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A comparative life cycle assessment of ETICS and ventilated façade systems with timber cladding

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ABSTRACT

The aim of this work is to evaluate the environmental impact of different solutions for building facade retrofitting. Based on Sustainable Construction, this study is carried out by applying the Life Cycle Assessment (LCA) methodology based on ISO 14044:2006 standard requirements. A "cradle-to-grave" life cycle analysis is developed for each solution, comprising the extraction of raw materials to the disposal phase, and then a comparative analysis was performed by considering the same functional unit: 1 m^2 of building facade for a 40-year time horizon. Four retrofit solutions are assessed: two External Thermal Insulation Composite Systems (ETICS), differing only in the insulation material, expanded polystyrene (EPS), and insulation corkboard (ICB); and two ventilated facade systems with different types of timber cladding, thermally modified timber, and painted timber. The data included in the inventory phase is mostly taken from technical documentation and from the Ecoinvent database, complemented with scientific literature and estimations when necessary. The LCA was performed using the SimaPro software applying both EPD (2018) and ReCiPe 2016 Endpoint (H) methods. Results of this study show that, phase-wise, the production and maintenance of the components materials have higher contribution in terms of environmental impact. On the other hand, by comparing the various solutions, the ventilated facade retrofit solution with heat treated timber cladding is the one that shows the highest environmental impact in almost every single category, whereas the cladding solution with painted timber finish is the one that shows the best environmental performance.

1. Introduction

Sustainable and rational energy use represents one of the many challenges cities face, since cities consume vast amounts of energy [71]. European buildings have long been prioritized for improving their energy efficiency [63]. In the European context, the construction sector is the main responsible for energy consumption - approximately 40 % [37], natural resource scarcity and waste generation (35 % of the EU's total waste generation) [93]. Also, this industry is on the top of the list of greenhouse gas contributors [28]. For the reasons, The EU adopted a European Climate Law, which establishes a target of being net carbon neutral by 2050 with a reduction goal of at least 55 % from 1990 levels by 2030. Accordingly, achieving a big emissions reduction within the buildings sector is a key action beside transport and energy sectors, where significant emissions reductions are possible to achieve with the implementation of a variety of energy strategies and measures.

The need to promote strategies and implement measures to reduce the consumption of natural resources [51], the use of fossil fuels, as well as to reduce carbon emissions [53] in both, new construction and building retrofitting [55], has been widely acknowledged in the literature and mainly include:

▪ Retrofitting the built environment since the majority of Europe's existing building stock is old [92] and in terms of energy efficiency and comfort, most buildings are severely underperforming [1]. This strategy enables the implementation of Nearly Zero-Energy Buildings (nZEB) [5] with the particular focus on envelope passive energy-saving and innovative technologies [9,86], and subsequent Renewable Energy Systems integration technologies and possible implications [52,56].

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▪ Optimization and efficiency in the use of non-renewable natural resources and reduction of the waste resulting from the end-of-life cycle of buildings [94]. This strategy involves promoting a greater use of renewable resources (raw materials and energy) in the manufacturing process of building products [3].

Hence, the sustainable improvements for building retrofitting [64], particularly the implementation of large-scale measures, should take into account, especially, the environmental impacts related to the materials production [58]. Currently, there is a wide range of renewable materials that can be used for retrofitting of building facades, which includes: wood, cork, recycled materials, polymer composites, among others. Insulation corkboard (ICB), e.g., is a natural and fully recyclable material produced from cork without the use of chemicals, since that only steam is used in the manufacturing process (autoclaving and bonding of cork granules) [85]. As a thermal insulation material, e.g., in the application of ETICS solutions, ICB can improve the energy efficiency of buildings.

Renewable natural resources are garnering increased attention, including wood. While wood as a building material has limitations regarding exposure to moisture and climatic conditions, its usage has been on the rise. With ongoing efforts to enhance its properties and increase durability through research, a new variant of building material, known as modified wood, has been developed [65]. Various methods of modifying wood are available to enhance its stability and durability. These include chemical modification, impregnation, thermal modification, and surface modification [35].

Life Cycle Assessment (LCA) is a technique used to assess the environmental impacts of a product or service, taking into account the entire life cycle from the acquisition of raw materials to the disposal of waste [41], and it can provide a reliable analysis of the impacts of building systems and materials over their entire life cycles. At each stage of the life cycle, the use of resources and the emissions are considered and measured, translating the environmental impacts. It is a holistic approach, based on today's sense of sustainability, as many construction and planning companies are becoming increasingly concerned about sustainability [76].

A few LCA studies regarding building facade retrofit have been conducted to support, as a decision-making tool, the evaluation of construction systems to enhance the general performance of buildings [33,88]. Also, it enables the comparison of different solutions to implement in each case. These research studies include comparative analysis of ETICS solutions using EPS and ICB as insulation materials, in terms of Energy, Economic and Environmental (3E) performance [79]; or considering not only various insulation materials but different facade systems as well, e.g., ventilated facade systems, under different climate conditions [77]. Some authors also contributed with the establishment of a tool, based on a multicriteria system, applied on several facade refurbishment proposals for a residential building [65]. One of the criteria involves an LCA study, which is carried out to evaluate the environmental impacts of the applied materials to each facade system, and their contribution to the overall sustainability performance. There are also authors that focus only on the study of the environmental impact related to the production stage of the components of a single construction system, e.g., ETICS, using data obtained from manufacturing plants [60]. However, no comparative LCA studies regarding complete ventilated facade systems with different timber claddings were found, as it is intended with this study by comparing it with ETICS solutions as well.

