Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Using Life Cycle Assessment in tenders to enhance the sustainable procurement of External Thermal Insulation Composite Systems

To cite this article: A Cardarelli *et al* 2022 *J. Phys.: Conf. Ser.* **2385** 012100

Using Life Cycle Assessment in tenders to enhance the sustainable procurement of External Thermal Insulation Composite Systems

A Cardarelli[1], I Baffo[1], S Ubertini[1] and M Barbanera[1]

[1]*Department of Economics Engineering Society and Business Organization (DEIM), University of Tuscia, Largo dell'Università s.n.c., Loc. Riello, 01100 Viterbo, Italy*

Abstract. Green Public Procurement (GPP) is a policy instrument to decrease the environmental impact of products and services and create environmental value for society. A new method for assessing environmental award criteria in GPP processes was developed to integrate environmental and economic criteria into public tenders for External Thermal Insulation Composite Systems (ETICS). The main objective of this study was to identify the effect that the inclusion of environmental impacts can have on decision-making in public procurement. At this scope, an environmental benchmark for the main phases of the supply chain (production, installation and disposal) of ETICS that use different insulating materials, including EPS and mineral wool, was defined for different Life Cycle Assessment (LCA) impact categories after a detailed literature review. Then the monetisation method of the externalities was applied to combine the environmental impacts and the direct costs associated with the manufacture of the ETICS system by obtaining a single score for the selection of the best bid from the environmental and economic point of view. This methodology was implemented in a spreadsheet and a case study was analysed as a practical application of the tool developed for the determination of the global index. The case study simulated a tender in which three contractors provided their bid for an ETICS system. The overall investigation of the results obtained in the case study showed that the environmental externalities have a rather limited incidence compared to direct costs (between 0.8 and 10%). However, even if the lower direct costs were provided by contractor 1 (87.72 €/m^2) in comparison to contractor 2 (87.80 €/m^2) and contractor 3 (92.74 €/m^2), the slightly higher environmental impacts caused the costs to rise. The most environmentally and economically advantageous bid was then provided by contractor 2, for which the global index was the lowest for each monetisation method applied. For all the impact categories considered, the production stage (A1-A3) represents the most significant contribution. The thermal insulation material and the finishing coat provide the greatest contribution to the environmental impact. The tool was designed to improve the knowledge of the economic and environmental performances of ETICS systems, which might be also used by public administrations to define minimum environmental requirements and maximum specific costs when preparing tenders for the energy requalification of buildings.

1. Introduction

The purchase of goods, services and works by governments and public authorities represents a significant share of the European economy, accounting for over 14% of European Union GDP [1]. In particular, public procurements have been considered fundamental for the promotion of sustainability across the EU in the Europe 2020 strategy [2]. For this reason, the European Commission has promoted the implementation of Green Public Procurement (GPP) principles in all Member States

through the development of GPP criteria to facilitate the inclusion of green requirements in public tender documents. The implementation of GPP criteria has the aim to revise the procedures for the procurement of goods and services and public works, taking into consideration not only their monetary cost but also the environmental burdens that they may cause along their life cycle. The European Commission provides support for public procurement through technical reports and tender criteria but the public authorities can independently decide what requirements include in their tender documents. However, even now, procurement procedures mainly still use the lowest price as the only award criterion [3], neglecting the broader costs arising from future costs of use or disposal and environmental externalities. In particular, these costs can be considerable, making the true costs of the good or service much higher than the initial purchase price. However, the application of the Life Cycle Costing (LCC) methodology in public tender procedures, including the monetisation of the environmental costs identified by the Life Cycle Assessment (LCA) analysis, has rarely been explored [4], even if the 2014/24/EU Directive on Public Procurement drastically reformed the process of awarding tenders by highlighting the importance of LCC. During the bidding process, several technical, economic, social and environmental specifications are included in the public tender documents, with an arbitrary weight percentage attributed to each of them, since EU GPP suggests a set of criteria but not a weighting system for them. Though environmental issues are gradually considered during procurement in the European context, they only represent around 10% of the overall weight [5].
In this context, in the present work, a simplified decision-support tool was developed to guide public authorities to select the most economically and environmentally advantageous offer, during the tender process for the building façade retrofit by the application of an External Thermal Insulation Composite System (ETICS). This tool was based on the environmental life cycle costing methodology, which uses an LCA model as a basis to estimate incurred costs in the product assessment, and the "total costs of ownership" (TCO) approach, which indicates that the analysis is carried out from the user's perspective.

2. Methodology

The main objective of the developed tool was to allow contractors that do not hold Environmental Product Declarations (EPD) of their ETICS systems to participate in tenders in which the offer is evaluated in both environmental product assessment cost (EPAC) and the total costs of ownership (TOC). This tool automatically determines the most convenient offer based on the thermal resistance (m^2K/W) required by the tender for the ETICS system. For this purpose, an environmental reference benchmark, ERB (a collection of environmental impact data), for ETICS that use different insulating materials, expanded polystyrene (EPS) and mineral wool (MW), was determined by using EPDs and scientific publications regarding LCA analysis. The ERB, based on different LCA impact categories and according to the thickness of the insulating material, was defined for the main stages of the supply chain (production, construction and disposal). Then, the costs associated with these environmental externalities were determined by applying monetisation methods. Then, by combining the EPAC and TOC, a global index, expressed in €/(m^2K/W), was determined. This global index allowed defining the most environmentally and economically feasible ETICS system, depending on the type and thickness of the thermal insulation material. Furthermore, a specific methodology was applied to take into account the durability of the external thermal insulation composite system and therefore estimate its service life.

2.1. Materials and system boundaries

In this work, for the development of the tool, ETICS systems with EPS and MW as insulation materials were considered, which are the most used insulating materials for the ETICS system in Europe, in 2020 [6]. External Thermal Insulation Composite Systems are kits that consist of prefabricated insulation board, bonded and/or mechanically fixed using anchors onto the wall, with reinforced undercoat and decorative finishes, as described in the guideline for European technical approval of External Thermal Insulation Composite Systems (ETICS) with rendering [7]. The system consists of a broad selection of adhesives, base coats and many renders (Figure 1). It provides a variety of solutions depending on the requirements of the building design, the investors and construction workers. Renders taken under consideration were as follows, mineral render (MR), acrylic render (AR), silicone render (SiR), and silicone-silicate render (Si-SiR). It is noteworthy that the wall structure was not included in the system boundaries studied.

