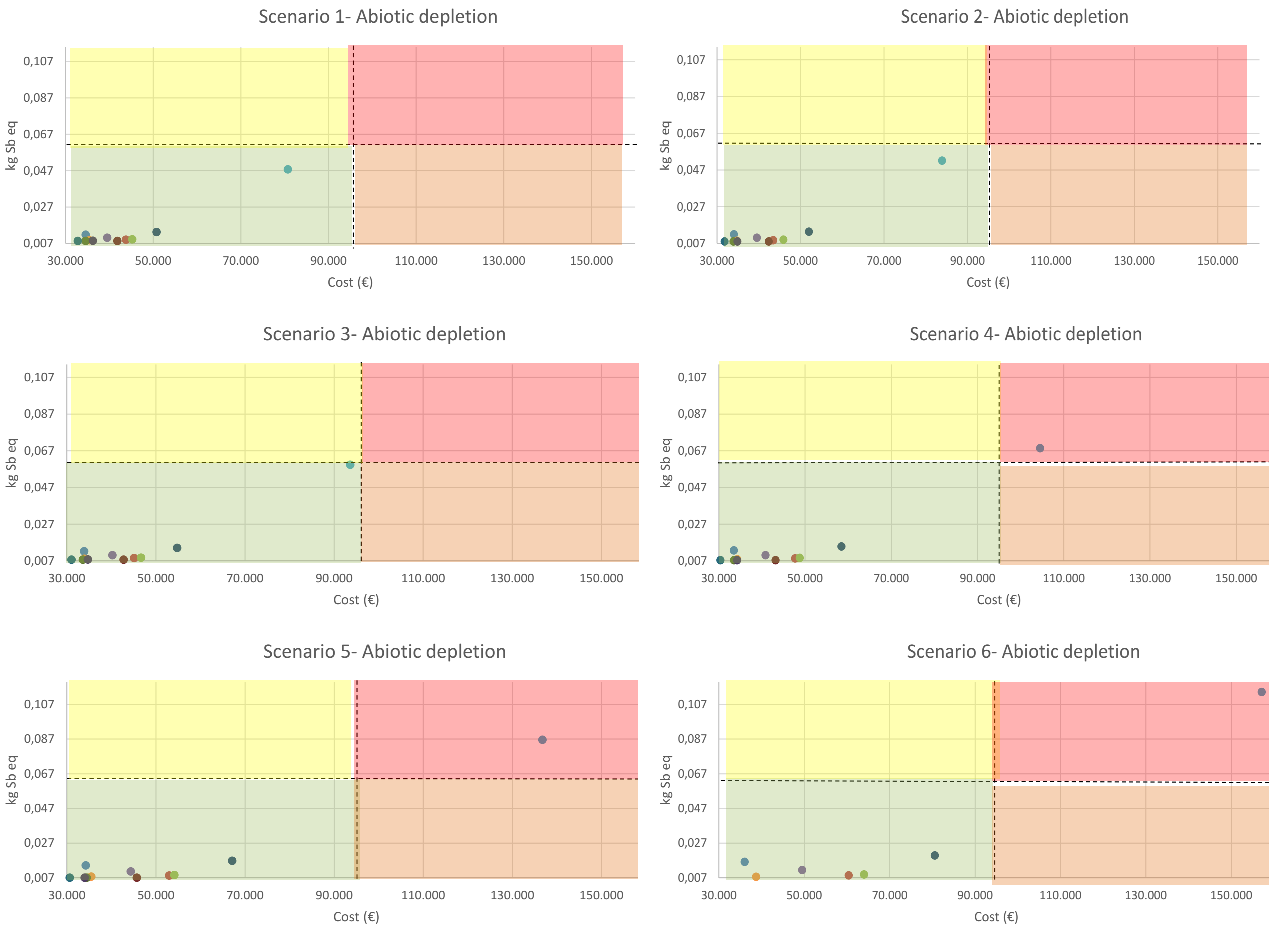


Figure A4. Eco-efficiency analysis: environmental impact (Abiotic depletion, kg Sb eq) vs economic cost (€)

Abiotic depletion (fossil fuels)

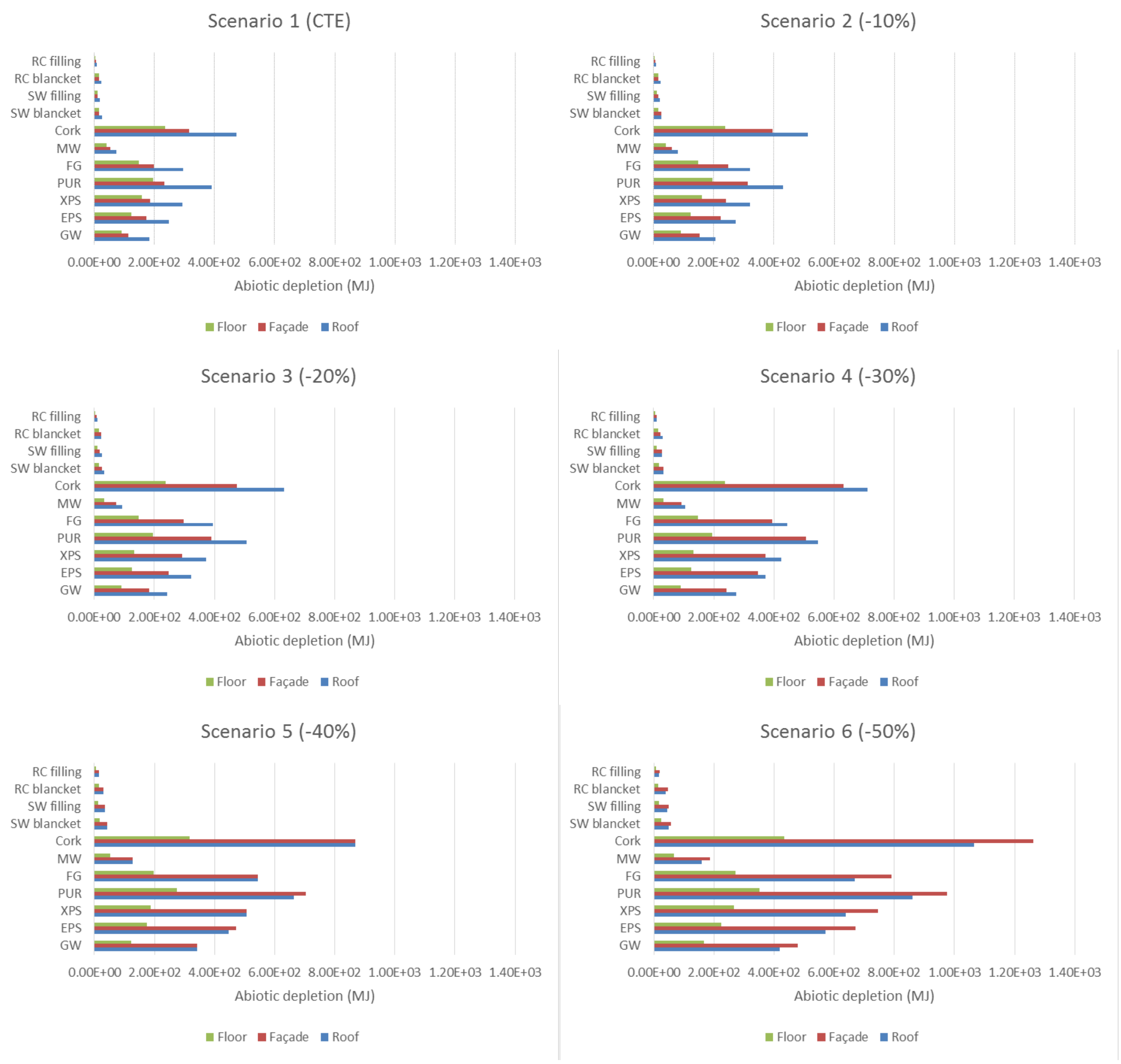
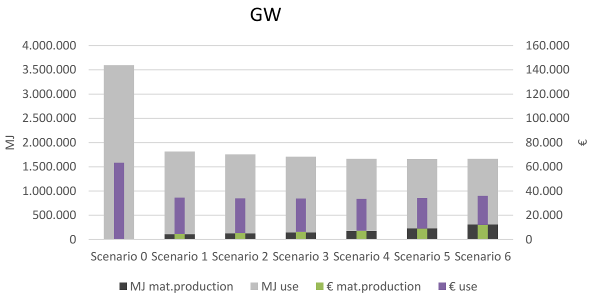


Figure A5. Environmental impact (Abiotic depletion fossil fuels, MJ) per 1 m2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario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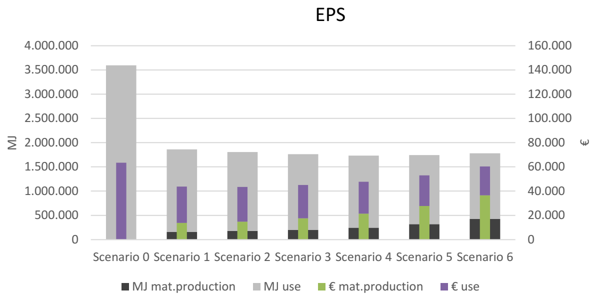
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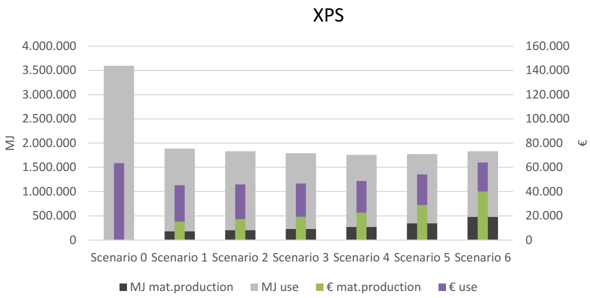
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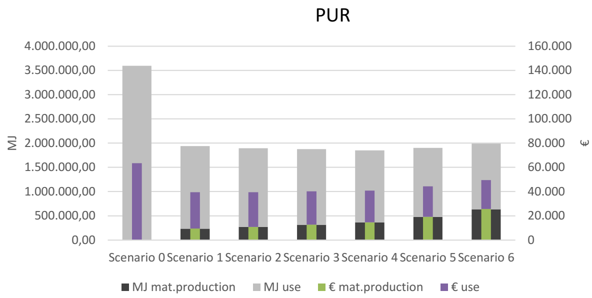
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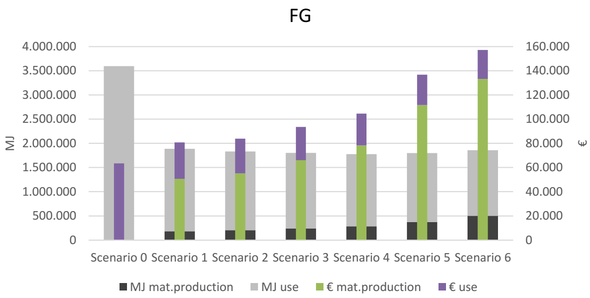
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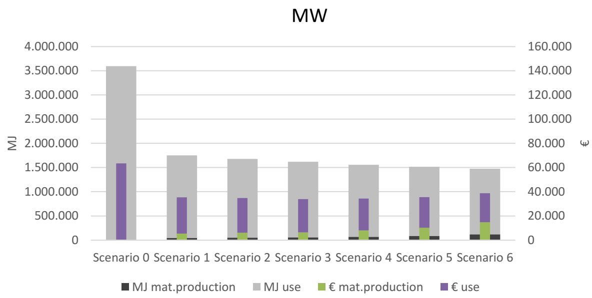
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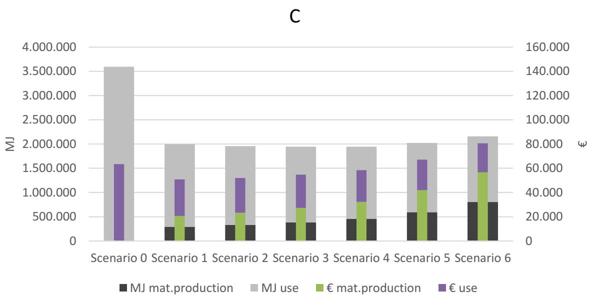
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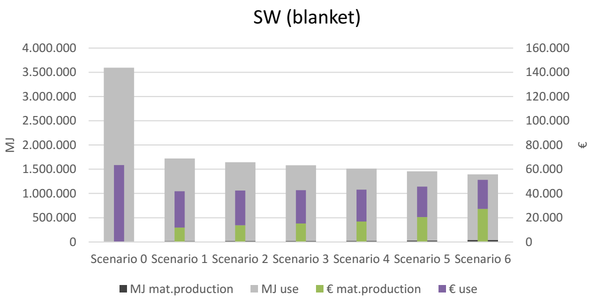
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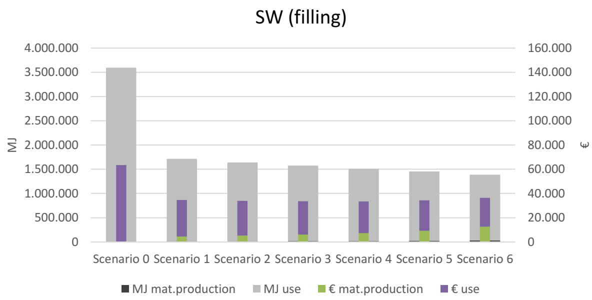
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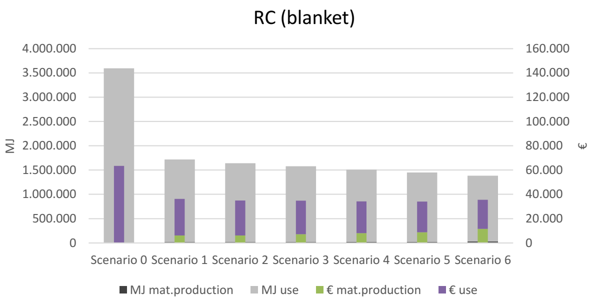
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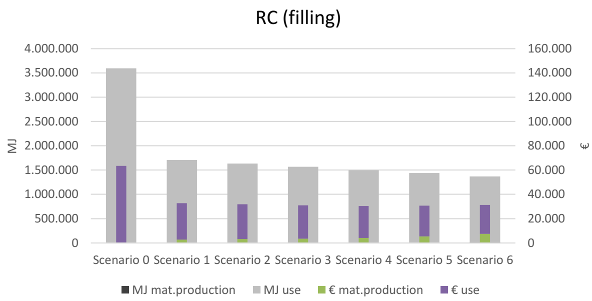
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MJ use
€ mat.production
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Figure A6. Cost and environmental impact of insulation material: Abiotic depletion fossil fuels, MJ