Most of the LCA studies related to the construction sector are conducted, specifically, to evaluate the manufacturing of a single building product and compare it with other materials. Some authors aimed to calculate the carbon footprint of an insulation material, e.g., ICB, following a life cycle approach, and compared it with other insulation materials available in the market [85]. Other authors focused on the environmental impact of the production of a based lime mortar, applied as a decorative mineral render for ETICS, and established a comparison with other system components [50]. Relevant LCA studies concerning the application of wood as facade cladding were also found. These research studies involve, e.g., the calculation of the carbon footprint of different timber claddings, or the environmental impact of thermally modified wood boards compared to untreated wood, comprising not only the manufacturing process [31] but the complete life cycle as well [32].

Several studies have attempted to perform LCA of ventilated facade systems in the past, yet with limited scope and variants, using small amounts of indicators, limited tools, and often a comparison of two materials. In [10] only the cradle-to-gate variant is addressed. Other authors compare a Multi-Active Façade system with an ETICS using EPS [72], however, this study is limited by the use of the online-calculator Eco2Soft. A ventilated facade with phase change materials (PCM) in its air chamber was studied using the EcoIndicator 99 in another study [15]. [90] focused on how LCA studies should be performed based on EN 15804/15978 was presented to assess the environmental impact of circular versus linear building façade elements. [4] compared recycled versus non-recycled insulation alternatives using Open LCA software, which has several limitations, using recycled cork, natural cork, and rock wool, as insulation materials. Finally, by using the CML 2 baseline 2002 as a baseline, [77] conducted a study in which the installation phase was included in assessing thermal insulation materials' environmental impacts.

The aim of this paper is to fill this gap by providing a detailed environmental impact assessment comparing an all-encompassing "cradle-to-grave" LCA analysis. SimaPro Software is used to compare ETICS and timber ventilated facade systems by using both EPD (2018) and ReCiPe 2016 Endpoint (H) methods of in a comprehensive way. Four solutions are studied: two External Thermal Insulation Composite Systems (ETICS), that differ in the insulation materials, expanded polystyrene (EPS), and insulation corkboard (ICB); two ventilated facade systems with different types of timber cladding, thermally modified timber and painted timber. Each solution is subjected to a cradle-to-grave life cycle analysis using ISO 14044:2006 standards encompassing extracting raw materials to disposing of them, and a detailed comparison analysis is performed utilizing the same functional unit of 1 m^2 of building façade with an R value of 1 m^2 K/W, like studies performed by [8,36,75,83]. Based on the analysis of previous studies focusing on LCA of various facade systems, the life cycle span of facade systems usually varied between 40 and 60 years [2,33,46,68,88,95]; Cardoso et al., 2023). Hence, a conservative value of 40 years is considered for life span in this study.

This paper is structured in the following sections. Section 1 provides a review of existing LCA studies related to building facade retrofitting solutions and building products. Section 2 contains a brief description of ETICS and ventilated facade systems, including their components, the advantages of their application, as well as the standards that specify the performance requirements for each system. Also, in Section 2 is described the LCA method adopted in this study. Section 3 describes the case study which includes the application of the different phases of the LCA methodology to the different solutions. Section 4 shows the results of the analysis and their interpretation, while section 5 introduces the main conclusions of this study as well as some ideas in future research.

2. Materials and methods

2.1. External Thermal Insulation Composite System (ETICS)

An External Thermal Insulation Composite Systems (ETICS) is a particular solution of application of thermal insulation from the outside of the building, used both in new construction and building retrofitting. It consists of an external thermal insulation material, adhesive (basic fixing), anchors (additional fixing), base coat, reinforcement (usually, a alkaline-resistant fiber glass mesh embedded in the base coat), finishing coat with paint or primer coat, and accessories, e.g., edge profiles, corner beads, expansion joint profiles, base profiles (Fig. 1). This system is widely applied for its well-known advantages, such as the reduction of thermal transmission through the outer walls, lower risks of surface condensations, increase of thermal inertia of the envelopes, and mitigation of thermal bridging effects. In addition, this system enables the use of thinner external walls and permits installation without causing disruption to the building's occupants. This enhances the durability of the facades and delivers a finished appearance that closely resembles traditional rendering [49,79].

The EU has established performance criteria for External Thermal Insulation Composite Systems, which are utilized for insulating building walls. These criteria are outlined in ETAG 004 [40], which also outlines the methods used to verify different aspects of performance, the assessment criteria for determining the suitability of these systems for specific uses, and the presumed conditions for their design and execution [27].

The two ETIC solutions examined in this study differ only in respect of the insulation material. One is based on expanded polystyrene (ETICS-EPS) (Fig. 1 a) whereas the other is based on insulation corkboard (ETICS-ICB) (Fig. 1b). However, both solutions are based on the DIERATHERM system, manufactured by DIERA.