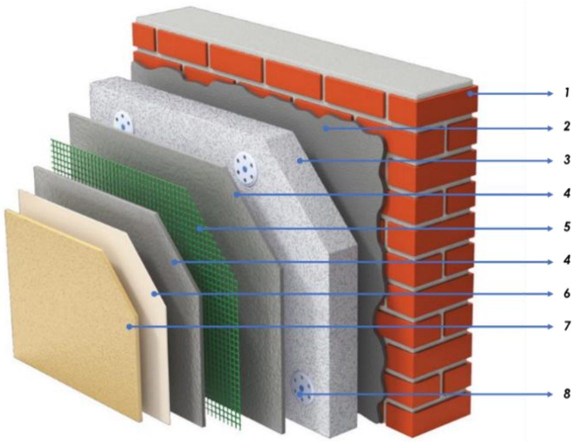


Figure 1. Layers arrangement in the ETICS system as described: (1) wall structure (substrate), (2) adhesive (basic fixing), (3) thermal insulation, (4) reinforcement layer (base coat) (5) glass fibre mesh, (6) primers (optional), (7) finishing coat (renders) and (8) anchor (if necessary, additional fixing).

The environmental impact analysis was achieved through the approach "from cradle to gate with options". In detail, the included life cycle stages based on the UNI EN 15804 were production, construction and disposal. In detail, for the production stage (A1-A3) the environmental impact data for each insulation material were acquired from several environmental product declarations or scientific publications regarding LCA studies. While, for the construction (A4-A5) and the disposal (C4) stages, data were determined by using the processes already existing within the Ecoinvent database of the Simapro software. Data were considered in a time range from 2014 to 2021 and related to products manufactured in Europe. For each stage (A1-A3, A4-A5 and C4), the environmental impact categories taken into consideration are listed in Table 1.

Table 1. Environmental impact categories considered for the environmental reference benchmark

Environmental Impact Categories	**Units**
Global Warming Potential (GWP)	kg CO_2 eq
Ozone Depletion Potential (ODP)	kg CFC-11 eq
Acidification Potential (AP)	kg SO_2 eq
Eutrophication Potential (EP)	kg $(PO_4)^{3-}$ eq
Formation Potential of Tropospheric Ozone (POCP)	kg Ethene eq
Abiotic Depletion Potential - mineral (ADP-minerals)	kg Sb eq
Abiotic Depletion Potential - fossil (ADP-fossil)	MJ

The production stage A1-A3

The methodology developed for determining the reference benchmark for the production stage was built based on environmental impact data found in the literature. The production stage involves the extraction and processing of raw materials entering the system (A1), the transport of raw materials from the supplier to the production plant and the transference of the processed products to the sorting hub (A2), the manufacturing processes of the materials carried out within the production site (A3), e.g. the products mixing, packaging, transport to the warehouse and storage. The collected literature references include 10 EPDs [8–21] and 3 LCA studies resulting from scientific publications [22–24]. For each reference, the value of each environmental impact category, depending on the thickness of the insulation material, was reported on a spreadsheet. Then, the equation of the interpolating line of the impact values, as the insulation thickness varies, was determined. In this way, it was possible to obtain the value of the relative environmental impact for any thickness of insulation material. Thus, the environmental reference benchmark for stage A1-A3 (ERB_{A1-A3}) was determined.

The construction stage A4-A5

The environmental impacts related to the phases of the supply chain identified by the construction stage (A4-A5) were determined analytically through the use of the Simapro software. This stage includes the transport (A4) and installation (A5) phases. In detail, A4 is identified in the transport from the production unit to the construction site. The environmental impact of the A4 phase was calculated by applying the EPD 2018 impact assessment method, related to 1 km per ton of insulating material transported by truck, train and ship respectively. The following processes of the Ecoinvent 3.7 database were considered:

- transport, freight, lorry 16-32 metric ton, euro5 {RER} | market for transport, freight, lorry 16 32 metric ton, EURO5 | APOS, U;
- transport, freight, sea, container ship {GLO} | market for transport, freight, sea, container ship | APOS, U;
- transport, freight train {Europe without Switzerland} | market for | APOS, U.

Once the environmental impact of A4 was defined, the corresponding environmental reference benchmark (ERB_{A4}) associated with the insulating material was determined. For this purpose, the values of the environmental impacts were multiplied for both the effective distance between the manufacturing and the construction site, expressed in km, and the weight (ton) of 1 m^2 of insulation material, determined according to Equation (1):

$$W = 1\ m^2 \text{ insulation material weight} = (\rho \cdot s)/1000 \tag{1}$$

where,

- ρ is the density [kg/m^3] of the insulation material (15 and 80 kg/m^3 for EPS and MW respectively);
- s is the thickness [m] of the insulation material.

The thickness of the insulating material s was obtained from the desired thermal resistance value (R_t) expressed in m^2K/W of the insulating material and from the relative thermal conductivity value (λ), respectively 0.034 and 0.035 W/mK for EPS and MW, according to Equation (2).

$$s = R_t \cdot \lambda \tag{2}$$

Besides, the environmental impacts concerning the installation phase (A5) were determined by considering the consumption of 1 l of water and 1 kWh of electricity. In this regard, the following processes of the Ecoinvent 3.7 database were considered, applying the EPD 2018 impact assessment method:

- Tap water {Europe without Switzerland} | market for | APOS, U;
- Electricity, low voltage {IT} | market for | APOS, U.

<u>*The disposal stage C4*</u>

The environmental impacts for the end-of-life phase arise from the operation of machines necessary for the processing of waste from ETICS. These operations include the removal of ETICS, collecting and loading of waste, transport to the disposal facility, etc. In detail, the ETICS can be subjected to non-selective or partially selective deconstruction [25]. In non-selective dismantling, single ETICS components are not separately recovered at the construction site and the ETICS accumulates as mixed waste. One method is scraping off or tearing down the ETICS using for example an excavator. Otherwise, partially selective deconstruction is generally performed manually and requires the use of scaffolding. Workers manually remove the plaster layers with the internal reinforcement fabric from the insulating material. After removing the plaster layers, the insulation boards are removed from the substrate. Thus, the potential for recovery, recycling and reuse of the materials that make up the external insulation systems was examined, to pursue circular economy objectives. Landfill disposal was assumed for the ETICS to account for the end-of-life phase. The corresponding environmental impact was determined through the use of the Simapro software. The following processes of the Ecoinvent 3.7 database were considered, applying the EPD 2018 impact assessment method:

- 1 kg Waste polystyrene {RoW} | treatment of waste polystyrene, sanitary landfill | APOS, U;
- 1 kg Waste mineral wool, for final disposal {Europe without Switzerland} | treatment of waste mineral wool, inert material landfill | APOS, U.