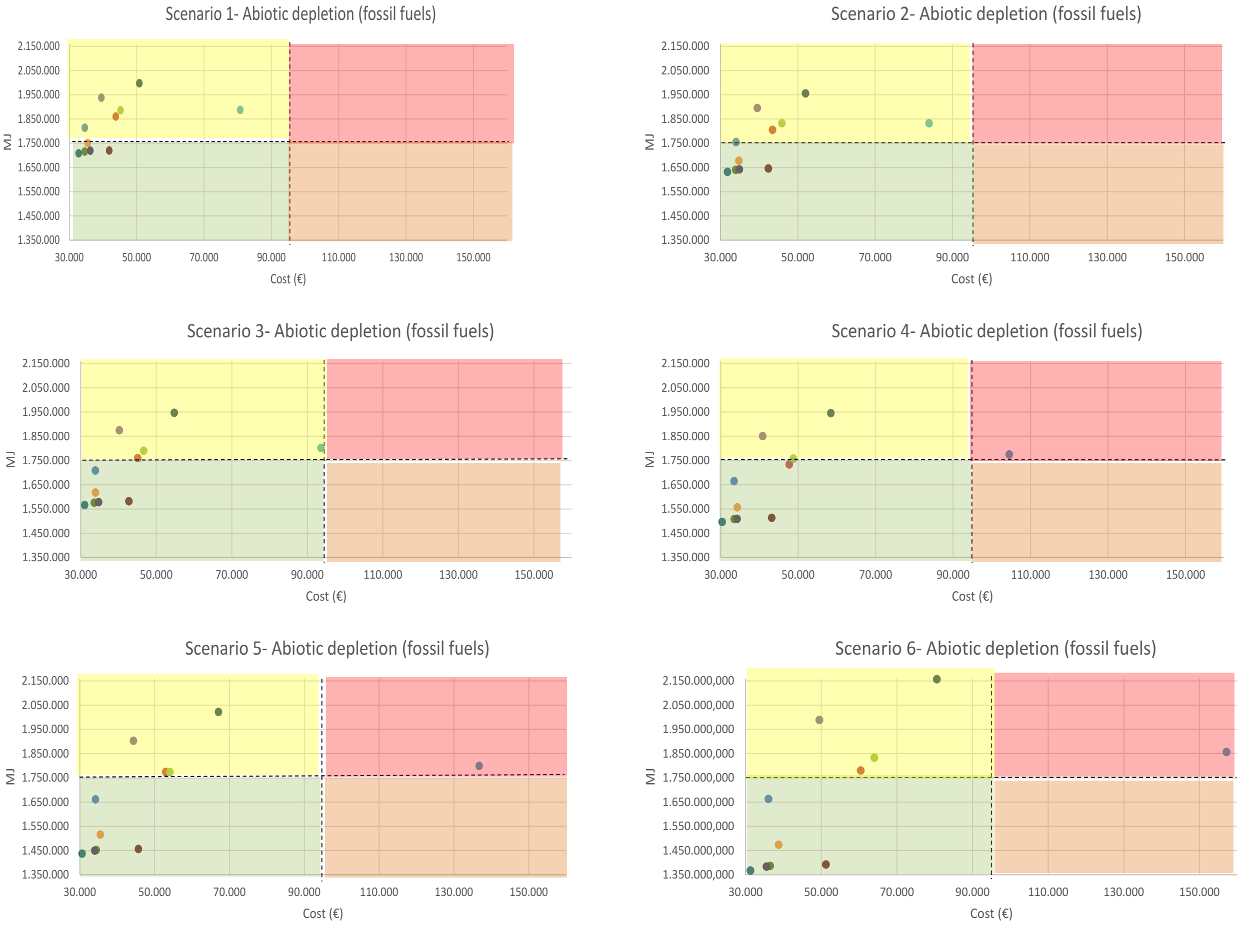


Figure A7. Eco-efficiency analysis: environmental impact (Abiotic depletion for fossil fuels, MJ) vs economic cost (€)

Global warming

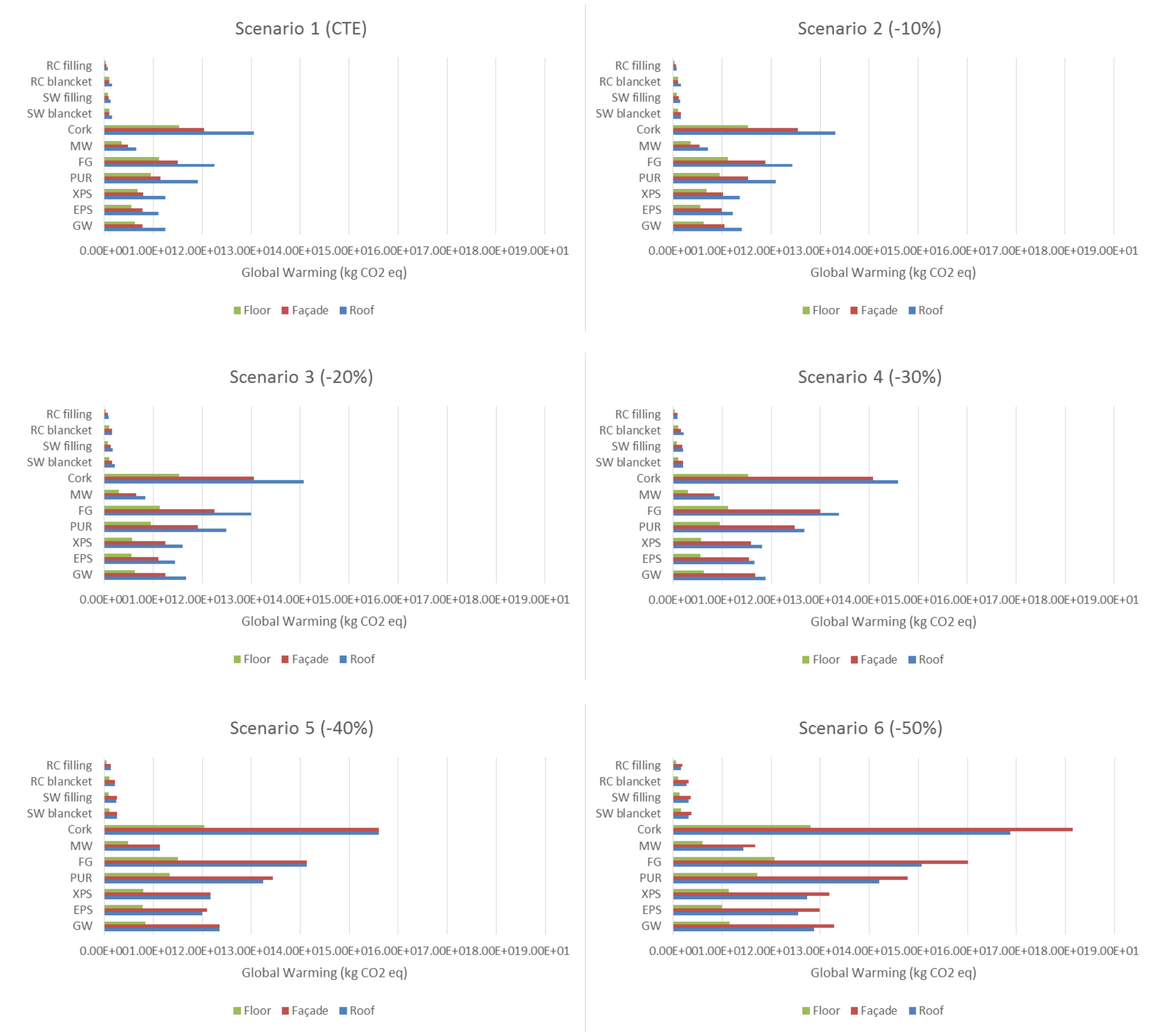
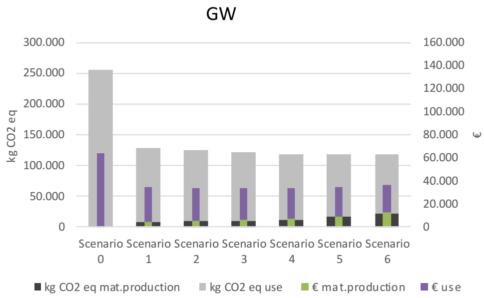
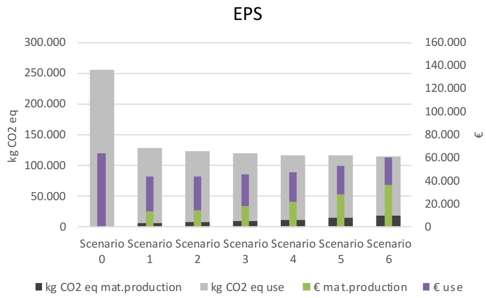
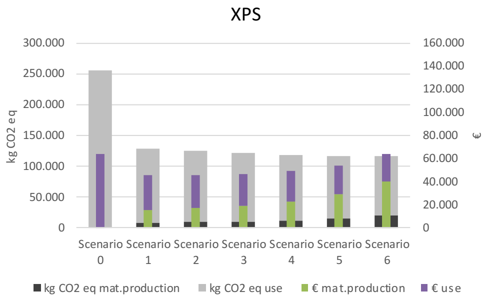
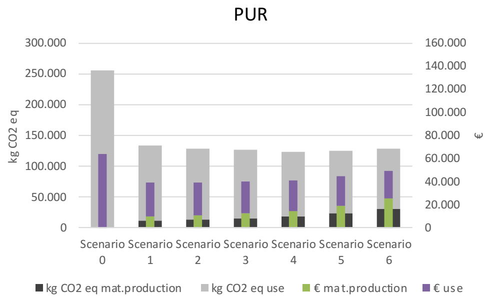


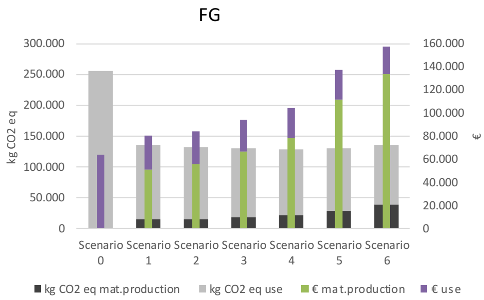
Figure A8. Environmental impact (Global Warming, kg CO2 eq) per 1 m2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario

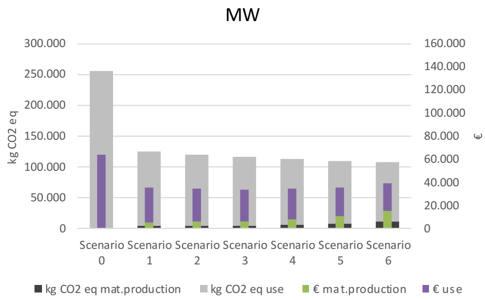

GW
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use

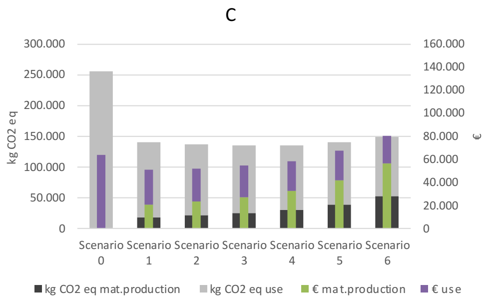

EPS
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use

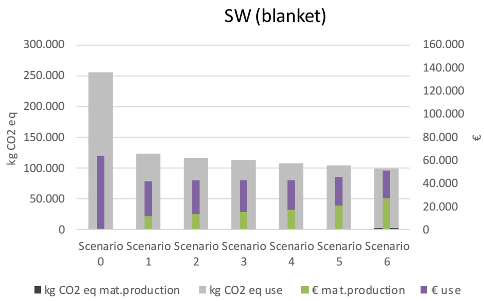

XPS
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use

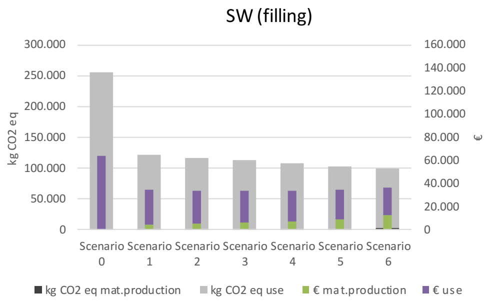

PUR
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use

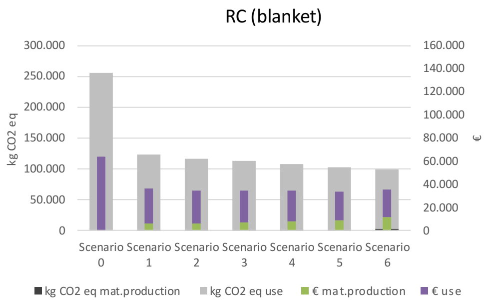

FG
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use


MW
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use


C
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use


SW (blanket)
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use


SW (filling)
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use


RC (blanket)
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use

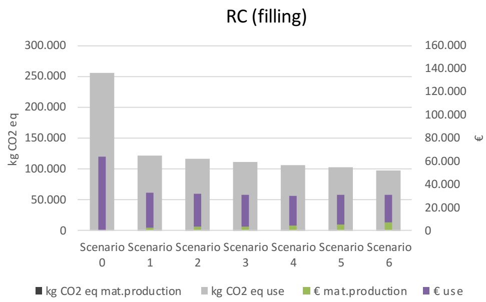

RC (filling)
kg CO2 eq
€
300.000 250.000 200.000 150.000 100.000 50.000 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kg CO2 eq mat.production kg CO2 eq use € mat.production € use

Figure A9. Cost and environmental impact of insulation material: Global Warming, kg CO2 eq

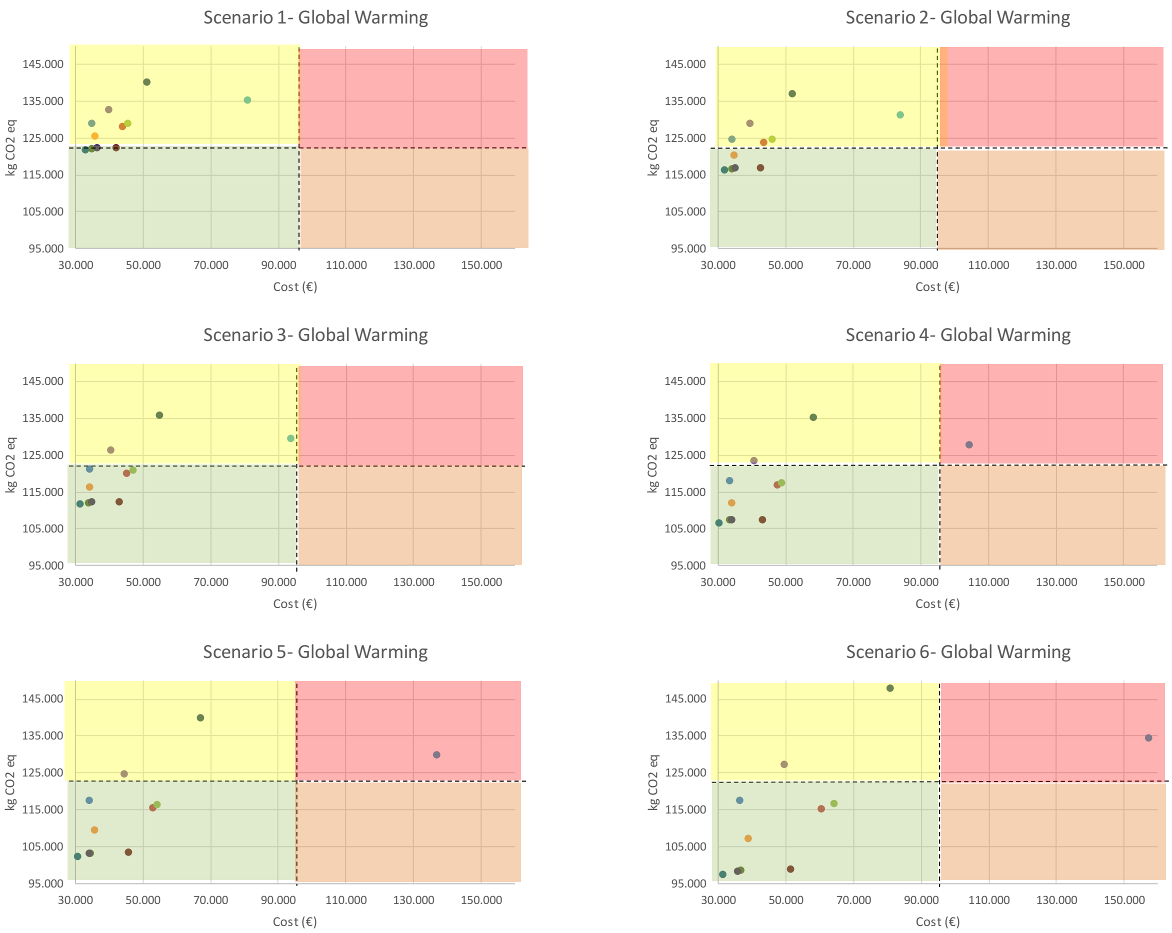


Figure A10. Eco-efficiency analysis: environmental impact (Global warming, kg CO2 eq) vs economic cost (€)