As specified by the ETA 14/0363 [26], the system based on EPS comprises the following components:

- Insulation material: expanded polystyrene (EPS) panels.
- Adhesive: The powder mortar comprises a blend of binders, including white cement CEM II/A L 52.5 N (br), along with siliceous sand, a non-toxic water retention agent, natural fibers, and synthetic resins.
- Base coat: a mortar in powder similar to that considered for the adhesive.
- The primer is formulated with an aqueous dispersion of inorganic mineral fillers, acrylic resins, pigments, quartz sand, and specific additives.
- The decorative thick finishing coat consists of a watery dispersion similar to the one used for the primer.
- The reinforced mesh is a fiberglass mesh with a 6 mm × 6 mm mesh size, in compliance with LNEC's Agrément Certificate DH 918 [16].
- The anchors are additional mechanical fasteners, as specified in ETA 08/0172 [23].
- The description of the ancillary materials is in compliance with clause 3.2.2.5 of ETAG 004 [27].

The thermal conductivity (λ) adopted for the insulation materials is 0,035 W/m. K for EPS and 0,040 W/m. K for ICB, respectively. Both insulation materials are 40 mm thick, which provides a similar thermal performance, i.e., approximately, the same thermal resistance, R = 1.00 m^2 K/W. unit. Insulation of this thermal resistance, applied to a building envelope resembling the constructive design of 1971–1990's buildings in Portugal consisting of a cavity wall made of clay hollow bricks, would meet the building regulation for residential buildings for the most representative winter climate zone (I1), U-value 0.5 W/ m^2 K.

2.2. Ventilated facade system

A ventilated façade is a multi-layered building envelope system that offers diverse options for the cladding material (steel elements, stone, concrete boards, timber boards, ceramic, and other composite elements), offering a wide range of architectural options [7,77]. The external cladding elements are mechanically fastened by cladding fixing devices to a subframe. Between the external cladding and the thermal insulation or external wall, there is a ventilated air gap, which, by allowing free air circulation, removes moisture and improves the energy performance (Fig. 2). The installation of the insulation material outside the main wall also reduces the thermal bridges effect [77]. The technical document which outlines the requirements for the complete ventilated façade system is ETAG 034 [24,47]. Additionally, each individual component of the system must also satisfy the national standards in addition to the criteria specified in this standard [73]. The ventilated air gap, e. g., according to the ETAG 034, is at least 20 mm, but locally it may be reduced to 5–10 mm, depending on the substructure and cladding; however, it cannot affect the hygrothermal efficiency of the entire system.

The two ventilated solutions examined in this study differ only in respect of the external cladding material. One is based on thermally modified wood (VENT-TMW) (Fig. 2 a) whereas the other is based on

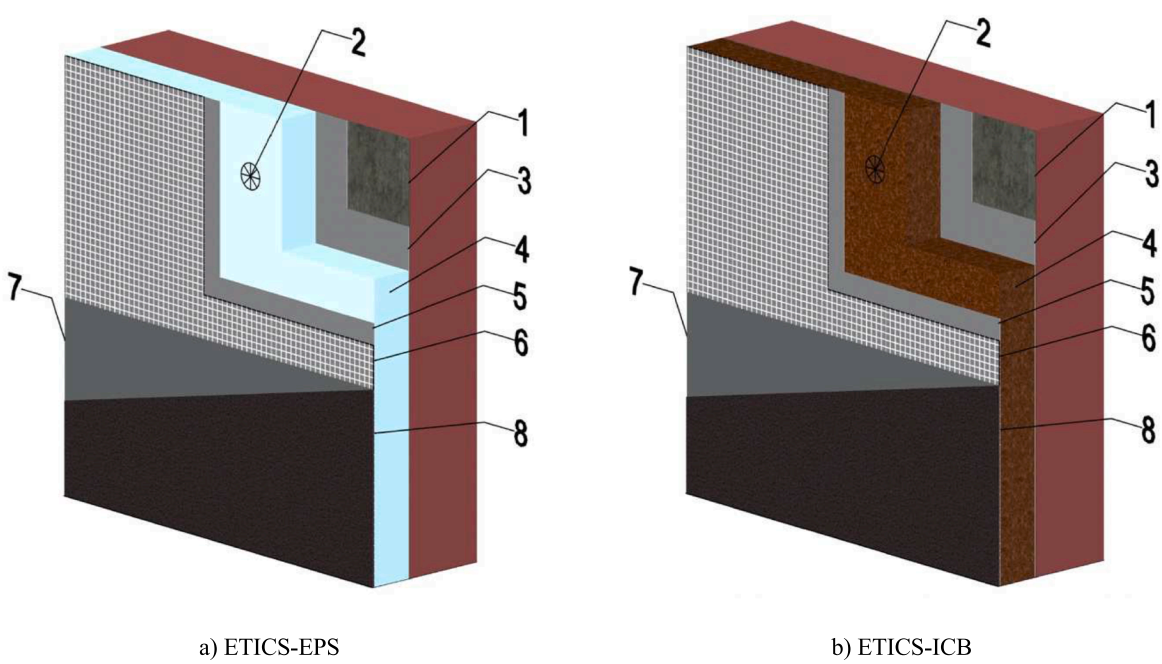
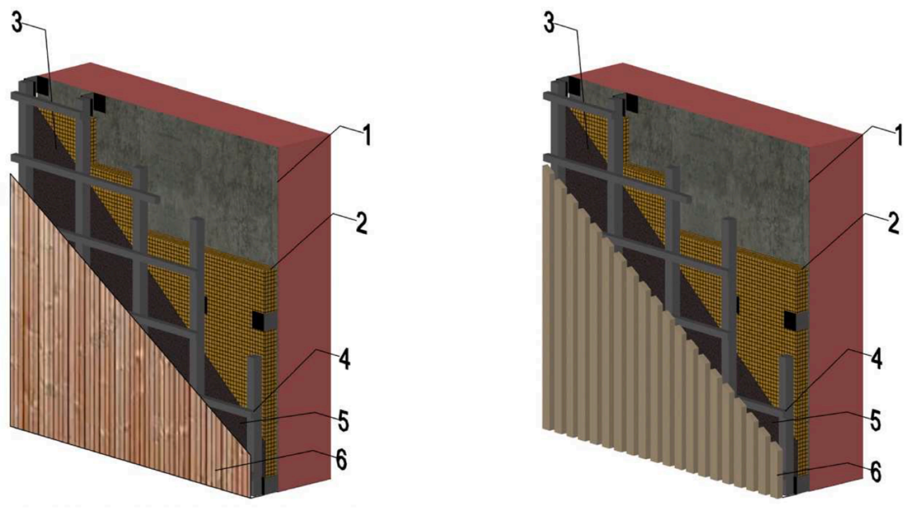