2.1. Service life prediction of ETICS

The awareness of the durability of the building components is essential to making a choice in terms of compatibility with the sustainability of their use, according to the differentiated obsolescence of the parts of the building and the type of maintenance to be adopted. The prediction of the service life, as indicated in UNI 11156:2006 (Evaluation of the durability of building components) [26], is based on the use of many methods, among which is the factorial method [27]. This methodology allows obtaining an Estimated Service Life (ESL) based on a reference service life (RSL), expected in current conditions of use, multiplied by different weighting coefficients related to the specific conditions of the element of the ETICS system. In this work, the factorial method was used to evaluate the ESL of ETICS systems by using the following expression (Equation (3)):

$$ESL = RSL \cdot A1 \cdot A2 \cdot B1 \cdot B2 \tag{3}$$

where, RSL for ETICS systems can be assumed to be equal to 25 years, according to what is reported in the European Technical Approval Guideline (ETAG 004) for ETICS systems [7] and A1, A2, B1 and B2 are weighting coefficients. In detail, A1 is the factor that takes into account the characteristics of the finishing material of the ETICS system (a value of 1.2 is considered in the case of ceramic finishing and 1 in the other cases); A2 takes into account the finishing colour (a value of 0.8 is considered for dark colours, 1 for white and 1.2 for the other); B1 is the factor that considers the type of the finishing coat of the ETICS system (a value of 0.8 is considered in the case of a rough finishing surface and 1 if smooth); B2 takes into account the level of protection of the ETICS system (a value of

1.2 is considered by using peripherical profiles for the protection of the edges, 1 in the case of plinth systems and 0.8 in the other cases). The values of each weighting coefficient were chosen according to the literature [27]. Within Equation (3), factors that did not depend on the characteristics of the ETICS system, e.g. the quality of execution, the conditions of the internal and external environment and the conditions of the use, were not taken into account.

2.2. Global index definition

Generally, the TOCs are related to the acquisition, use, maintenance and end-of-life (disposal). In this work, the acquisition costs arose from the costs offered by the contractor of the tender. They are represented by the sum of the ownership costs of each material that composes the ETICS system (OC_m), the manpower for the installation (OC_{in}) and future removal (OC_{fr}) and, the rental of equipment and scaffolding (OC_{rent}). Instead, the costs associated with the use, maintenance and disposal were neglected. This is because the use and maintenance costs of an ETICS system can be considered approximatively the same for each insulation material and their disposal costs have no relevant differences. In addition, it is well known that building façades are more vulnerable and prone to deterioration as they are constantly exposed to aggressive external agents [28,29]. The knowledge of the estimated service life of ETICS is essential for planning and establishing maintenance plans. An adequate selection of materials and so the adoption of more durable ETICS solutions, promoting a higher service life, is crucial to achieving a more sustainable construction, thus minimising renovation costs, the resources used and the environmental impacts. In this sense, the ESL was also considered for the calculation of TOCs, quantifying the costs related to the different frequencies of renovation of the ETICS system, according to the following equation (Equation (4)):

$$\mathrm{TOC}\ [€/\mathrm{m}^2] = (OC_m+OC_{in}+OC_{rent}+OC_{fr})\cdot \frac{\mathrm{RSL}}{\mathrm{ESL}} \tag{4}$$

Thus, if ESL determined (Equation (3)), as a function of the characteristics of the ETICS system, is lower than the reference service life (25 years), an extra cost will be charged due to the early renovation of the ETICS system. On the other hand, the EPACs associated with the environmental reference benchmark of each life cycle stage were determined by using a monetisation method. Several monetisation methods have been developed to convert environmental impacts into monetary units. In this work, Ecotax 2002 [30], Stepwise 2006 [31], Ecovalue 08 [32] and Environmental Prices [33] monetisation methods were used. The monetisation factors (MF) based on the ReCiPe 2016 [34] impact categories are presented in Table 2. Since the methods were built in different eras, the monetary values are not referred to in the same year. Thus, in Table 2 these values were updated to 2020, to make them comparable.

Table 2. Monetary values of environmental externalities updated to 2020.

Environmental Impact Categories	**Monetisation factors**			
	ECOTAX02	**STEPWISE06**	**ECOVALUE08**	**ENVIRONMENTAL PRICES**
GWP [€/kgCO_2 eq]	0.09	0.1	0.25	0.0577
ODP [€/kg CFC-11 eq]	178.59	136.56	-	31
AP [€/kg SO_2 eq]	2.65	0.19	3.81	5.07
EP [€/kg $(PO_4)^{3-}$ eq]	4.22	1.49	27.69	5.75
POCP [€/kg Ethene eq]	71	0.7	5.08	0.71
ADP - mineral [€/kg Sb eq]	-	-	-	-
ADP - fossil [€/MJ]	0.03	0.005	0.00051	-

Therefore, the EPAC of the ETICS system is determined by using Equation (5). In detail, the EPAC for each monetisation method k-th was determined by multiplying the sum of the environmental reference benchmark value of each stage i-th for each impact category j-th ($(\mathrm{ERBstg}_i)\mathrm{cat}_j$) by the corresponding monetary factors of each monetisation method k-th of each impact category ($\mathrm{MFmethod}_{k,\,\mathrm{cat}j}$).

$$\mathrm{EPAC}\ [€/\mathrm{m}^2] = \sum_j \left\{ \left[\sum_i (\mathrm{ERBstg_i})_{cat_j} \right] \cdot \mathrm{MFmethod}_{k,cat_j} \right\}_{method_k} \tag{5}$$

Finally, by combining the TOC and EPAC, a global index depending on the thermal resistance (R_t) of the ETICS system was determined according to Equation (6).

$$\text{Global index}\ [€/(\mathrm{m}^2\mathrm{K/W})] = \frac{\mathrm{TOC} + \mathrm{EPAC}}{\mathrm{R_t}} \tag{6}$$

3. Results

3.1. Environmental reference benchmark

The estimation of the environmental impacts was developed by defining a reference benchmark for each life cycle stage, A1-A3, A4-A5 and C4. The objective of defining a benchmark was:

- to give producers/distributors/contractors the possibility to use the calculated benchmark to compare their activities and costs (TOCs and EPACs) with reference values;

- to allow public administrations to use reference values as an evaluation criterion within public tenders, loans, incentives, etc.

<u>*Stage A1-A3*</u>

The environmental reference benchmark for the production stage was estimated from a thorough literature review. A detailed analysis of the data collected showed that many of the impact categories units of some references were different from that considered in this study (Table 1). In detail, the impact categories AP and POCP were reported in moles H^+ eq and kg NMVOC eq, respectively, while the eutrophication potential in kg P eq. For this reason, many references [9,21] were excluded from the determination of the reference benchmark to give uniformity to the data collected. Furthermore, both references [12,13] and [15] considered an additional component to those selected in this work (Figure 1). In detail, a polyvinyl chloride (PVC) profile was used to provide mechanical strength. For the references [12,13], the amount of material associated with the PVC profile was 0.93 kg/m^2. Its percentage contribution for the impact categories GWP, AP, EP and ADP-Fossil was therefore consistent: 12, 40, 12 and 13% respectively. For this reason, in order to reduce the error during data interpolation, it was not taken into consideration for the determination of the reference benchmark. On the other hand, the amount of material associated with the PVC from the reference [15], turns out to be much lower, 0.12 kg/m^2. Consequently, the weight percentage in terms of environmental impact was in line with the trend obtained globally with all the references. The results corresponding to the environmental reference benchmark obtained from the analysis developed are displayed in Figure 2 and Figure 3, respectively considering the EPS and MW as insulation material. The graphs relating to ODP, EP and ADP-Mineral were not reported as they provided an R^2 value of less than 0.4, both for the EPS and MW. Thus, only the reference benchmark regarding GWP, AP, POCP and ADP-Fossil impact categories were selected. A possible explanation for the data of ODP, EP and ADP-Mineral that do not proceed in a valid linear trend (R^2> 0.4) might be that many references presented ETICS environmental impacts as a function of different finishing coat (renders) [8,9,17–20,24].