Ozone layer depletion

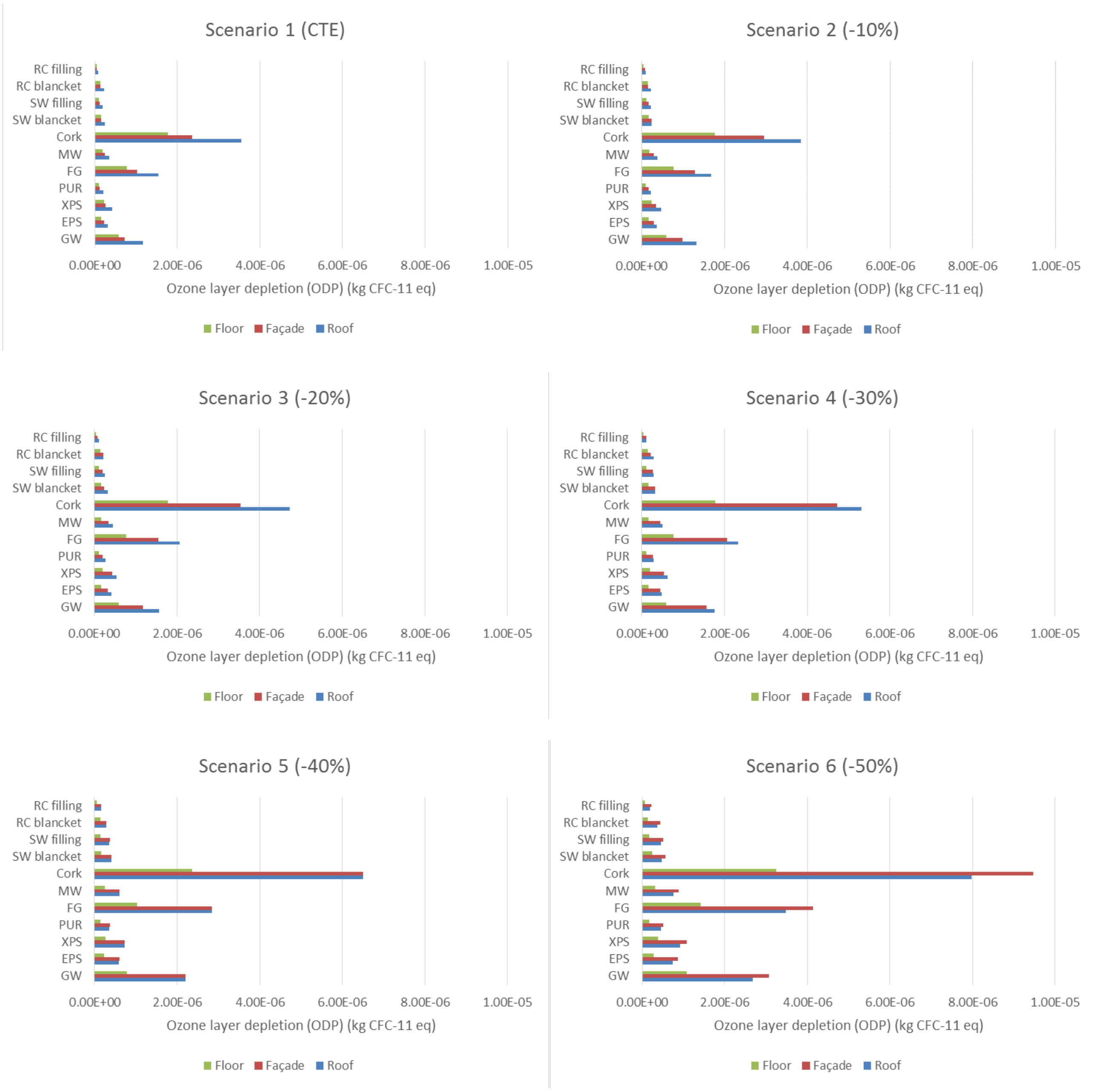
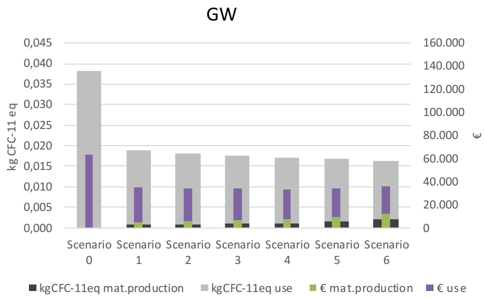
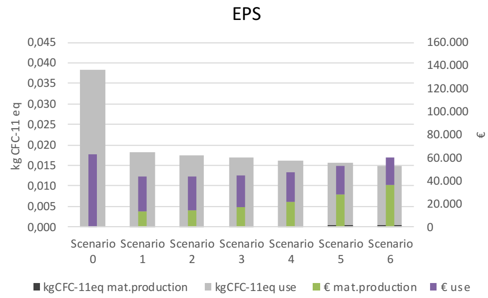
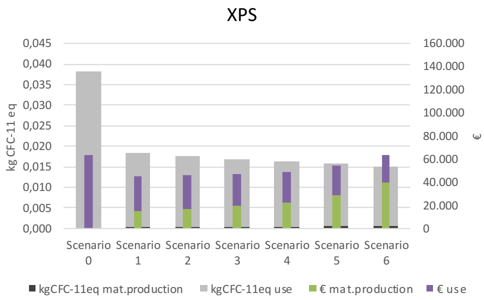
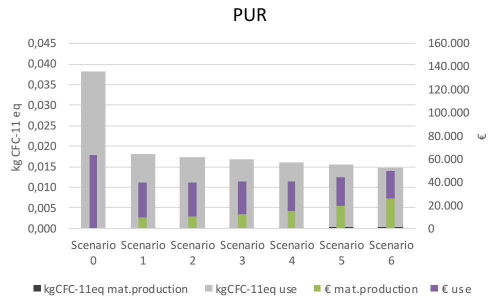


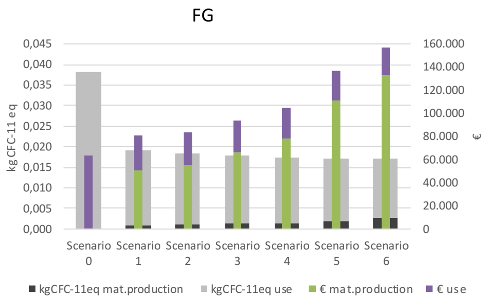
Figure A11. Environmental impact (Ozone layer depletion, kg CFC-11 eq) per 1 m2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario

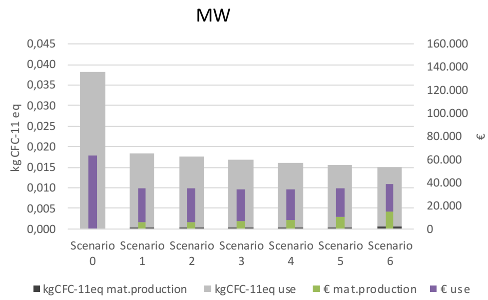

GW
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use

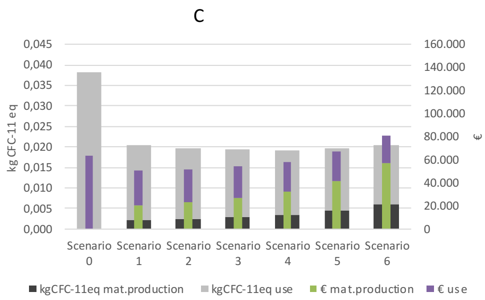

EPS
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use

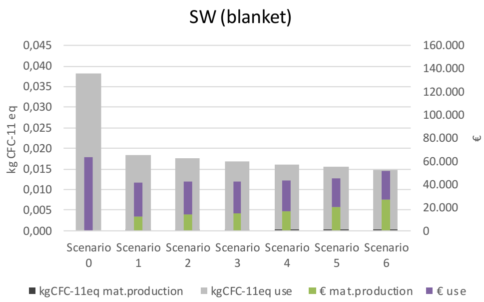

XPS
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use

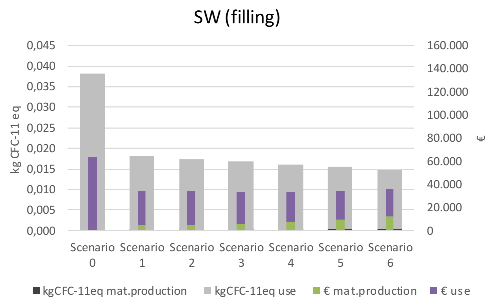

PUR
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use

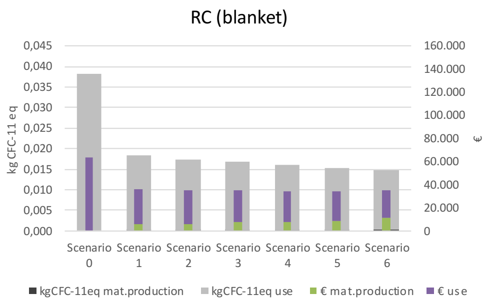

FG
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use


MW
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use


C
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use


SW (blanket)
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use


SW (filling)
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use


RC (blanket)
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use

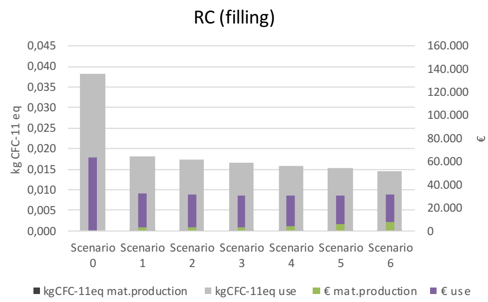

RC (filling)
kg CFC-11 eq
0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgCFC-11eq mat.production
kgCFC-11eq use
€ mat.production
€ use

Figure A12. Cost and environmental impact of insulation material: Ozone layer depletion, kg CFC-11 eq

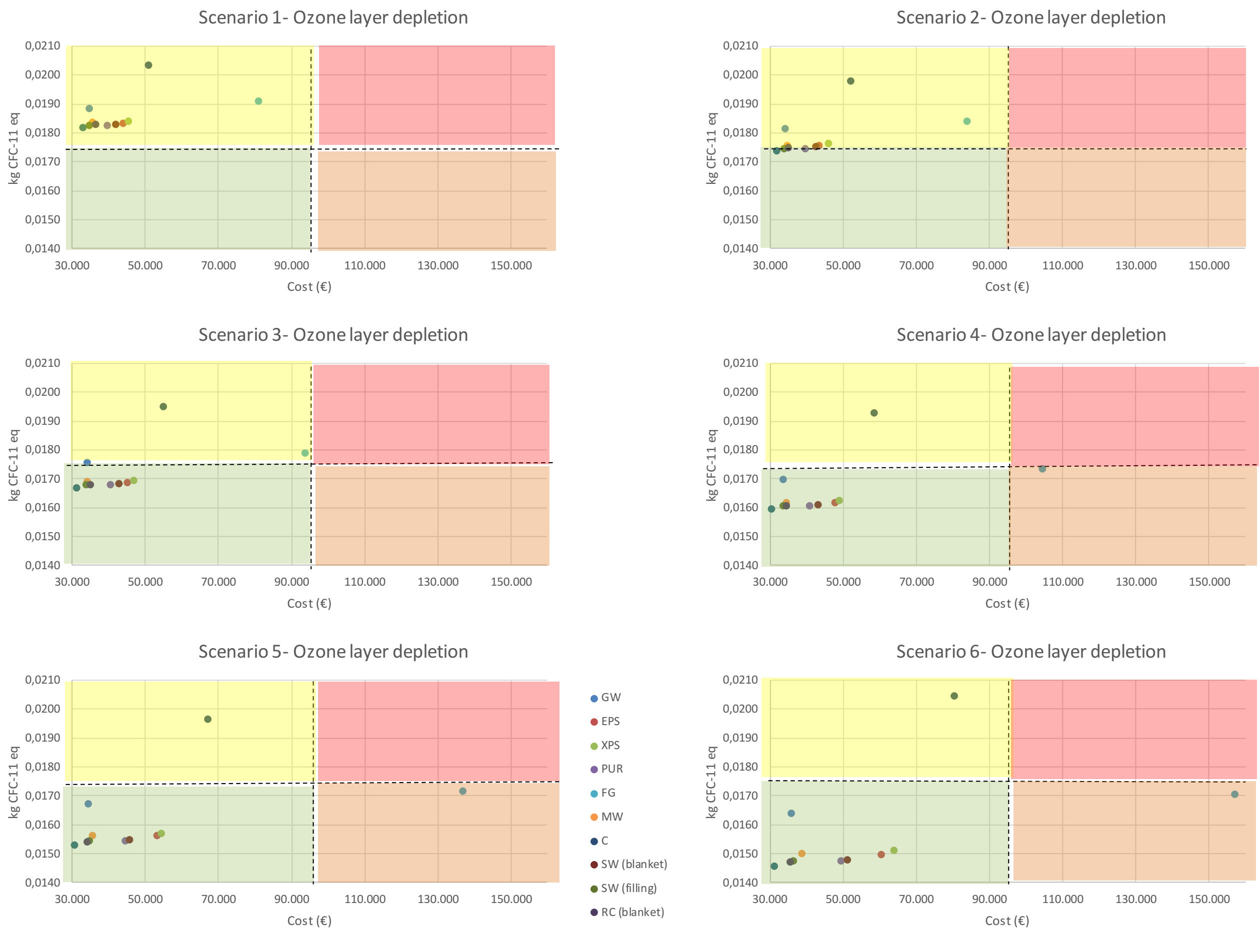


Figure A13. Eco-efficiency analysis: environmental impact (Ozone layer depletion, kg CFC-11 eq) vs economic cost (€)