Fig. 1. Illustration of an external insulation system: (1) substrate (wall structure), (2) anchor (additional fixing), (3) adhesive (basic fixing), (4) thermal insulation: EPS on a) and ICB on b), (5) base coat, (6) fiber glass mesh, (7) primer, (8) finishing coat.



a) VENT-TMW b) VENT-UPW

Fig. 2. Illustrative example of a ventilated facade system: (1) substrate (wall structure), (2) thermal insulation (MW), (3) waterproofing membrane (4) subframe, (5) ventilated air gap, (6) external cladding.

untreated painted wood (VENT-UPW) (Fig. 2 b). Both claddings are 26 mm thick.

The ventilated facade systems examined in this study are based on ETAG 034 [24] and consist of:

- Insulation material: mineral wool (MW) was adopted for both solutions.
- Breather membrane: a waterproofing breathable membrane with the purpose of protecting the insulation material against weathering (e.g., in the case of an open-joint cladding situation).
- Subframe: an intermediate assembly of horizontal and vertical, timber or metal (galvanized steel, stainless steel or aluminium alloy) profiles.
- Fixing devices: both for cladding and subframe, which include rivets, screws, brackets, profiles, or any special fixing devices.
- Ventilated air gap: A layer of air that provides moisture removal and drainage by allowing efficient ventilation.
- External cladding: timber cladding.
- Ancillary materials: any supplementary elements, e.g., to form joints (sealants, corner strips, etc.) or to achieve continuity (mastics, joint covers, gaskets, trims, etc.).

The mineral wool is 40 mm thick and has a thermal conductivity of 0,040 W/m. K, providing the same thermal resistance as EPS and ICB above, namely, R = 1.00 m^2 K/W. unit. The choice of the mineral wool is justified by the following considerations. According to a technical report published by the Joint Research Centre of the European Commission in 2018 [29] MW is, along with EPS, the most used insulation material in the building industry in Europe due to its very high energy and acoustic performance per unit cost. In addition, the stone wool insulation offers excellent fire resistance (ideal when insulating around combustible wood) and much higher water vapour permeability than EPS [19] (an ideal property which lowers the risk of interstitial condensation due to water vapor diffusion).

Given that according to the technical literature guidelines [18] the external timber cladding should be considered open joint cladding for drainage of incidental moisture, the ventilated air gap the airflow in the cavity is mainly influenced by the wind effect [69]. As such, the thermal resistance of the air space is negligible, and therefore, the thermal resistance of the ventilated façade system is similar to ETICS above.

2.3. Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a technique utilized to assess the environmental impact of a product, service, or activity during its entire life cycle. For the construction industry, LCA typically encompasses the production, use, construction, and end-of-life stages (Fig. 3) according to EN 15804:2012 + A2:2019 [20] and EN 15978:2011 [34,91]. At each stage of the life cycle, the inputs (raw materials and energy) and outputs (emissions to air and water, and solid waste) are identified and quantified, thus, LCA allows for the calculation of overall environmental impacts across categories such as global warming, ozone layer depletion, soil and water acidification, eutrophication, and abiotic depletion for both non-fossil and fossil resources [70]. A comparative LCA can be performed to evaluate the environmental impacts of two or more products with similar functionality, by adopting the same functional unit, system boundary, data quality and impact assessment [41].

The LCA methodology is based on ISO 14044:2006 standard [41]. The process is systematic and is divided into four phases (Fig. 4):

Goal and Scope Definition: Identifying and describing the product, service or activity, the aim of the study, functional unit, system boundaries, impact assessment method, impact categories, assumptions, limitations, etc.