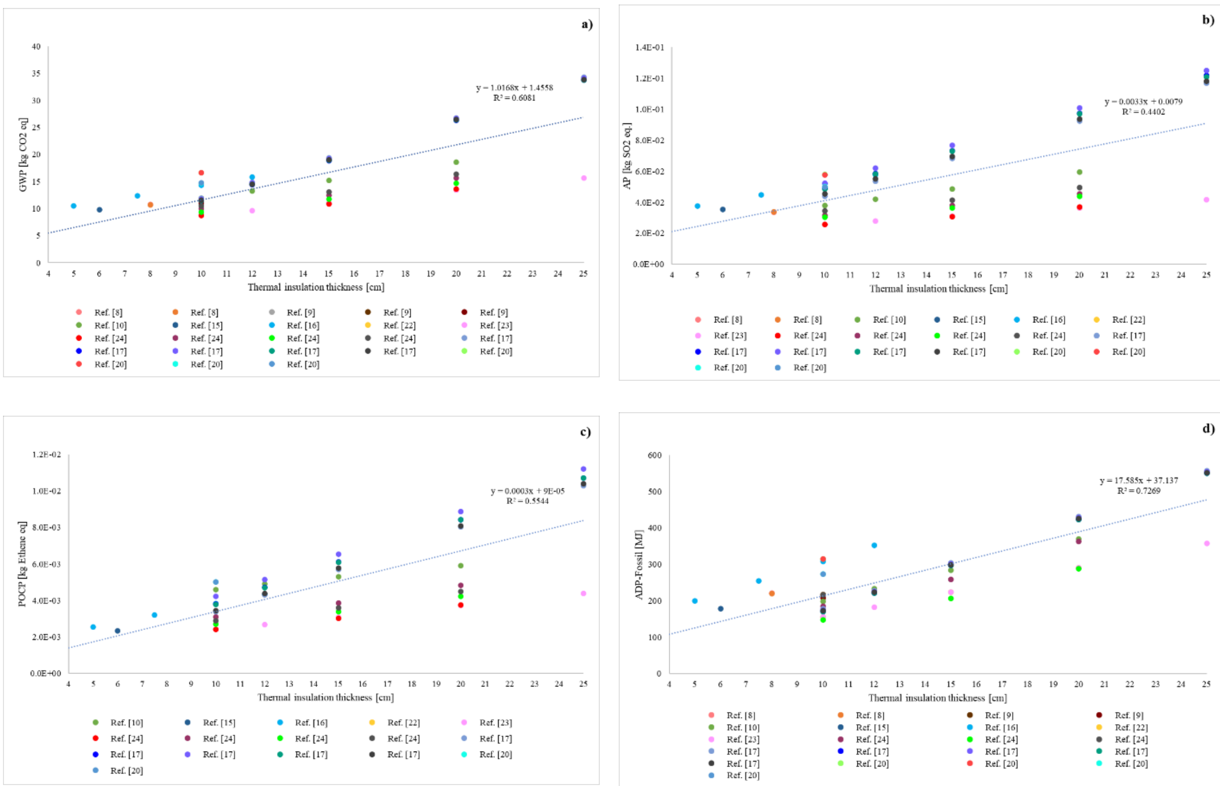


Figure 2. Environmental reference benchmark for stages A1-A3 for EPS regarding the impact categories a) GWP, b) AP, c) POCP and d) ADP-fossil.

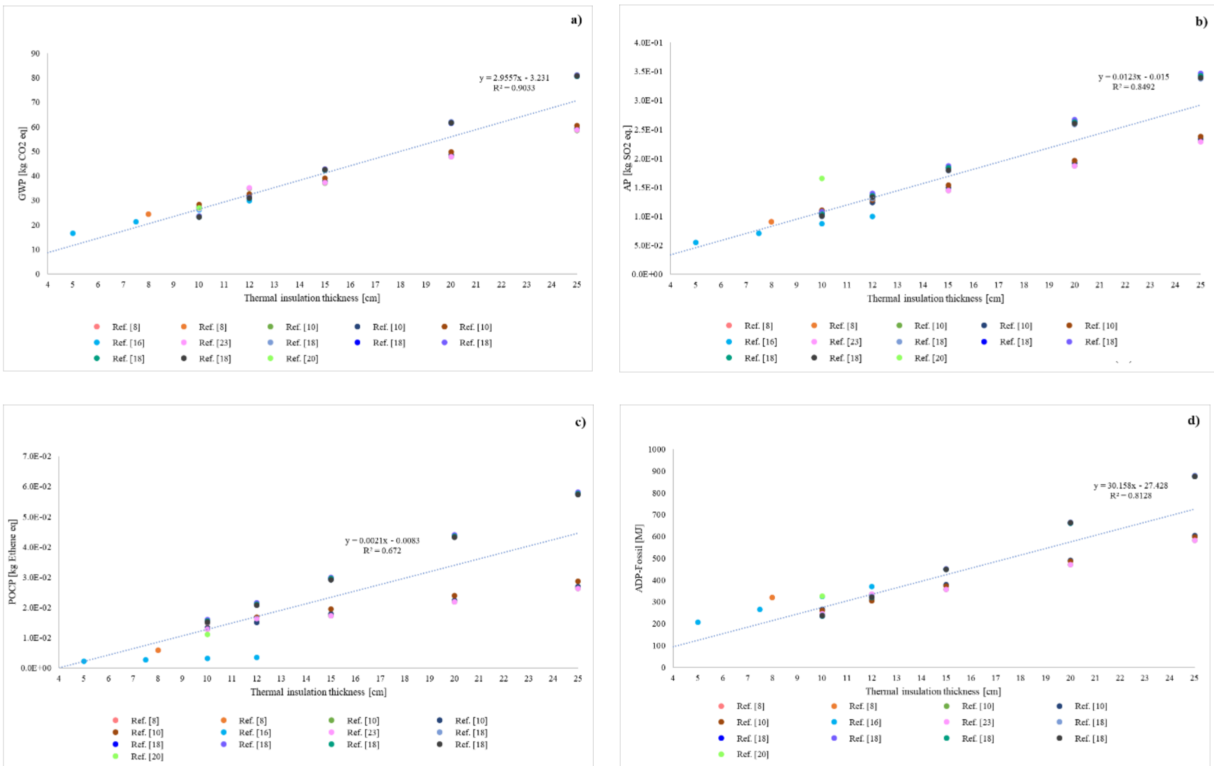


Figure 3. Environmental reference benchmark for stages A1-A3 for MW regarding the impact categories a) GWP, b) AP, c) POCP and d) ADP-fossil.