Photochemical oxidation

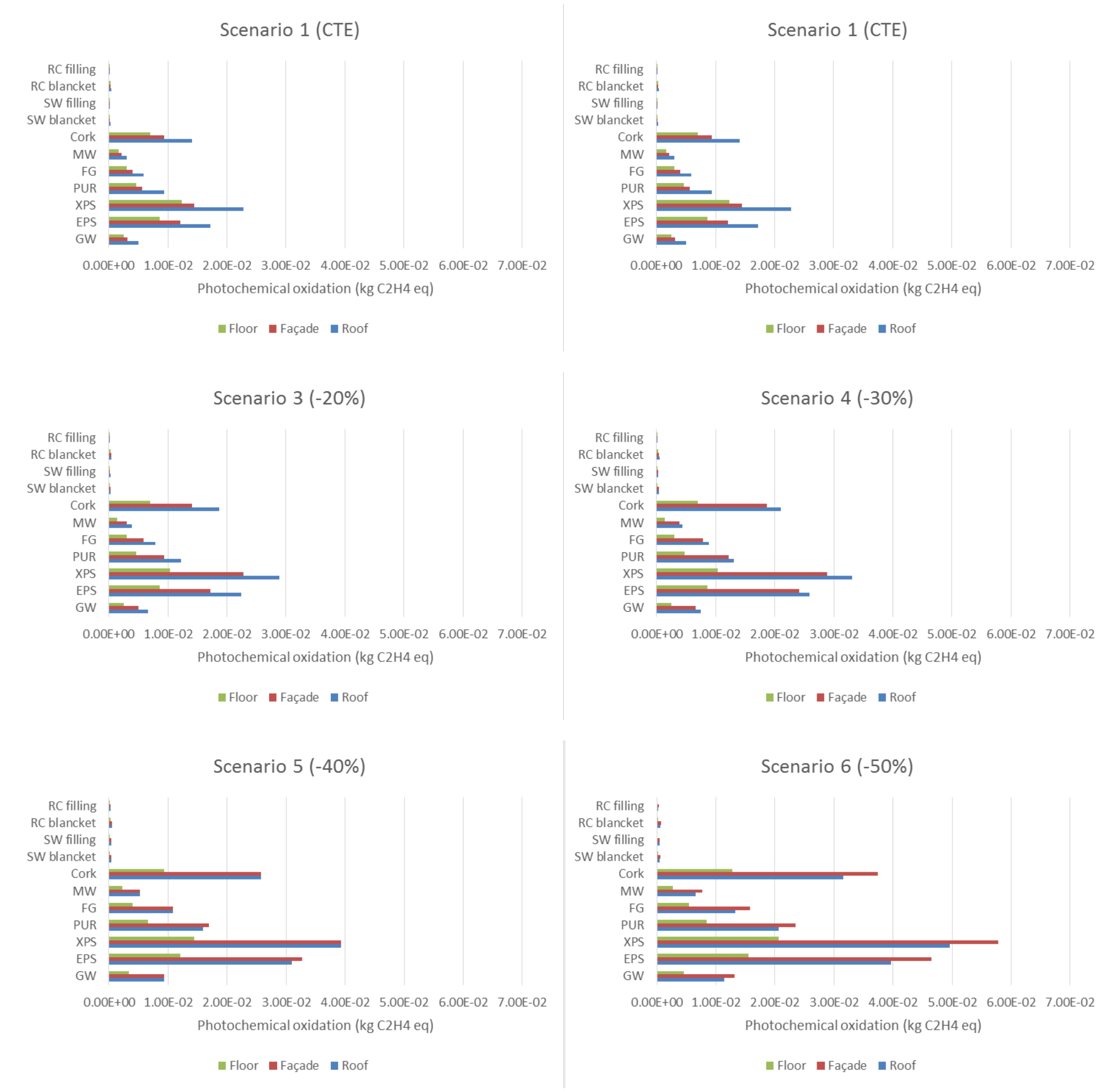
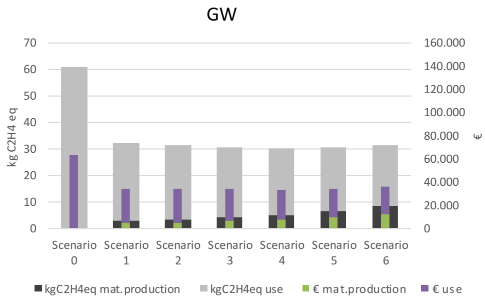
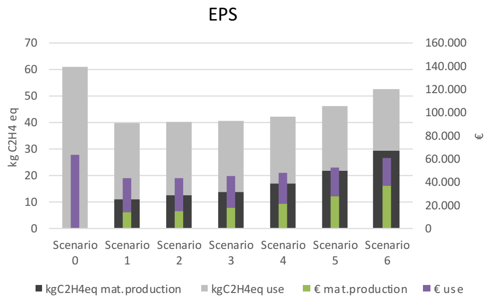
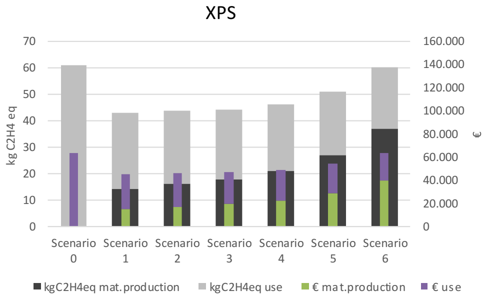
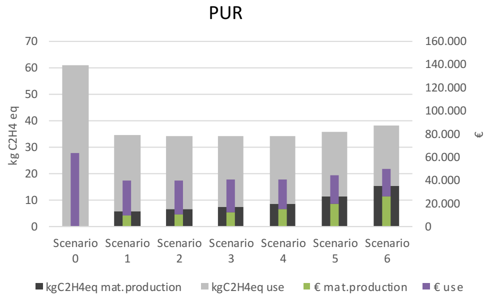


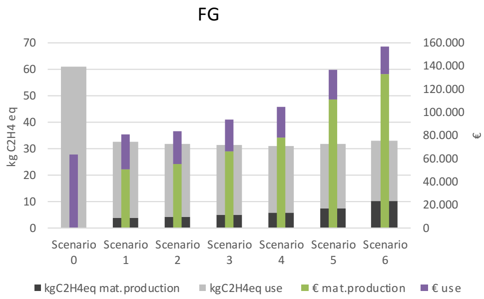
Figure A14. Environmental impact (Photochemical oxidation, kg C2H4 eq) per 1 m2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario

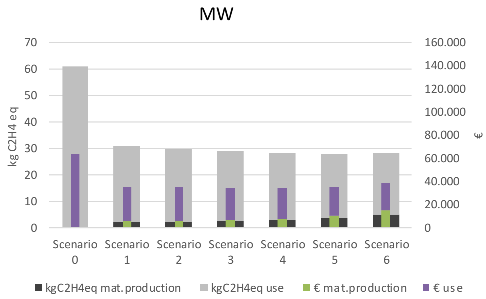

GW
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use

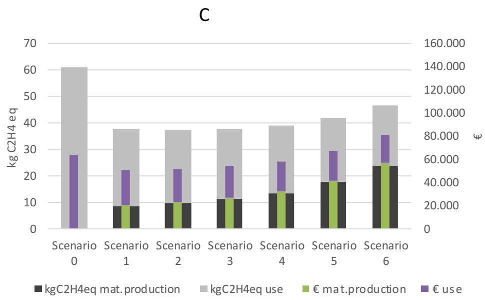

EPS
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use

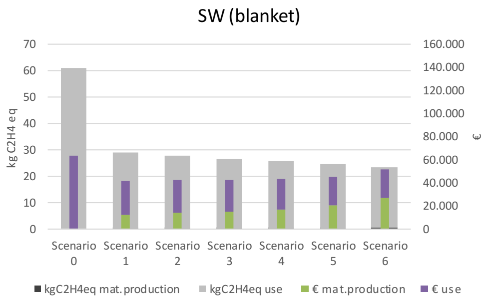

XPS
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use

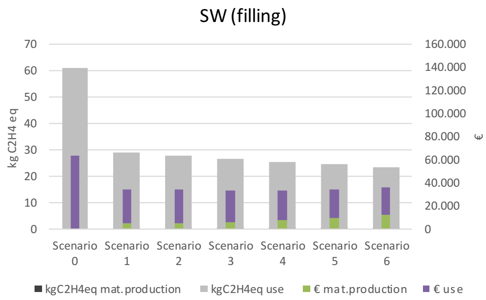

PUR
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use

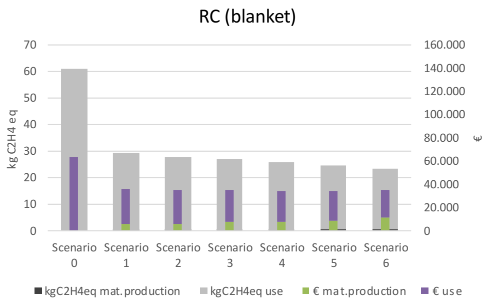

FG
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use


MW
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use


C
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use


SW (blanket)
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use


SW (filling)
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use


RC (blanket)
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use

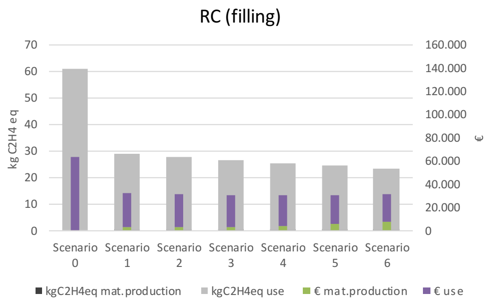

RC (filling)
kg C2H4 eq
0 10 20 30 40 50 60 70
0 20.000 40.000 60.000 80.000 100.000 120.000 140.000 160.000
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgC2H4eq mat.production kgC2H4eq use € mat.production € use

Figure A15. Cost and environmental impact of insulation material: Photochemical oxidation, kg C2H4 eq

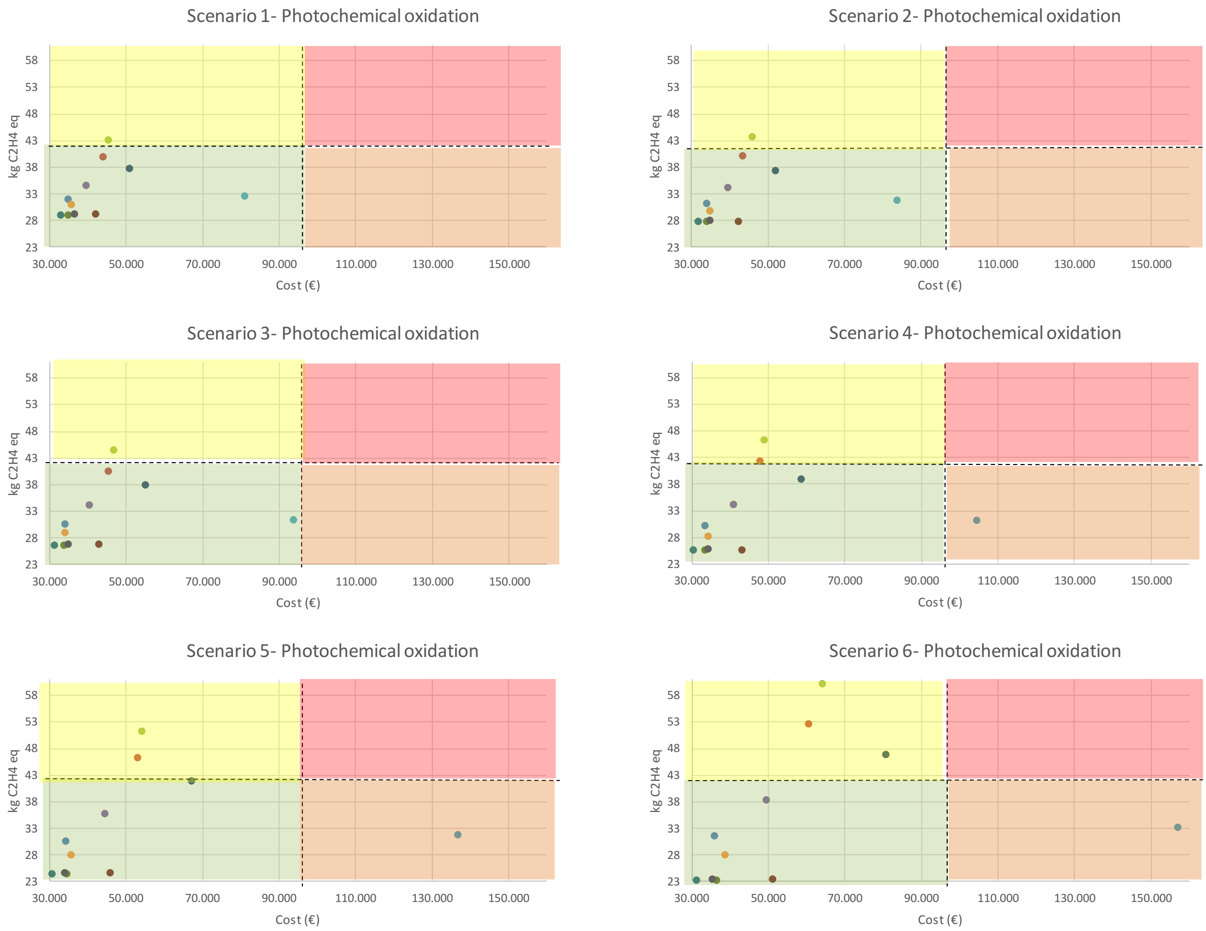


Figure A16. Eco-efficiency analysis: environmental impact (Photochemical oxidation, kg C2H4 eq) vs economic cost (€)