Life Cycle Inventory (LCI) involves the collection of data related to raw materials, energy consumption, emissions, waste, etc., to quantify the inputs and outputs of each life cycle stage. The sources for this inventory can include various LCA databases, technical documentation (e.g., EPDs and ETAs), site-specific data, studies found in the literature, and more.

Life Cycle Impact Assessment (LCIA) is the evaluation of potential environmental impacts. This stage includes the selection of impact categories, category indicators, and characterization models, the allocation of the inventory data to the chosen impact categories – known as classification, and the calculation of category indicator results – known as characterization. This process involves converting LCI results to a common unit by applying characterization factors and aggregating the converted results within the same impact category.

Interpretation: Analysing the results based on LCI and LCIA, drawing the main conclusions, limitations, and possible recommendations. Since LCA is an iterative process, the occurrence of uncertainty in the

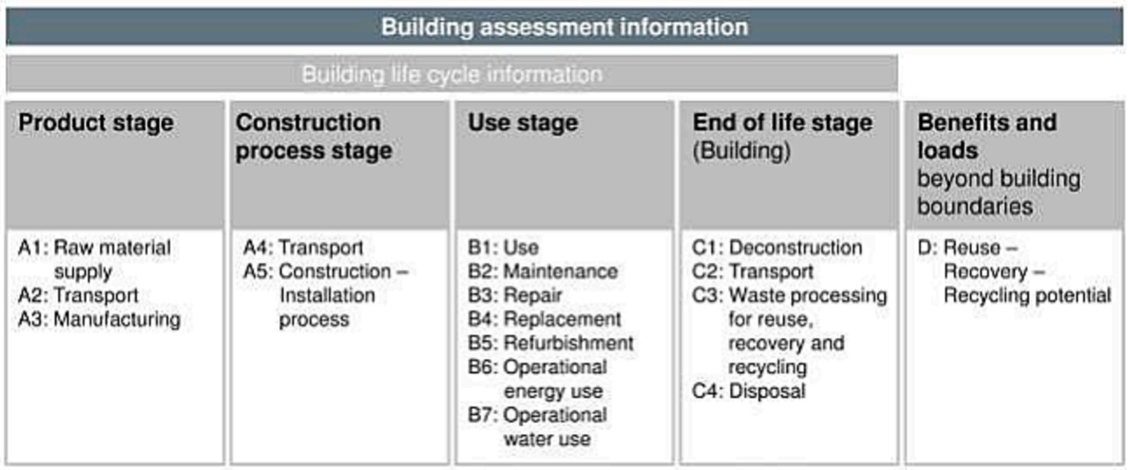


Fig. 3. Life cycle stages considered for buildings and construction materials according to EN 15804 and EN 15978 for sustainable buildings (EN 15804:2012 + A2:2019, 2019), [22] (adapted from Sustainability considerations for the construction phase of steel structures [76].

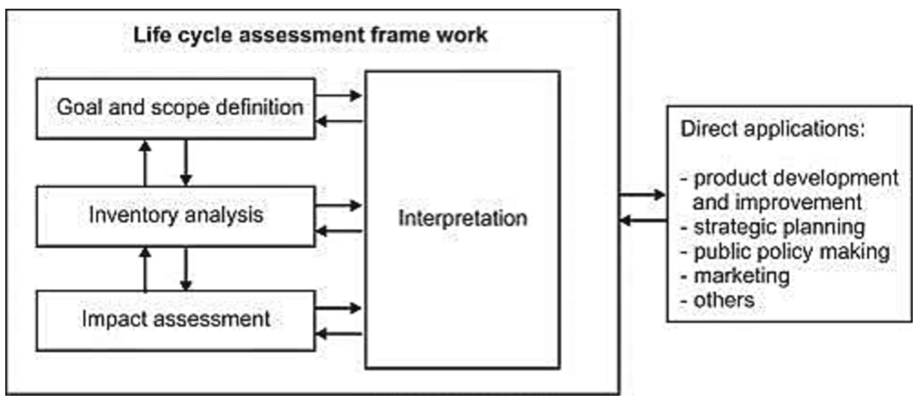


Fig. 4. LCA phases according to ISO 14044 [41] (adapted from Environmental Management: Science and Engineering for Industry [61].

results can lead to a revision of the scope of the study, as well as the nature and quality of the data collected for the inventory phase.

The impact assessment methods adopted were EPD (2018) and ReCiPe 2016 Endpoint (Hierarchist) using the SimaPro 9.2 software.

3. Case study

3.1. Goal and scope definition

This study aims to evaluate the environmental impacts of solutions for building facade retrofitting which are most likely to occur in deep renovation retrofitting and to determine which one is more sustainable. As mentioned above, four solutions are examined: two ETICS, one with EPS and the other with ICB as insulation materials (abbreviated as ETICS-EPS and ETICS-ICB, respectively), and two ventilated facade systems with different timber claddings: one including thermally modified wood and the other untreated painted wood (abbreviated as VENT-TMW and VENT-UPW, respectively). The analysis results intend to demonstrate whether, e.g., ICB, which is produced from a renewable natural resource (cork), is a more environmentally friendly choice for thermal insulation than EPS. Also, the environmental impact of heat-treated wood used for external cladding is compared with untreated wood taking into consideration the energy-intensive manufacturing process.