In detail, considering the reference [8] as an example, it was detected that it provided the environmental impact for the ETICS system composed of EPS or MW as a function of different finishing coats (renders) among which, acrylic and siloxane. From the analysis of the percentage contribution of the individual elements of the ETICS system on the total environmental impact of the system, it was observed that the render had the major influence on the category of ODP, EP and ADP-Mineral respectively by 60.6, 41.3 and 81.7 % in the case of EPS while 76, 40 and 86 % for MW. For this reason, the results regarding the latter environmental impact categories were not taken into consideration. Thus, for each impact category selected (GWP, AP, POCP and ADP-Fossil), the equation of the interpolating line of the impact values as the insulation thickness varies was determined. In this way, it was possible to obtain the value of the relative environmental impact for any thickness of insulation (reference benchmark). The equation of the interpolating line for each impact category with the relative value of R^2 is displayed in the graphs in Figure 2 and Figure 3, for both the EPS and the MW. Moreover, from the analysis of the references, the environmental impact percentage for each component of the ETICS system was also determined.

Stage A4-A5

The environmental reference benchmark associated with the transport phase (A4) was expressed as 1 km per ton of insulating material transported by each conveyance and reported in Table 3. Then, by using Equation (1) and Equation (2) the ERB_{A4} can be related to the type and thickness of specific insulation material (EPS or MW).

Table 3. Environmental reference benchmark for the transport phase A4

Conveyance	**Impact Categories**			
	GWP [kg CO_2 eq/tkm]	AP [kg SO_2 eq/tkm]	POCP [kg Ethene eq/tkm]	ADP-fossil [MJ/tkm]
Truck	1.65E-01	5.15E-04	2.07E-05	2.45E+00
Train	4.50E-02	2.82E-04	9.52E-06	5.42E-01
Ship	9.28E-03	2.44E-04	6.21E-06	1.19E-01

Moreover, for the installation stage A5, the environmental impacts produced by the consumption of 1 l of water and 1 kWh of electricity were multiplied by the average consumption of water, 2.635 l/m^2, and electricity, 0.085 kWh/m^2, obtained from the literature references analysis [15,16]. Thus, the environmental reference benchmark of the installation stage (ERB_{A5}) was calculated by the sum of the environmental impacts associated with the average consumption of water and electricity for the ETICS system with EPS or MW (Table 4).

Table 4. Environmental reference benchmark for the installation phase A5

ETICS	**Impact Categories**			
	GWP [kg CO_2 eq]	AP [kg SO_2 eq]	POCP [kg Ethene eq]	ADP-fossil [MJ]
EPS/MW	3.68E-02	1.45E-04	6.63E-06	4.84E-01

Stage C4

The end-of-life phase (C4) refers to the environmental impact produced by the disposal of the insulating material. The scenario assumed for stage C4 is landfilling. The corresponding environmental reference benchmark is indicated in Table 5. Then, the ERB_{C4} can be related to the type of specific insulation material (EPS or MW) by multiplying the values by the weight of the insulation material determined according to Equation (1), expressed in kg. Eventually, if the manufacturer of the ETICS system foresees the recovery, recycling and reuse of the materials making up the system, to pursue circular economy objectives, the overall environmental impact associated with this phase may not be considered.

Table 5. Reference benchmark for the disposal stage C4

ETICS	Impact Categories			
	GWP [kg CO_2 eq]	AP [kg SO_2 eq]	POCP [kg Ethene eq]	ADP-fossil [MJ]
1 kg EPS	1.33E-01	1.75E-04	2.28E-05	2.44E-01
1 kg MW	5.15E-03	4.40E-05	1.53E-06	1.45E-01

3.2. Determination of the global index: A case study

A case study was analysed as a practical application of the tool developed for the determination of the global index. The framework can be described as a tender for ETICS system application on a building façade in which the contracting public administration established a prerogative for assigning, the most economically and environmentally advantageous offer. With this aim, TOCs and EPACs were considered. In this case study, for the reasons extensively discussed in the previous paragraphs, only the environmental impact categories of GWP, AP, POCP and ADP-Fossil were considered.
Three different contractors were chosen to take part in the tender and indicated respectively as Co1, Co2 and Co3. The characteristics of each bid are reported in Table 6.

Table 6. Inputs of each contractor offer

Contractor	**1**	**2**	**3**
Insulation material	EPS	EPS	MW
ρ (kg/m^3)	15	15	80
λ (W/mK)	0.034	0.034	0.035
$ERBstg_{A1-A3}$	EPD	Tool	Tool
$ERBstg_{A4-A5}$	Tool	Tool	Tool
$ERBstg_{C4}$	Tool	Tool	Tool
Conveyance (km)	Truck (50)	Truck (50)	Truck (50)
Water consumption (l/m^2)	2.635	2.635	2.635
Electricity consumption (kWh/m^2)	0.085	0.085	0.085
Disposal	Landfilling	Landfilling	Recycling

It should be noted that, while Co1 made use of the EPD of its ETICS system for the determination of the environmental reference benchmark regarding the stage A1-A3 ($ERBstg_{A1-A3}$), Co2 and Co3 employed the tool developed in this work. Thus, the $ERBstg_{A1-A3}$ of Co1 is reported in Table 7, while the corresponding for Co2 and Co2 can be directly determined from Figure 2 and Figure 3.

Table 7. Environmental reference benchmark of stages A1-A3 regarding contractor 1.

Impact Categories	Stage A1-A3			
	GWP [kg CO_2 eq]	AP [kg SO_2 eq]	POCP [kg Ethene eq]	ADP-fossil [MJ]
Co1	1.08E+01	3.34E-02	3.06E-02	2.21E+02

Moreover, the ERB for the installation ($ERBstg_{A4\text{-}A5}$) and disposal ($ERBstg_{C4}$) stages were determined through the tool by all the contractors (Table 3, Table 4 and Table 5).
In order to provide an ETICS system with a thermal resistance of 2.34 m^2K/W, specified by the tender, the thickness of the EPS and MW should be 8 and 8.2 cm respectively, calculated according to Equation (2).
The TOCs arose from the costs offered by the contractor of the tender. The costs corresponding to each material were determined by multiplying the cost expressed in €/kg of the components of the ETICS system proposed by Co1, Co2 and Co3 and its relative consumption (kg/m^2), as listed in Table 8. It should be mentioned that the price of the insulation material is dependent only on the thickness and not on its relative consumption. Furthermore, for the installation of the ETICS systems, the anchors were not considered necessary. Thus, they were not included in the evaluation of the global index.