Acidification

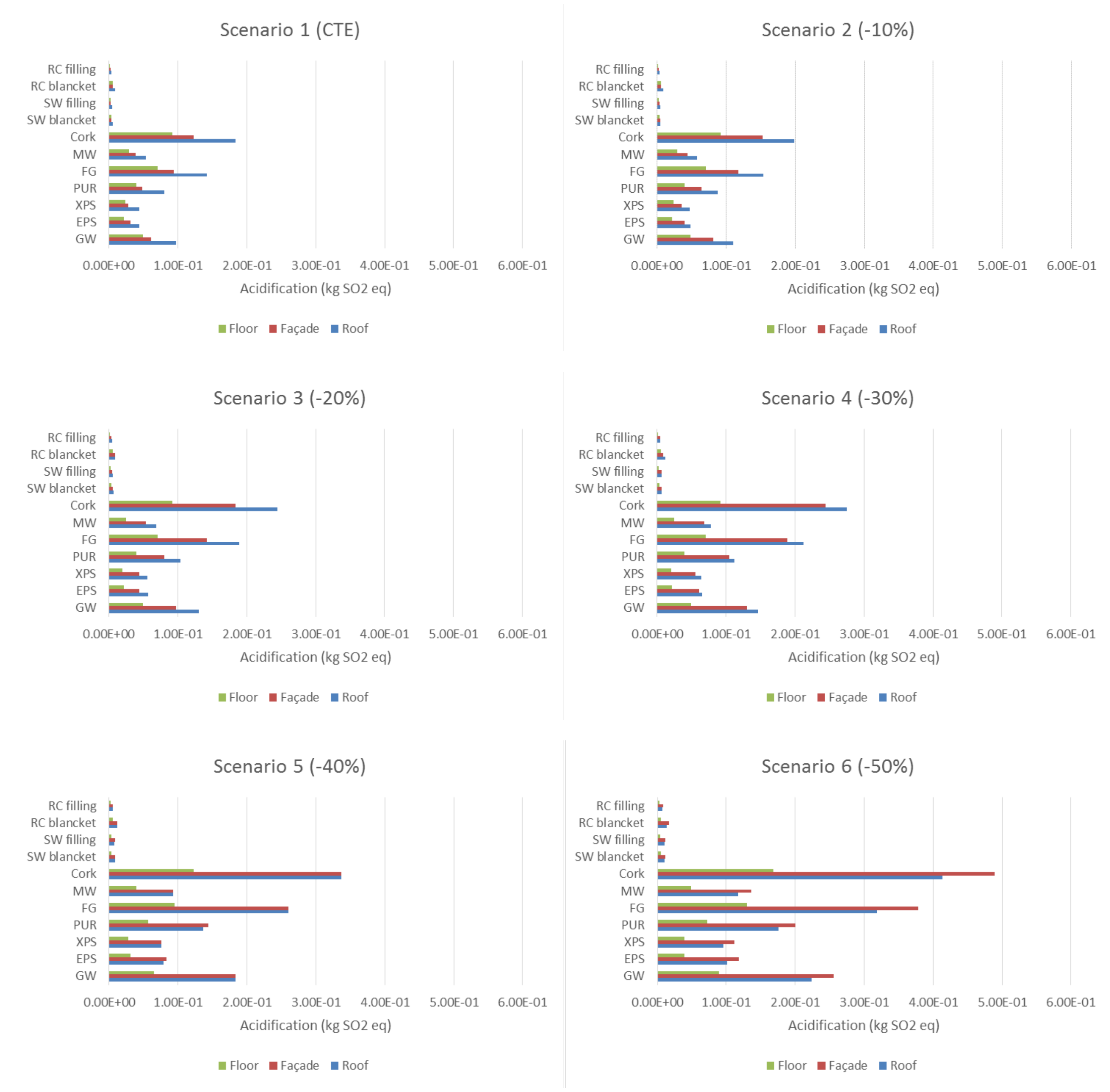
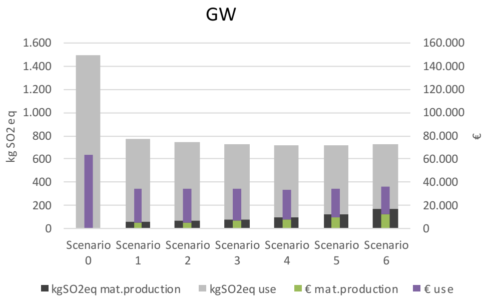
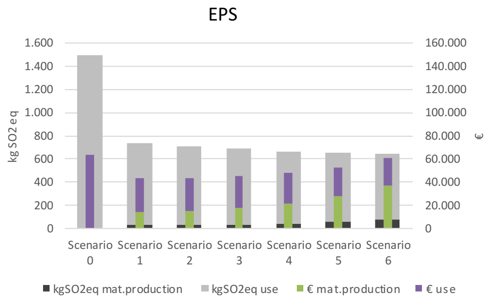
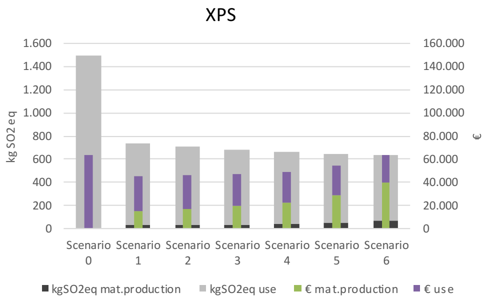
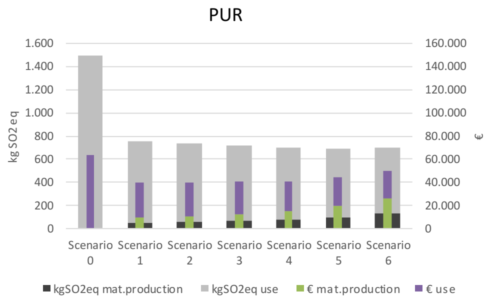


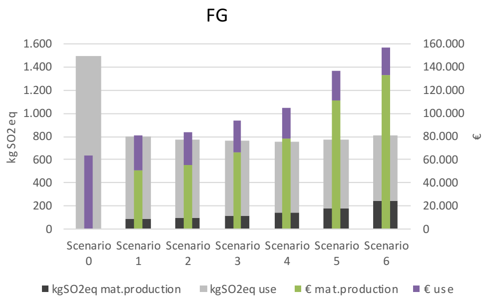
Figure A17. Environmental impact (Acidification, kg SO2 eq) per 1 m2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario

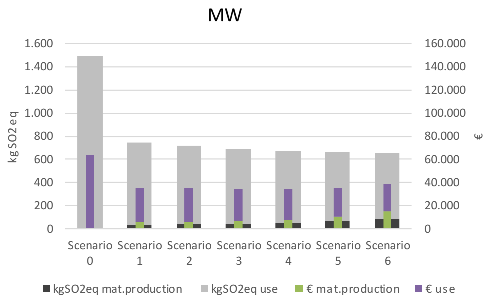

GW
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use

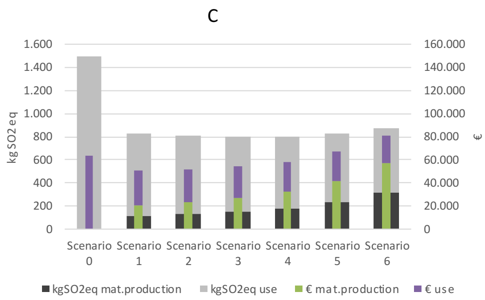

EPS
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use

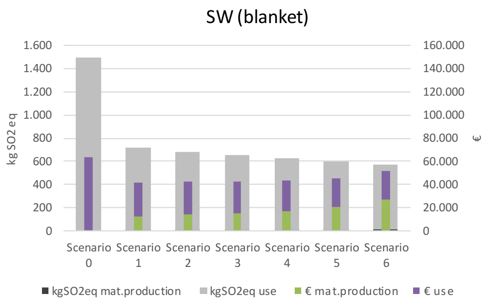

XPS
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use

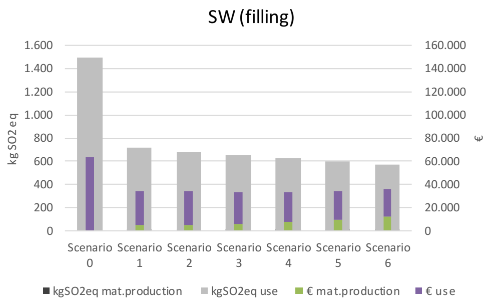

PUR
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use

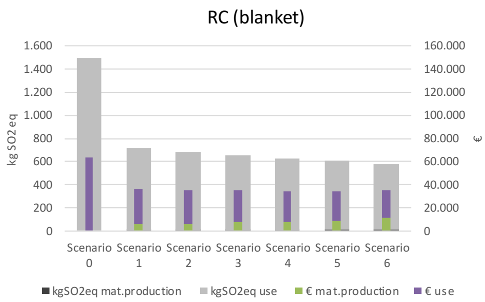

FG
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use


MW
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use


C
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use


SW (blanket)
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use


SW (filling)
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use


RC (blanket)
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use

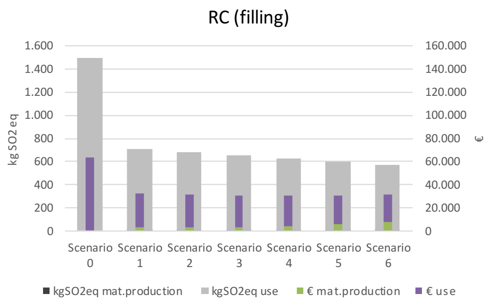

RC (filling)
kg SO2 eq
€
1.600 1.400 1.200 1.000 800 600 400 200 0
160.000 140.000 120.000 100.000 80.000 60.000 40.000 20.000 0
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgSO2eq mat.production kgSO2eq use € mat.production € use

Figure A18. Cost and environmental impact of insulation material: Acidification, kg SO2 eq

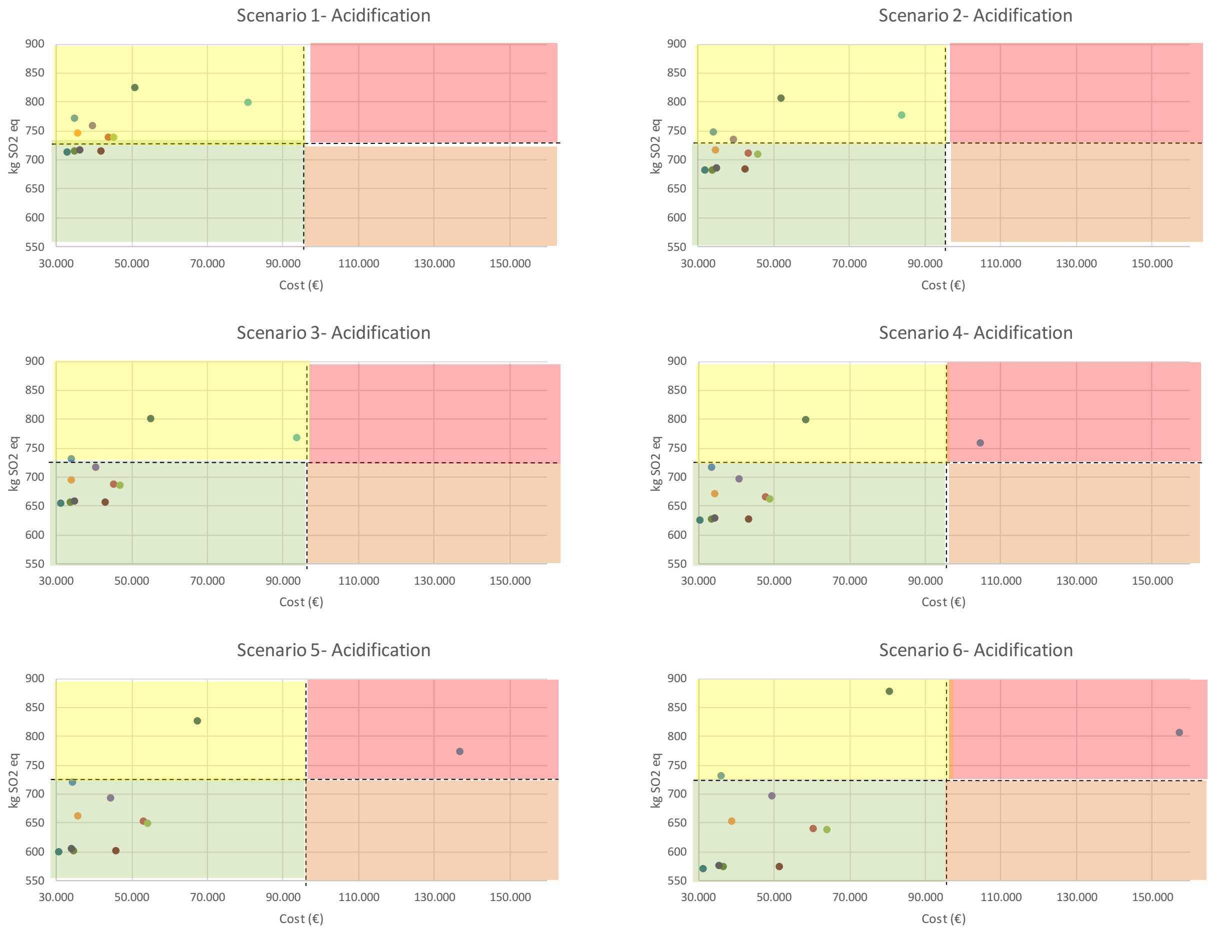


Figure A19. Eco-efficiency analysis: environmental impact (Acidification, kg SO2 eq) vs economic cost (€)