An LCA analysis is performed to identify the advantages and drawbacks of each solution. The energy demand, resources, emissions and waste generation are quantified considering the complete life cycle of each solution. This methodology can provide reliable and detailed results, but it is considered a long and iterative process which depends, above all, on the accuracy of the data and possible omissions or assumptions made.

The target audience for this LCA includes the academic community, companies and organizations that want to know more about this methodology and its relevance for the sustainability of the construction sector, either new or refurbished and renovated buildings. To the best knowledge of the authors, this is the first study employing both EPD (2018) and ReCiPe 2016 Endpoint (H) methods to perform an LCA study for two ventilated facade systems with different timber claddings to make the overall results broader, with more detail, and more useful for different comparisons for future studies.

3.2. Functional unit

The functional unit (FU) provides a reference to which the input and output data are normalized [41]. For this study, the Product Category Rules (PCR) for thermal insulation materials is used as a reference [14] since they do not exist specifically for ETICS and ventilated facade systems. To make the comparative analysis possible, as mentioned in the introduction above, the same functional unit is adopted for all solutions, defined as 1 m^2 of facade, incorporating thermal insulation materials with a thermal resistance (R) equal to 1 m^2 K/W, for a 40-year life cycle.

3.3. System boundaries

A "cradle-to-grave" approach is considered for each solution. The scope of the study and the system boundaries are shown in Figs. 5 and 6, and each life cycle stage is described below, including the assumptions made. It should be noted that some system components related to each solution (see 2. "Materials and Methods" section) are not included in this study, such as fixing devices and accessories. These exclusions are justified in the 3.4 "Assumptions and limitations" subsection below.

The first life cycle stage includes the extraction and production of raw materials. To produce some components, e.g., dry premixed mortars, different raw materials are incorporated into their formulation: mixed binders (agglomerates), aggregates (natural or artificial sand), additions (fibers, fillers) and admixtures [70]. In other cases, such as for the production of EPS insulation boards, complex chemical processes are required in order to obtain the raw material (polystyrene polymer) [89].

The transportation stage is divided in two: from the extraction site to the manufacturing plant, and then to a hypothetical construction site,