Table 8. Price and amount of consumption for each component of the ETICS systems proposed by Co1, Co2 and Co3.

ETICS Components	Co1		Co2		Co3	
	Consumption [kg/m²]	Price [€/kg]	Consumption [kg/m²]	Price [€/kg]	Consumption [kg/m²]	Price [€/kg]
Adhesive	4.50	0.84	5.50	0.84	7.00	0.84
Thermal insulation	/	7.20	/	8.86	/	16.28
Base coat	5.20	1.62	4.50	1.62	5.50	1.62
Glass fibre mesh	0.16	16.36	0.15	16.36	0.15	16.36
Primer	0.30	22.30	0.20	22.30	0.20	22.30
Finishing coat	2.60	3.10	2.50	3.92	2.50	3.92

The cost of manpower for the installation of the system depends on the thickness and type of the insulation material. Thus, according to the commercial prices, was found to be 43.48 €/m^2 for EPS of 8 cm and 39.11 €/m^2 for 8.2 cm of MW. For all the contractors the cost of the rental of equipment and scaffolding was set equal to 2.5 €/m^2 per month. Furthermore, a unique removal cost of 21.90 €/m^2 was inferred, calculated according to the following assumptions:

- specialised worker: 0.1 h (26.44 €/h);
- skilled worker: 0.15 h (24.60 €/h);
- unskilled worker (common worker): 0.15 h (22.14 €/h);
- disposal with collection on bins at the construction site (including container rental): (7.66 €/m^2);
- overheads: 15%;
- business profit: 10%.

The TOCs were calculated according to Equation (4) which includes the estimated service life calculated by Equation (3). In detail, the weighting coefficients A1, A2, B1 and B2 were 1, 1.2, 1 and 1 respectively. The ESL determined for each ETICS system was 30 years.
The TOC associated with each contractor is provided in Table 9.

Table 9. Direct costs of the ETICS systems proposed by each contractor.

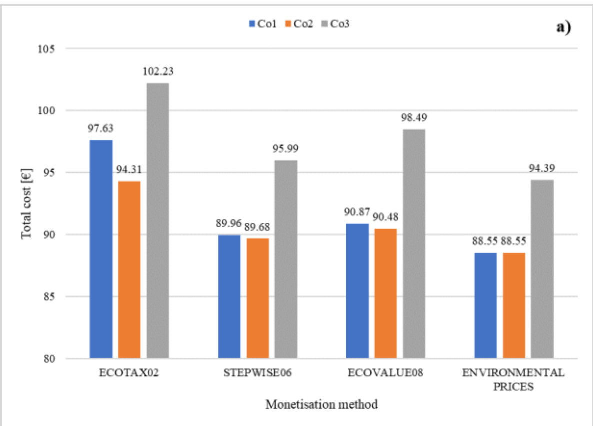
Contractor	OC_m [€/m^2]	OC_{in} [€/m^2]	OC_{rent} [€/m^2 per month]	OC_r [€/m^2]	TOC [€/m^2]
1	37.38	43.48	2.50	21.9	**87.72**
2	37.48	43.48	2.50	21.9	**87.80**
3	47.78	39.11	2.50	21.9	**92.74**

Once the environmental reference benchmark associated with the ETICS system of each contractor was determined, the EPAC for each monetisation method were calculated according to Equation (5). The numerical values for each contractor are presented in Table 10.

Table 10. EPACs for each contractor.

	ECOTAX02	STEPWISE06	ECOVALUE08	ENVIRONMENTAL PRICES
Contractor 1				
GWP	9.90E-01	1.10E+00	2.75E+00	6.35E-01
AP	8.95E-02	6.42E-03	1.29E-01	1.71E-01
POCP	2.18E+00	2.14E-02	1.56E-01	2.18E-02
ADP-fossil	6.66E+00	1.11E+00	1.13E-01	-
EPAC [€/m^2]	**9.91E+00**	**2.24E+00**	**3.15E+00**	**8.28E-01**
Contractor 2				
GWP	8.80E-01	9.77E-01	2.44E+00	5.64E-01
AP	9.24E-02	6.63E-03	1.33E-01	1.77E-01
POCP	1.97E-01	1.94E-03	1.41E-02	1.97E-03
ADP-fossil	5.34E+00	8.90E-01	9.08E-02	-
EPAC [€/m^2]	**6.51E+00**	**1.88E+00**	**2.68E+00**	**7.43E-01**
Contractor 3				
GWP	1.90E+00	2.11E+00	5.27E+00	1.22E+00
AP	2.21E-01	1.58E-02	3.18E-01	4.23E-01
POCP	6.43E-01	6.34E-03	4.60E-02	6.43E-03
ADP-fossil	6.72E+00	1.12E+00	1.14E-01	-
EPAC [€/m^2]	**9.48E+00**	**3.25E+00**	**5.74E+00**	**1.64E+00**

The total cost represented by the sum of TOC and ETOC is reported in Figure 4a. Finally, the global index expressed in €/(m^{2}K/W) was determined according to Equation (6) and shown in Figure 4b.



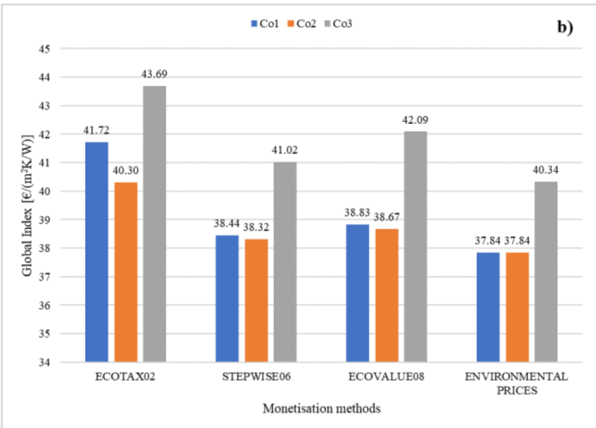


Figure 4. Total cost and global index of each contractor.