Eutrophication

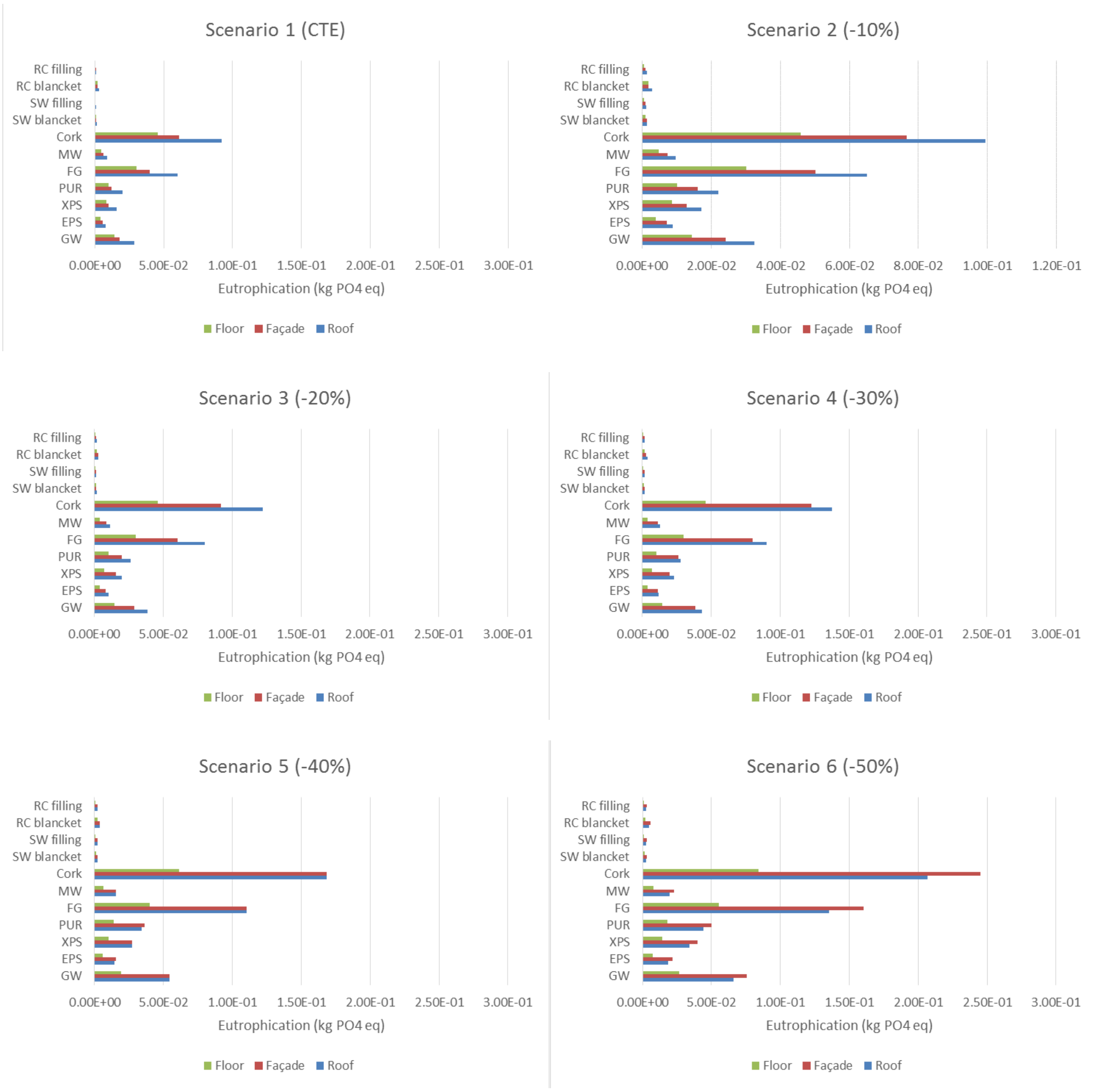
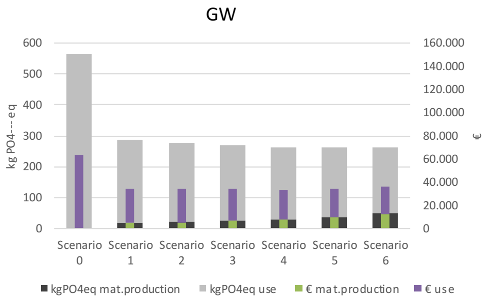
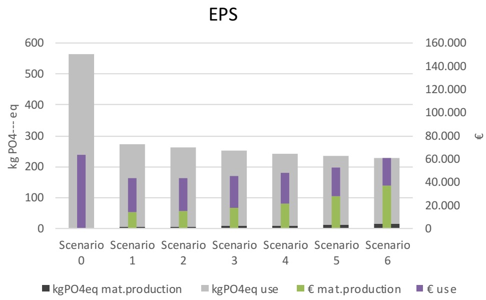
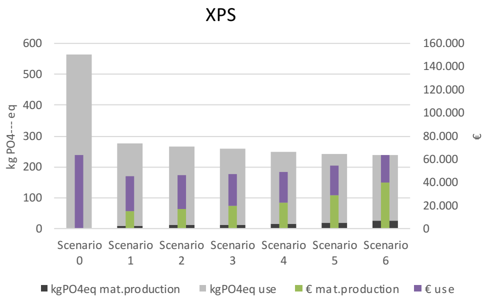
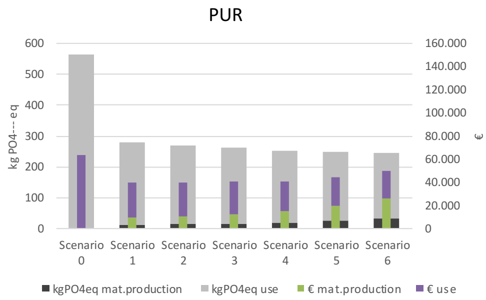


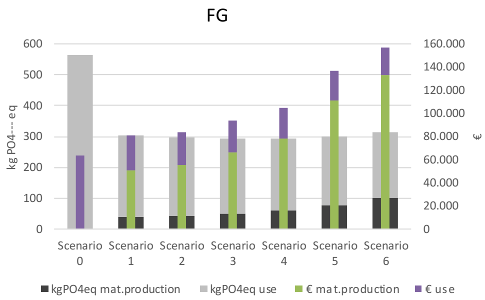
Figure A20. Environmental impact (Eutrophication, kg PO4 eq) per 1 m2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario

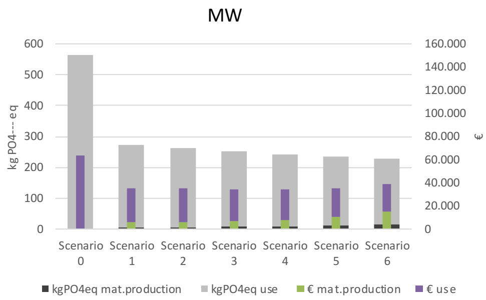

GW
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use

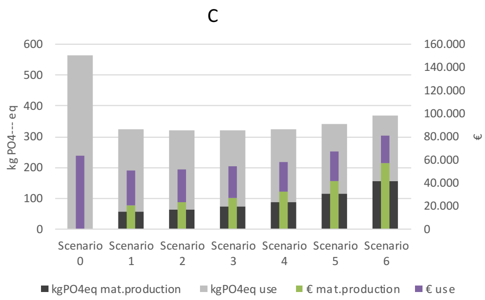

EPS
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use

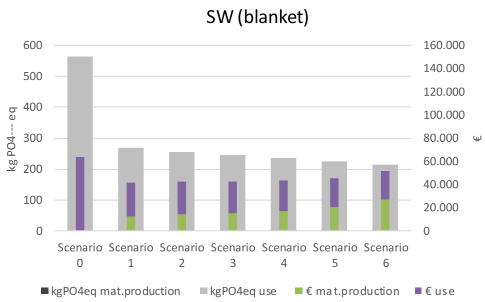

XPS
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use

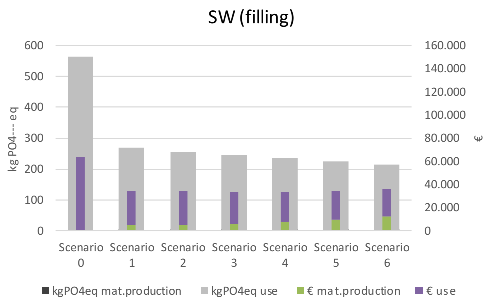

PUR
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use

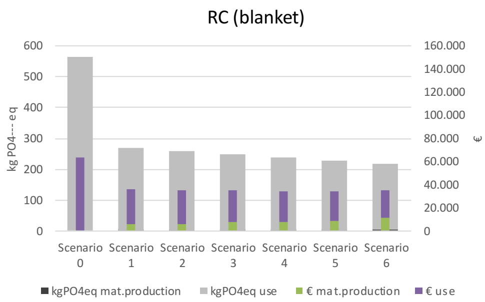

FG
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use


MW
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use


C
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use


SW (blanket)
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use


SW (filling)
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use


RC (blanket)
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use

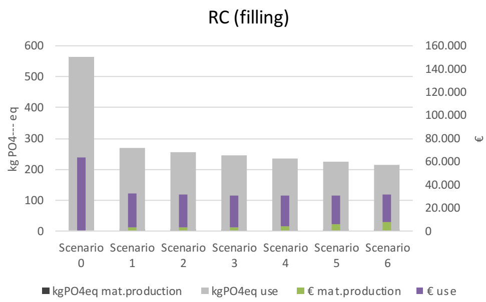

RC (filling)
kg PO4--- eq
€
Scenario 0 Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5 Scenario 6
kgPO4eq mat.production kgPO4eq use € mat.production € use

Figure A21. Cost and environmental impact of insulation material: Eutrophication, kg PO4 eq

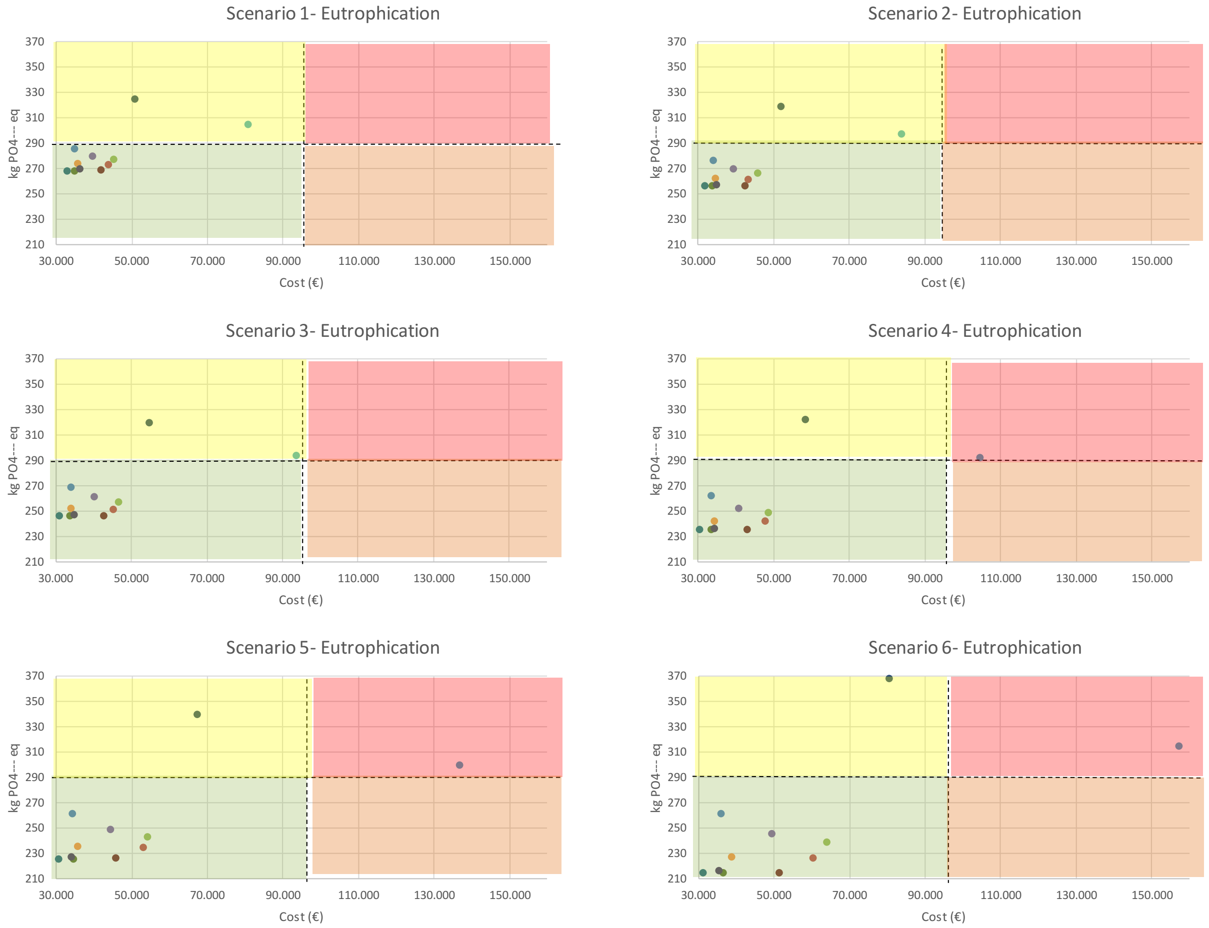


Figure A22. Eco-efficiency analysis: environmental impact (Eutrophication, kg PO4 eq) vs economic cost (€)

ReCiPe

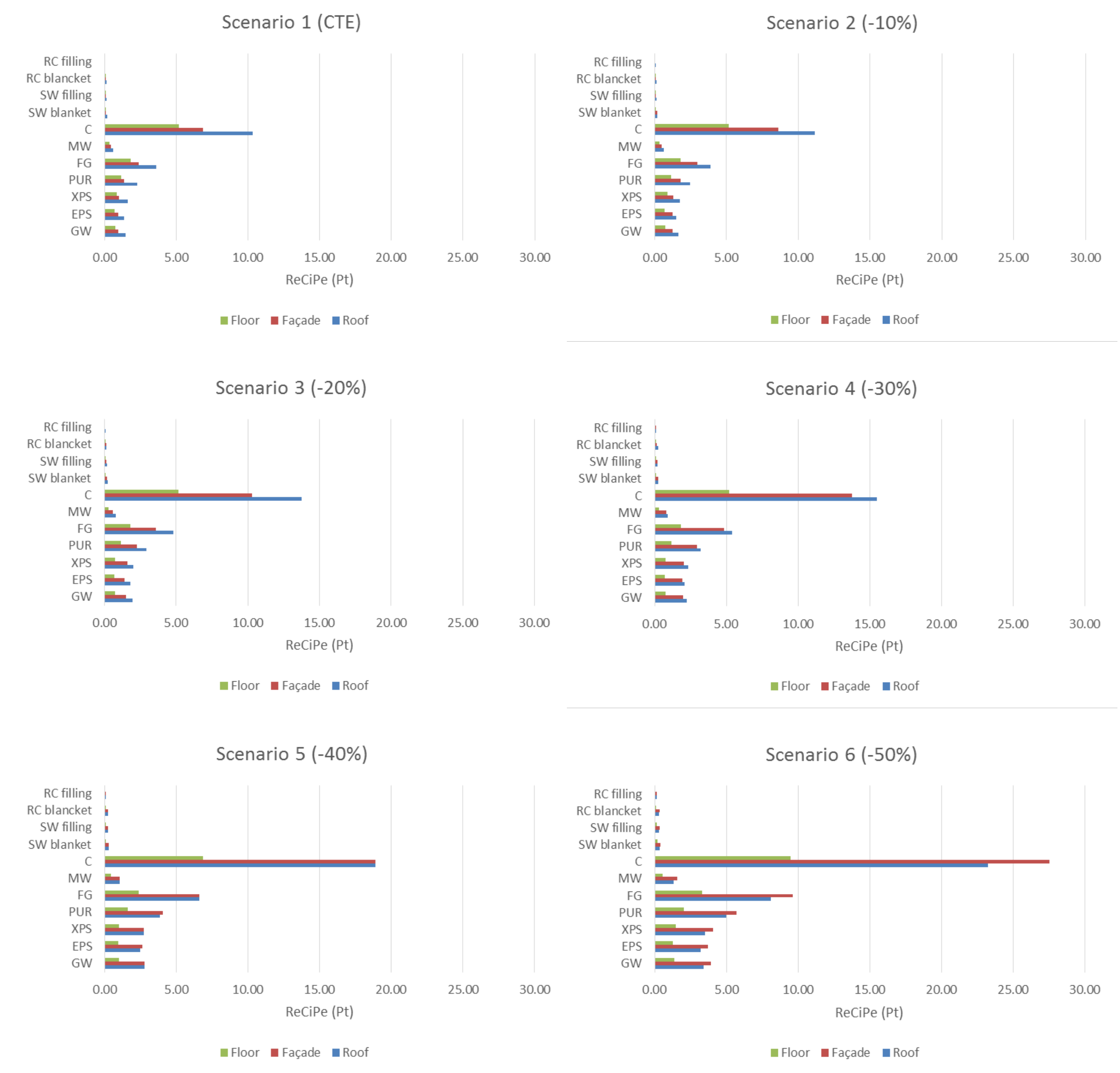
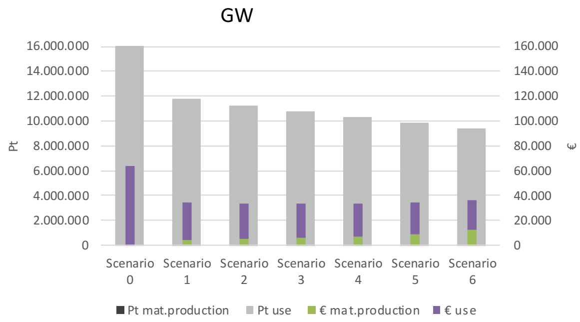
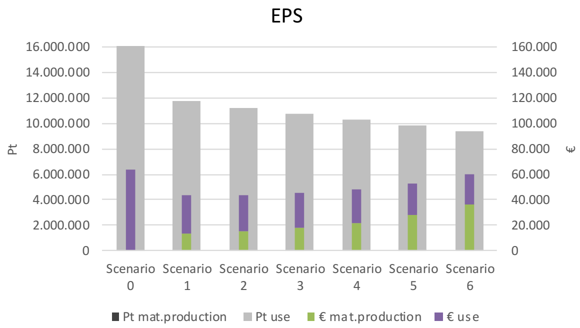
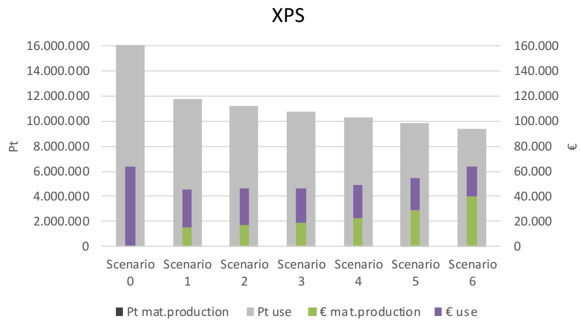
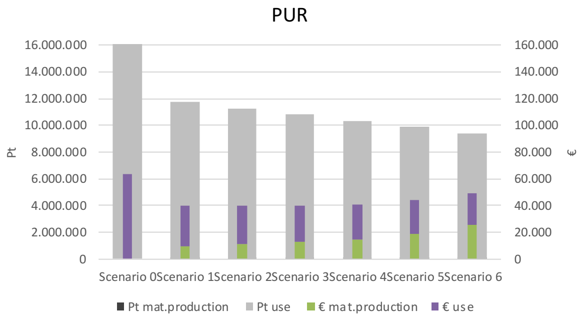