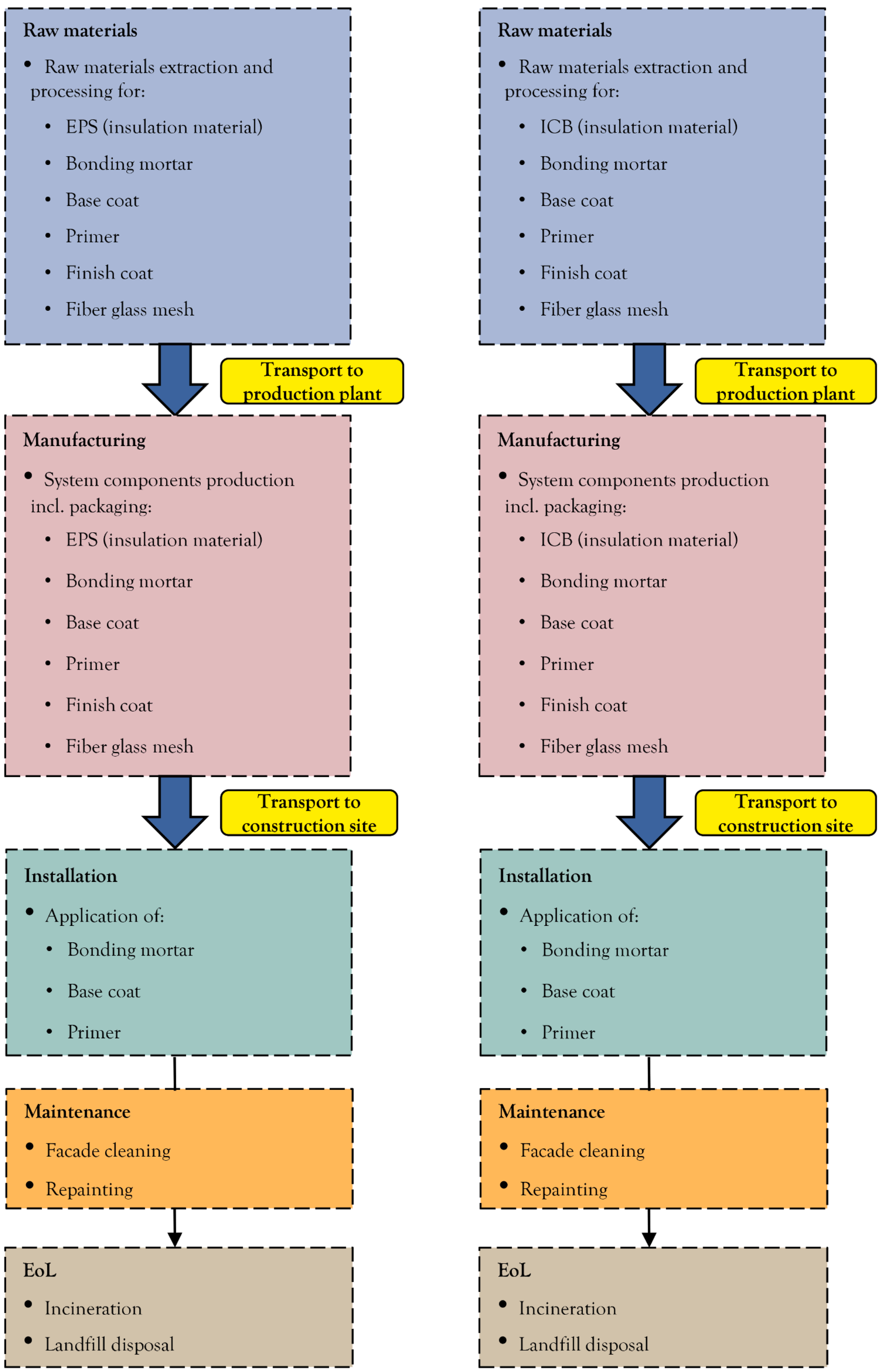


Fig. 5. System boundaries of ETICS with EPS (left) and with ICB (right) as insulation materials.

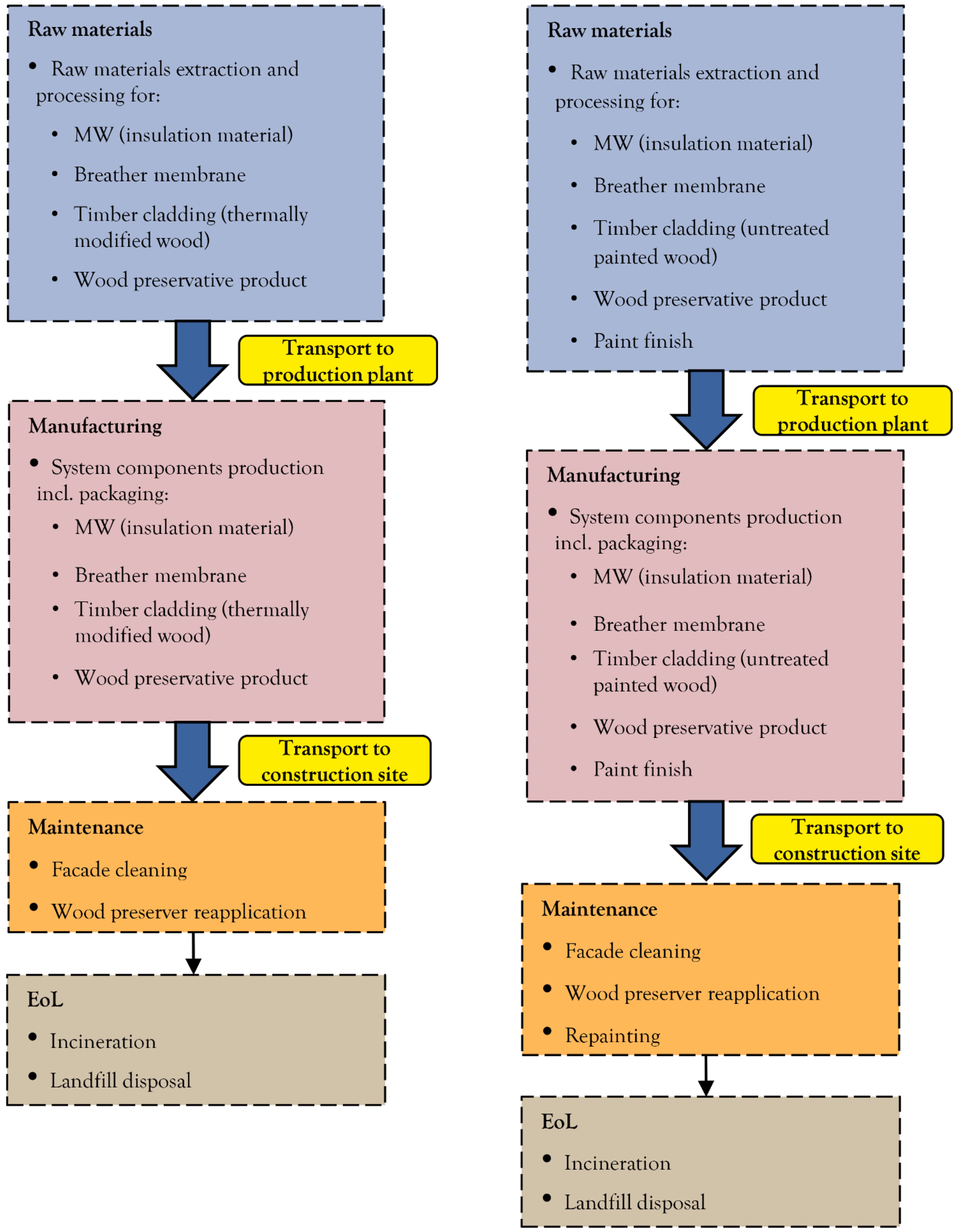


Fig. 6. System boundaries of ventilated facade systems with timber cladding: thermally modified wood (left) and untreated painted wood (right).

located at Benfica parish (Lisbon, Portugal). Some components are not transported directly to the construction site, but for a distribution center, and, therefore, this intermediate route is also considered when applicable. For the accounting of fuel consumption, all distances are covered by truck for each material except for the breather membrane, which it was also necessary to consider sea transportation.