The results displayed in Figure 4 show that the most environmentally and economically advantageous bid is provided by contractor 2. Otherwise, the offer of Co3 attained higher values. It resulted in between 6.6 and 8.4 % higher than that of Co2, while Co1 at most of 3.5%. It should be noted that even if the cost related to environmental externalities has a very low incidence rate on the total cost (between about 0.8 and 10 %), for this case study, it was the deciding factor. Indeed, even if the lower direct costs were provided by Co1 (87.72 €/m^2) in comparison to Co2 (87.80 €/m^2) and Co3 (92.74

€/m^2), the slightly higher environmental impacts caused the costs to rise. Furthermore, this case study demonstrated that the proposed tool might be a useful instrument for companies producing ETICS systems. As well as assessing the overall cost-effectiveness, can be selectively estimated the environmental impact associated with each stage of the product life cycle. From the ERB values reported in Figure 2 and Figure 3 and in Table 3, Table 4, Table 5 and Table 7 it can be seen that high environmental impact is due to the production stages A1-A3, both for Co1, Co2 and Co3. Moreover, the contractor can detect, within the production stage, the component that produces the greatest impact (Figure 5).

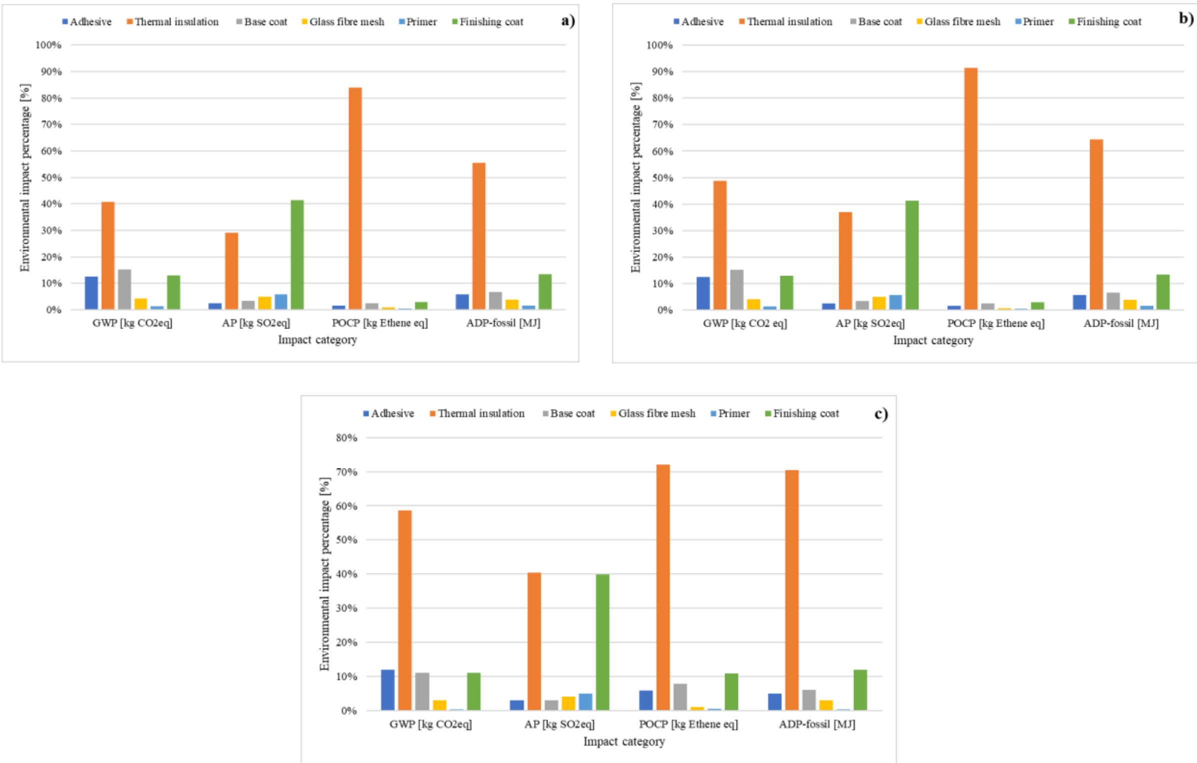


Figure 5. Environmental impact percentage over the production stage for each ETICS system component of a) Co1, b) Co2 and c) Co3.

In this case study, it can be seen how, for contractors 1 and 2, the largest percentage contribution is provided by the insulating material with respect to GWP, POCP and ADP-fossil, while for the AP category, by the finishing coat. Instead, for Co3, which provided the ETICS with the mineral wool, the greatest contribution for all impact categories is associated with the production of the insulating material, which can therefore be identified as the phase of the process that could benefit most from efficiency actions. In addition, it should be mentioned that, since the commercial thickness of MW panels is generally a multiple of 2, 10 cm should be considered. Thus, by maintaining all the parameters previously used, the offer of Co3 will be characterised by a higher price and global index. But, clearly provides an ETICS system with a higher thermal resistance (2.85 m^{2}K/W). In this condition, it is interesting noticing that, by considering changing the weighting coefficient B2 of Equation (3) from 1 to 1.2, thus using a better level of protection for the ETICS system, the ESL increases up to 36 years. Thus, the total direct cost of the system drops to 78.54 €/m^2 and the global index become 31.74, 28.98, 30.08 and 28.28 €/(m^{2}K/W) respectevely for ECOTAX02, STEPWISE06, ECOVALUE08 and ENVIRONMENTAL PRICES. Therefore, the most environmentally and economically bid is provided by contractor 3.

4. Conclusions

This study aimed to develop a useful tool to evaluate the economic and environmental performance of external thermal insulation composite systems for building façades. In particular, the tool might be used by both the manufacturer of ETICS systems to have a preliminary estimation of the environmental impacts associated with their product, identifying which phases of the life cycle should be improved from an environmental point of view, and the public administrations during the preparation of tenders for the energy requalification of buildings to identify the most environmentally and economically advantageous solution. The analysis of the Environmental Product Declarations and LCA studies resulting from scientific publications allowed determining a reference environmental benchmark based on four impact categories (GWP, AP, POCP, ADP-Fossil) for two different ETICS systems composed of EPS and MW as insulation material. The overall investigation of the results obtained in the case study showed that the environmental externalities have a rather limited weight compared to direct costs (at most 10%). Moreover, for all the impact categories considered, the production stage (A1-A3) represents the most significant contribution. In detail, the thermal insulation material and the finishing coat provide the greatest contribution to the environmental impact. This result could be useful for manufacturers to increase the environmental sustainability associated with their ETICS system. Indeed, they might improve the production process of these components, e.g. by reducing the consumption of fossil resources or by increasing the efficiency of the production process, so as to reduce the environmental impacts. As obtained from the LCC analysis, this would ensure a reduction in costs associated with the marketed ETICS system.