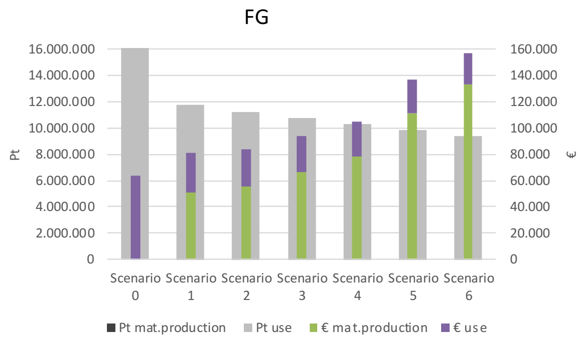
Figure A23. Environmental impact (ReCiPe, Pt) per 1 m2 of each element of the building's envelope (roof, floor or façade) by type of insulation material and by scenario

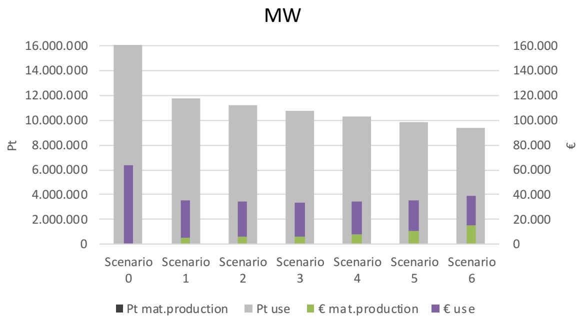

GW
16.000.000
14.000.000
12.000.000
10.000.000
8.000.000
6.000.000
4.000.000
2.000.000
0
Pt
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt mat.production
Pt use
€ mat.production
€ use

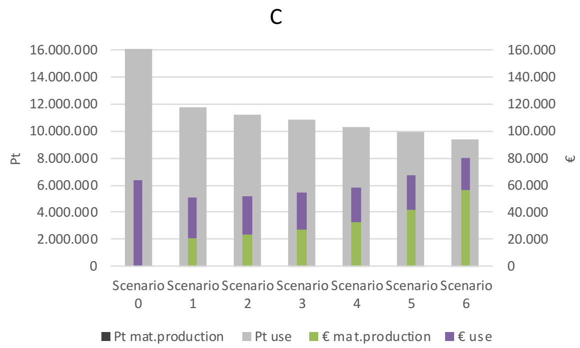

EPS
16.000.000
14.000.000
12.000.000
10.000.000
8.000.000
6.000.000
4.000.000
2.000.000
0
Pt
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt mat.production
Pt use
€ mat.production
€ use

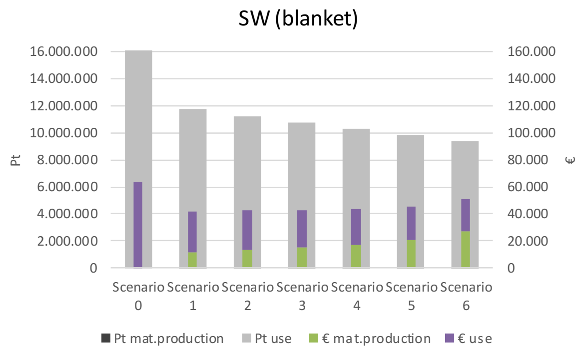

XPS
16.000.000
14.000.000
12.000.000
10.000.000
8.000.000
6.000.000
4.000.000
2.000.000
0
Pt
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt mat.production
Pt use
€ mat.production
€ use

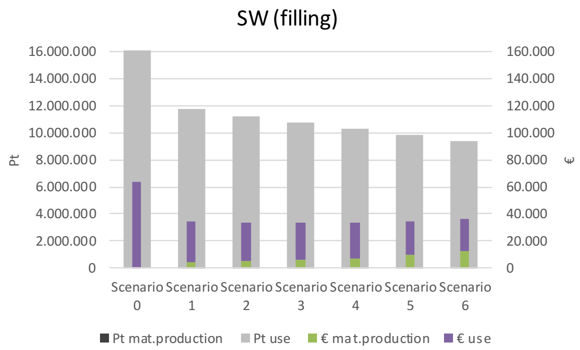

PUR
16.000.000
14.000.000
12.000.000
10.000.000
8.000.000
6.000.000
4.000.000
2.000.000
0
Pt
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0Scenario 1Scenario 2Scenario 3Scenario 4Scenario 5Scenario 6
Pt mat.production
Pt use
€ mat.production
€ use

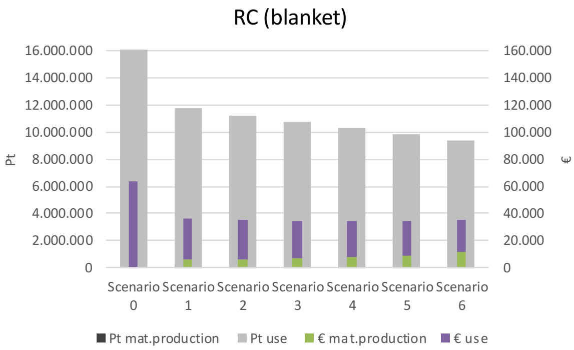

FG
16.000.000
14.000.000
12.000.000
10.000.000
8.000.000
6.000.000
4.000.000
2.000.000
0
Pt
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt mat.production
Pt use
€ mat.production
€ use


MW
16.000.000
14.000.000
12.000.000
10.000.000
8.000.000
6.000.000
4.000.000
2.000.000
0
Pt
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt mat.production
Pt use
€ mat.production
€ use


C
16.000.000
14.000.000
12.000.000
10.000.000
8.000.000
6.000.000
4.000.000
2.000.000
0
Pt
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt mat.production
Pt use
€ mat.production
€ use


SW (blanket)
16.000.000
14.000.000
12.000.000
10.000.000
8.000.000
6.000.000
4.000.000
2.000.000
0
Pt
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt mat.production
Pt use
€ mat.production
€ use


SW (filling)
16.000.000
14.000.000
12.000.000
10.000.000
8.000.000
6.000.000
4.000.000
2.000.000
0
Pt
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
€
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt mat.production
Pt use
€ mat.production
€ use



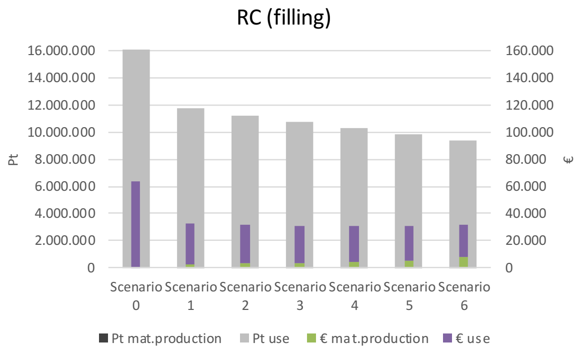


Figure A24. Cost and environmental impact of insulation material for 50-years life span: ReCiPe, Pt

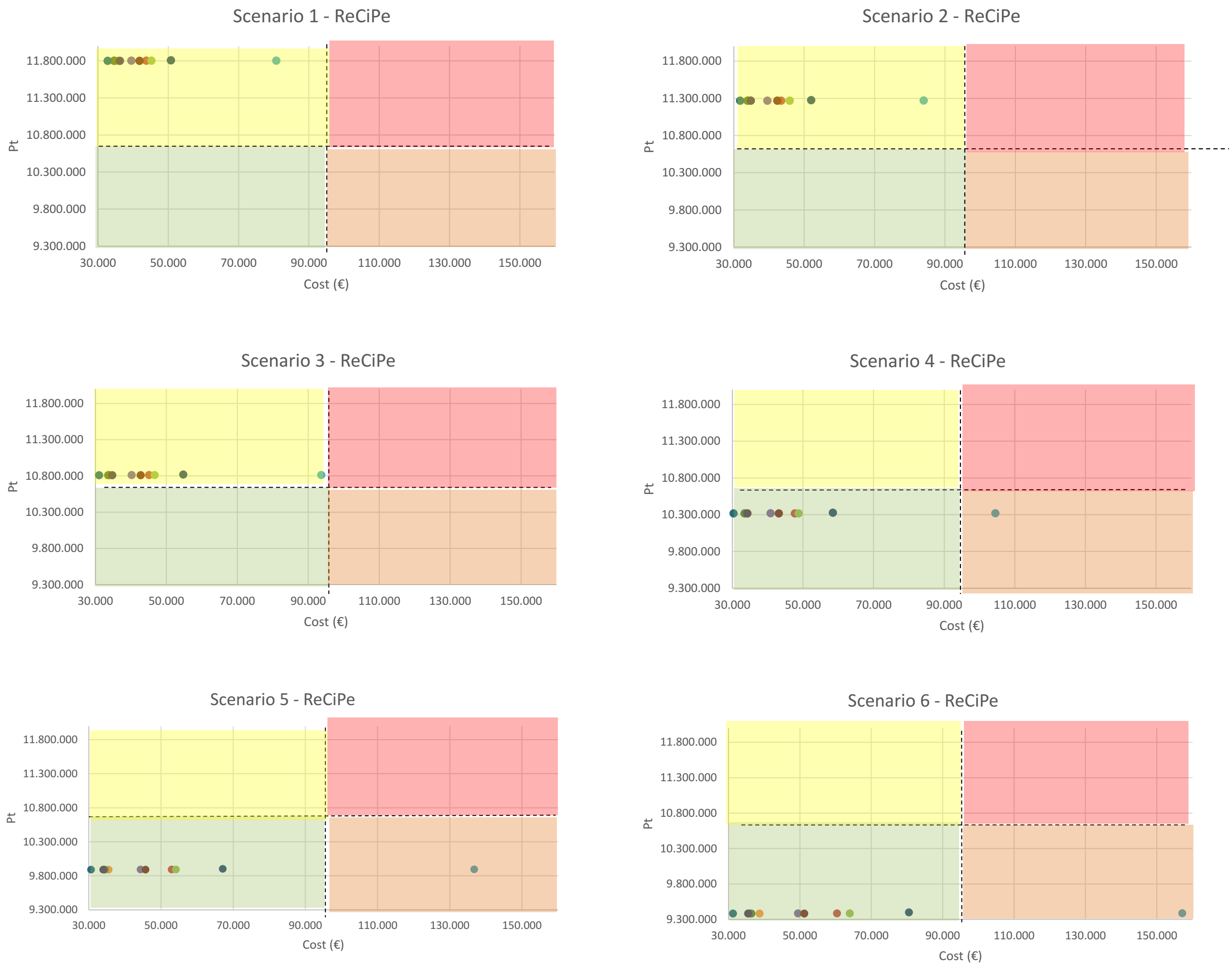
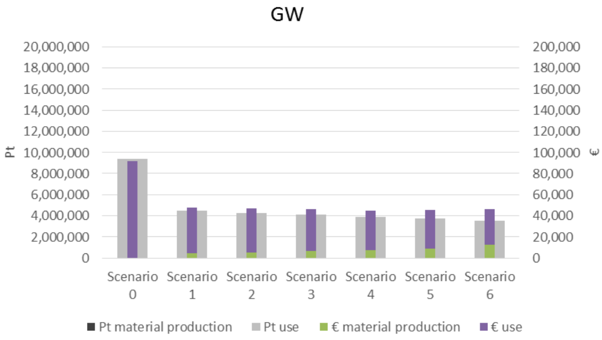
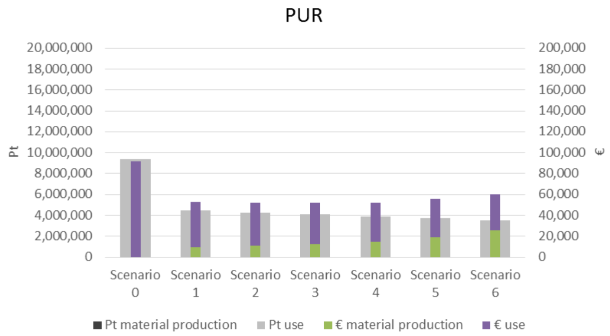
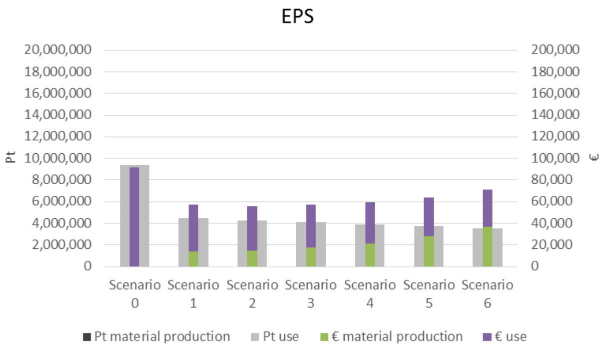


Figure A25. Eco-efficiency analysis: environmental impact (Pt, ReCiPe) vs. economic cost (€)


GW
Pt
€
20,000,000
18,000,000
16,000,000
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt material production
Pt use
€ material production
€ use


PUR
Pt
€
20,000,000
18,000,000
16,000,000
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Scenario 0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt material production
Pt use
€ material production
€ use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Scenario 6
Pt material production
Pt use
€ material production
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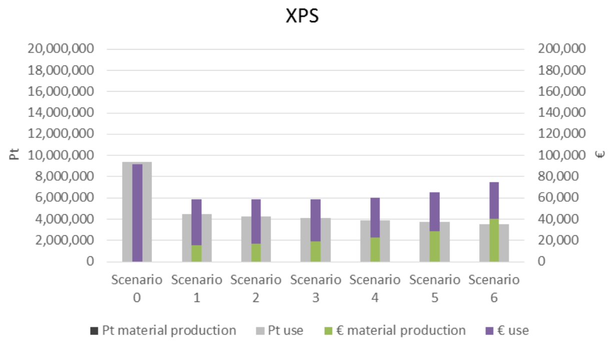
XPS
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Pt material production
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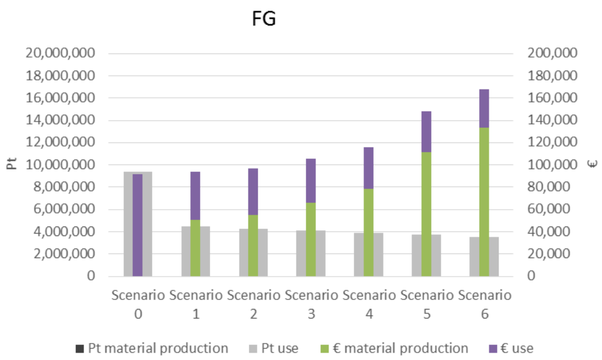
FG
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Scenario 6
Pt material production
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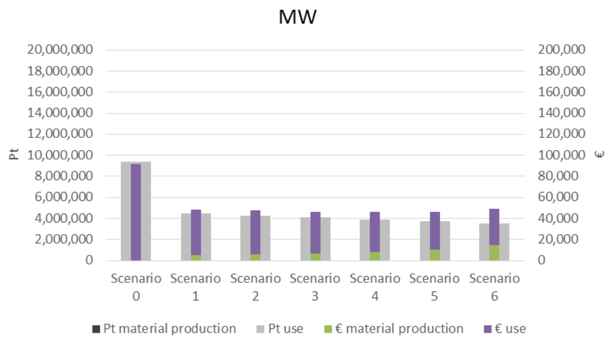
MW
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Scenario 1
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Scenario 6
Pt material production
Pt use
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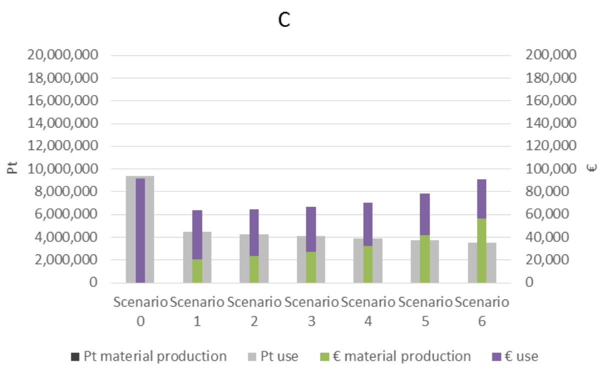
C
Pt
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Scenario 6
Pt material production
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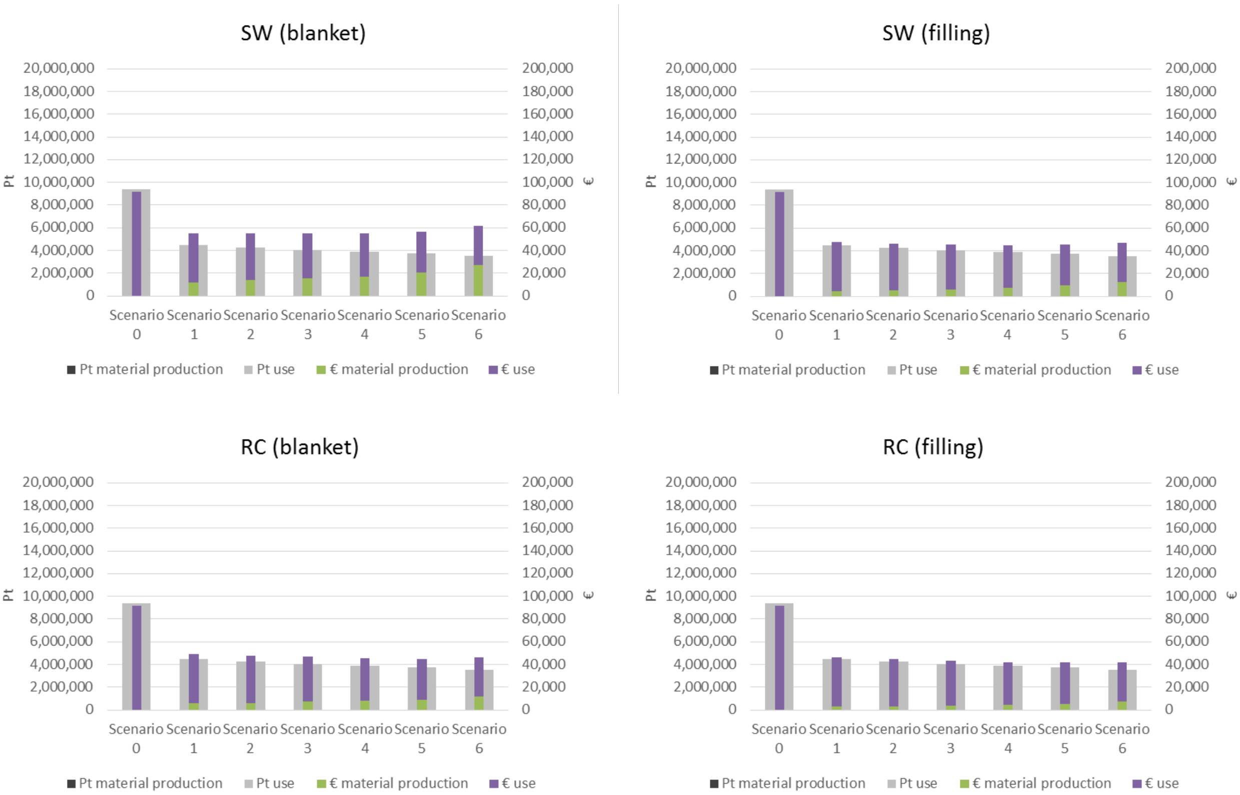
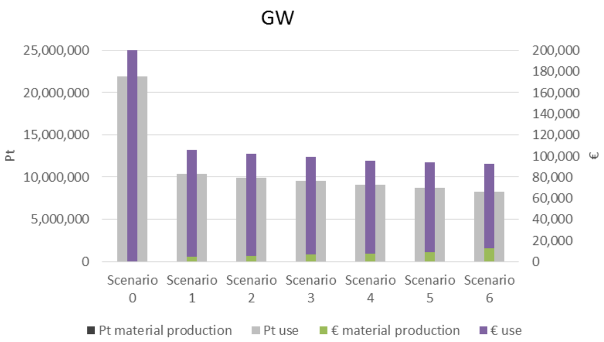


Figure A26. Cost and environmental impact of insulation material for 30-years life span: ReCiPe, Pt


GW
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Scenario 0
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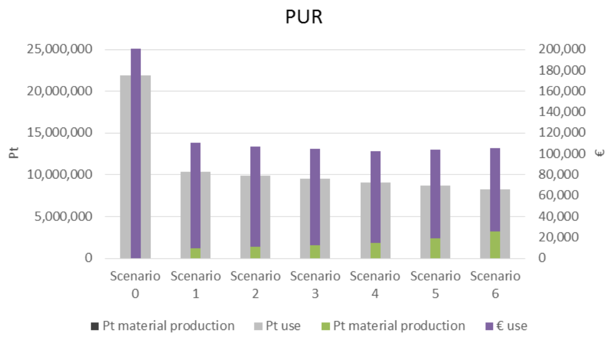
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Pt material production
Pt use
€ material production
€ use


PUR
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Scenario 0
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Scenario 5
Scenario 6
Pt material production
Pt use
Pt material production
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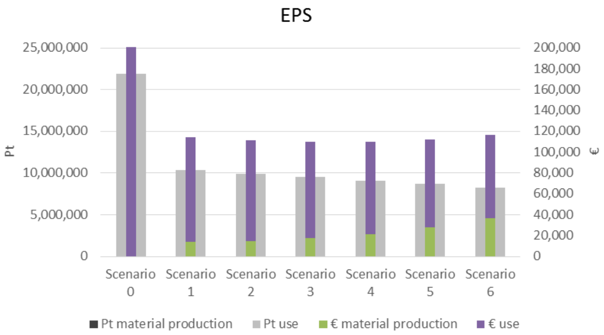
EPS
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Scenario 0
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Pt material production
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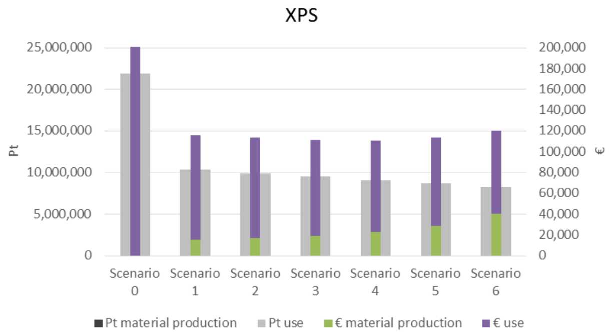
XPS
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Scenario 0
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Scenario 6
Pt material production
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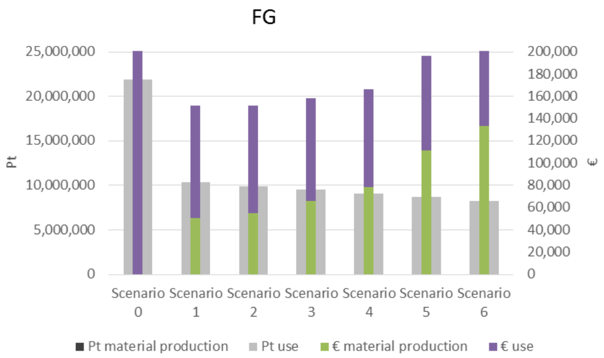
FG
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Pt material production
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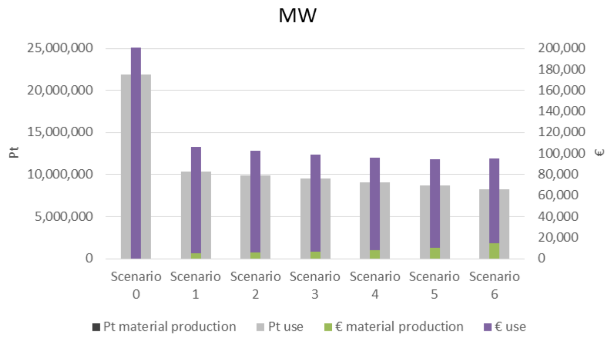
MW
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Scenario 0
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Scenario 6
Pt material production
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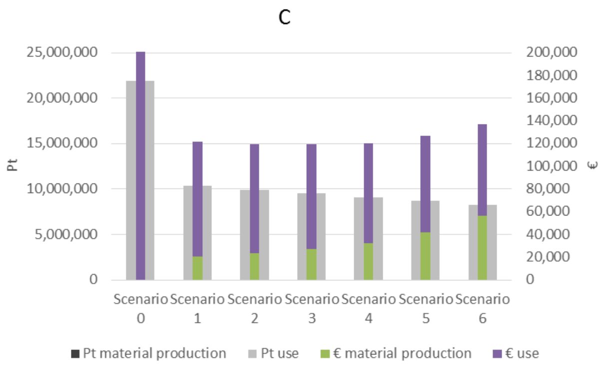
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Scenario 0
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Scenario 6
Pt material production
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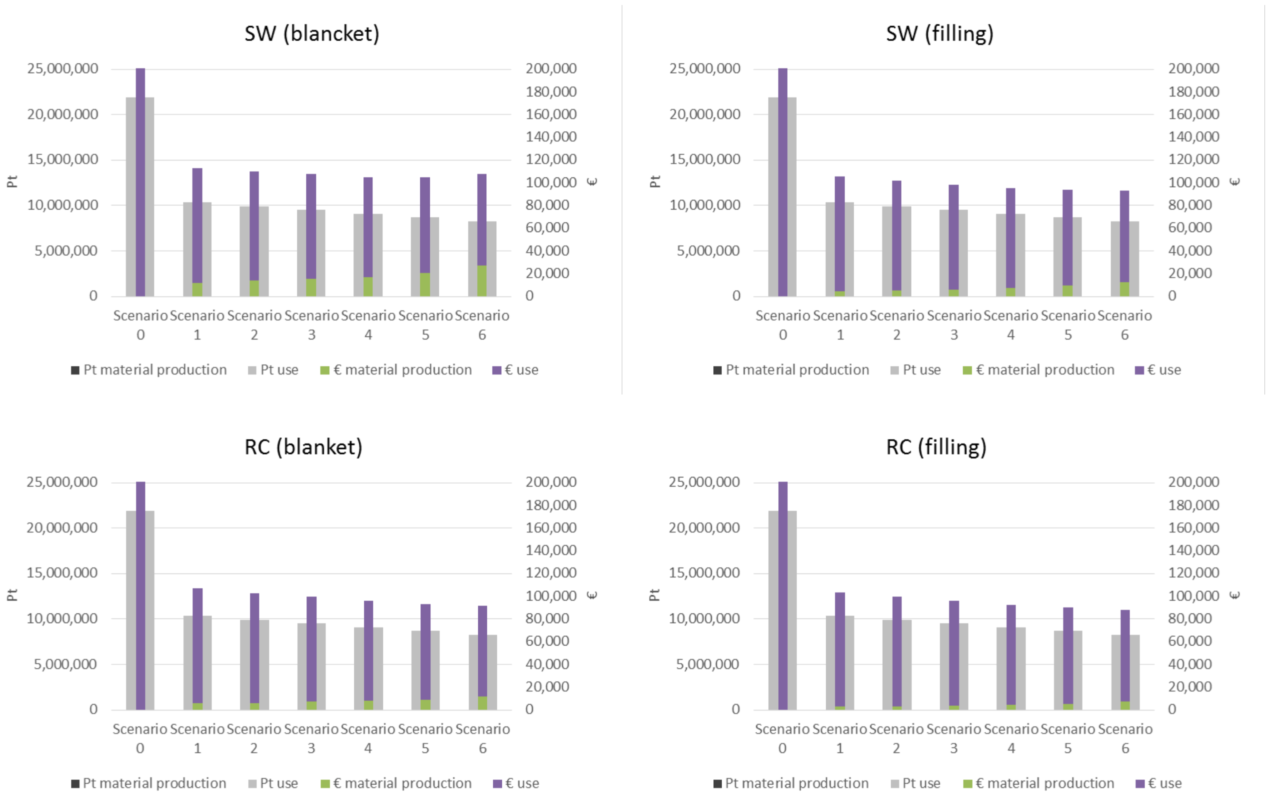

Figure A27. Cost and environmental impact of insulation material for 70-years life span: ReCiPe, Pt