References

[1] European Commission (2022a). Public Procurement and the Single Market. Https://Single-Market-ScoreboardEcEuropaEu/Policy_areas/Public-Procurement_en 2022.
[2] European Commission. Europe 2020. A strategy for smart, sustainable and inclusive growth, COM(2010) 2020 final. n.d.
[3] Berg JB, Thuesen C, Jensen PA. Procurement innovation as a vehicle for sustainable change – a case study of the Danish model of strategic partnerships. CI 2022. https://doi.org/10.1108/CI-04-2021-0067.
[4] De Giacomo MR, Testa F, Iraldo F, Formentini M. Does Green Public Procurement Lead to Life Cycle Costing adoption? Proceedings 2018;2018:16760. https://doi.org/10.5465/AMBPP.2018.16760abstract.
[5] Braulio-Gonzalo M, Bovea MD. Relationship between green public procurement criteria and sustainability assessment tools applied to office buildings. Environmental Impact Assessment Review 2020;81:106310. https://doi.org/10.1016/j.eiar.2019.106310.
[6] EAE. European ETICS market 2020/2021. 5th European ETICS Forum 2021 2021.
[7] EOTA. ETAG 004 - Guideline for European Technical Approval of external thermal insulation composite system (ETICS) with rendering 2013.
[8] MAPEI. Environmental Product Declaration, MAPEI Sistemi per isolamento termico a cappotto:Mapetherm EPS, Mapetherm XPS, Mapetherm M.Wool 2017;Certificate No. S-P-00914.
[9] BAUMIT. External Thermal Insulation Composite System (ETICS) by BAUMIT Bulgaria EOOD 2021;Certificate No. 231/2021.
[10] Atlas. Environmental Product Declaration, Atlas ETICS External Thermal Insulation Composite System with Silicate Renders 2014;Certificate No. 021/2014.
[11] Institut Bauen und Umwelt e.V. UMWELT- Produktdeklaration, WDVS mit EPS Dämmplatten geklebt und gedübelt, Verband für Dämmsysteme, Putz und Mörtel e.V. 2017;Certificate No. EPD-WDV-20170077-IBG2-DE.
[12] Institut Bauen und Umwelt e.V. UMWELT- Produktdeklaration, WDVS mit Mineralfaser Dämmplatten geklebt und gedübelt, Fachverband Wärmedämm Verbundsysteme e.V. 2017;Certificate No. EPD-WDV-20170078-IBG1-DE.
[13] Institut Bauen und Umwelt e.V. UMWELT- Produktdeklaration, WDVS mit Schienenbefestigung, Fachverband Wärmedämm Verbundsysteme e.V. 2017;Certificate No. EPD-WDV-20170080-IBG1-DE.

[14] Institut Bauen und Umwelt e.V. UMWELT- Produktdeklaration, WDVS mit Mineralfaser Lamellen Dämmplatten geklebt, Verband für Dämmsysteme, Putz und Mörtel e.V. 2017;Certificate No. EPD-WDV-20170081-IBG2-DE.
[15] Grupo PUMA S.L. Declaración Ambiental de Producto, Sistema Traditerm EPS/EPS-G (SATE/ETICS) 2018;Certificate No. 007-003.
[16] Berger. Berger External Thermal Insulation & Composite Systems (ETICS), Environmental Product Declaration 2020;Certificate No. S-P-01418.
[17] HENKEL Operations Sp. Z o.o. Environmental Product Declaration ETICS-CERESIT CERETHERM UNIVERSAL EPS 2016;Certificate No. 036/2016.
[18] HENKEL Operations Sp. Z o.o. Environmental Product Declaration ETICS-CERESIT CERETHERM UNIVERSAL MW 2016;Certificate No. 040/2016.
[19] HENKEL Operations Sp. Z o.o. Environmental Product Declaration ETICS-CERESIT CERETHERM UNIVERSAL XPS 2016;Certificate No. 041/2016.
[20] San Marco Group SpA. Dichiarazione Ambientale di Prodotto Sistema Marcotherm EPS, EPS Color, Rock, PU 2019;Certificate No. S-P-01538.
[21] SETTEF. Dichiarazione Ambientale di Prodotto SISTEMA DI ISOLAMENTO TERMICO A CAPPOTTO THERMOPHON P, PV, MINERAL, NATURAL 2021;Certificate No. S-P-03093.
[22] Michałowski B, Michalak J. Sustainability-oriented assessment of external thermal insulation composite systems: A case study from Poland. Cogent Engineering 2021;8:1943152. https://doi.org/10.1080/23311916.2021.1943152.
[23] Michalak J, Czernik S, Marcinek M, Michałowski B. Environmental burdens of External Thermal Insulation Systems. Expanded Polystyrene vs. Mineral Wool: Case Study from Poland. Sustainability 2020;12:4532. https://doi.org/10.3390/su12114532.
[24] Michałowski B, Marcinek M, Tomaszewska J, Czernik S, Piasecki M, Geryło R, et al. Influence of Rendering Type on the Environmental Characteristics of Expanded Polystyrene-Based External Thermal Insulation Composite System. Buildings 2020;10:47. https://doi.org/10.3390/buildings10030047.
[25] Heller N, Flamme S. Waste management of deconstructed External Thermal Insulation Composite Systems with expanded polystyrene in the future. Waste Manag Res 2020;38:400–7. https://doi.org/10.1177/0734242X20904413.
[26] UNI 11156:2006, Valutazione della durabilità dei componenti edilizi 2006.
[27] Marques C, Brito J de, Silva A. Application of the factor method to the service life prediction of ETICS. International Journal of Strategic Property Management 2018;22:204–22. https://doi.org/10.3846/ijspm.2018.1546.
[28] Kus H, Nygren K. Microenvironmental characterization of rendered autoclaved aerated concrete. Building Research & Information 2002;30:25–34. https://doi.org/10.1080/09613210210122316.
[29] Silva A, de Brito J, Gaspar PL. Service life prediction model applied to natural stone wall claddings (directly adhered to the substrate). Construction and Building Materials 2011;25:3674–84. https://doi.org/10.1016/j.conbuildmat.2011.03.064.
[30] Eldh P, Johansson J. Weighting in LCA Based on Ecotaxes - Development of a Mid-point Method and Experiences from Case Studies. Int J Life Cycle Assessment 2006;11:81–8. https://doi.org/10.1065/lca2006.04.015.
[31] Weidema BP. Using the budget constraint to monetarise impact assessment results. Ecological Economics 2009;68:1591–8. https://doi.org/10.1016/j.ecolecon.2008.01.019.
[32] Ahlroth S, Finnveden G. Ecovalue08–A new valuation set for environmental systems analysis tools. Journal of Cleaner Production 2011;19:1994–2003. https://doi.org/10.1016/j.jclepro.2011.06.005.
[33] De Bruyn S, Ahdour S, Bijleveld M, De Graaff L, Schep E, Schroten A, et al. Environmental prices handbook 2017-methods and numbers for valuation of environmental impacts. Delft: CE Delft 2018.
[34] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 2017;22:138–47. https://doi.org/10.1007/s11367-016-1246-y.