For the manufacturing stage, it is not only considered the resources and energy consumption related to the industrial processes, but the emissions to air and water, and the solid waste generated as well. The packaging of the different components is also included in this life cycle stage.

In the case of the ETICS solutions, the application of mortars needs to be considered. The water and energy consumption (the electricity consumed by the concrete mixer) related to the kneading process of mortars is included in the installation stage. Also, the primer adopted must be only applied after dilution with clean water, in a proportion of 20 % to 30 % [17], so the related water consumption is also accounted for. For the ventilated facade systems, no inputs are considered for this life cycle stage.

The maintenance stage is mainly related to facade cleaning and repainting operations. The facade cleaning is the same for each system and is performed prior to the repainting, using a low-pressure water jet. Regarding repainting operations, both ETICS solutions require the application of the finish coat at every 10 years (Sousa, 2023) until the end of the life cycle (40 years), while for the ventilated facade systems, it depends on the type of timber cladding. In the case of thermally modified wood (VENT-TMW), it includes the application of a wood preservative product, at every 5 years (7 applications), to prevent the natural graying of wood. As for the untreated painted wood (VENT-UPW), it not only includes the application of the wood preserver but the paint finish as well, at every 10 years (3 applications each).

The end-of-life treatment of the different components mainly include landfill disposal and incineration. The recycling is excluded as an alternative option because there are no specific processes for this purpose in the Ecoinvent database, as well as due to the complexity associated with the creation of specific scenarios for this operation. In the case of ETICS, the components cannot be separated, e.g., ICB is landfilled since it is considered contaminated with the application of glue, mortar or paint, according to the European List of Wastes (LoW) [30]. Also, the fiberglass mesh is embedded in the base coat [see 2.1 External Thermal Insulation Composite System *(ETICS)* subsection], i.e., it is considered inseparable from it, so the same type of EoL treatment is applied, landfill disposal. Another example is the treated or painted wood which can only be disposed of in specific landfills due to the presence and release of toxic products [44,87]. However, for this study, it is assumed that both the preservative product and the finish paint are removed from the external cladding and distinct EoL processes are adopted. Therefore, landfill disposal is used as EoL treatment for preservative product and paint waste, while the incineration process is considered for wood.

4. Assumptions and limitations

The following components were not included in this study:

Wall structure (usually consisting of cavity walls without thermal insulation and traditional factory-made mortars as rendering).
Fixing devices (anchors, in the case of ETICS, and screws or rivets, in the case of ventilated facades; as well as the subframes).
Accessories and ancillary materials (profiles, trims, gaskets, ventilation strips, cappings, etc.).

Additionally, the quantification of the timber claddings for LCI purposes does not take into consideration the disposition of the profiles (horizontal or vertical) or the type of joint (open or overlapping). The exclusion of these components is based on the difficulty to quantify the aforementioned elements, e.g., the number of screws to be used in the cladding fixings of ventilated facades, and the lack of quantified data about the auxiliary substructures needed for the LCI phase, given the functional unit adopted. Also, it was intended to give more relevance to the remaining components of each system, namely, thermal insulation and external cladding. The consideration of the missing components would make more sense, e.g., in LCA studies applied to buildings. Nevertheless, the environmental impact in terms of CO_2 emissions in production of 1 kg of some of the excluded components have been reported in the literature [45,68] as follows: hollow concrete block – 0.11 kg CO_2/kg; reinforcement mesh – 2.56 CO_2/kg; aluminium frames – 8.25 CO_2/kg; and timber frame – 0.11 CO_2/kg.

The distances accounted for both road and sea transportation of the different components correspond to estimations provided by Google Maps platform. Approximate distances considered in previously published LCA studies are also used.

4.1. Life cycle inventory

The primary sources for this inventory include manufacturing companies and suppliers of each system, as well as technical documentation, e.g., European Technical Approvals (ETAs) and EPDs; specially to gather input and output data concerning mass quantities and manufacturing processes. Complemented data on certain raw materials, e.g., for mortars formulation, or related to the maintenance of the systems are taken from previously published studies.

In the absence of more specific data related with certain materials, their transportation and end-of-life treatment, input and output data included in the unit processes from the Ecoinvent v3 database are used as an approximation. Although, in some cases, it was necessary to create specific unit processes or make changes related to inputs (raw materials, energy and fuels consumed) and outputs (emissions), which included additional measurements, calculations or estimations. The transportation data considered for each component, as mentioned in the 3.3 "System boundaries" subsection, are related to distances from the extraction of materials to the production site, and then to a hypothetical construction site, located at Benfica parish (Lisbon, Portugal).

The complete life cycle inventory data for both ETICS and ventilated facade systems are available in Appendix A. Supplementary data of this paper.

4.2. Life cycle impact assessment

Both EPD (2018) and ReCiPe 2016 Endpoint (Hierarchist) were chosen as the impact assessment methods. EPD is a method that was created for the elaboration of environmental production declarations (EPDs), standardized documents that provide LCA-based information on environmental aspects of products over their life cycle, allowing the comparison between products with the same function [66]. Different studies have recognized the value of using EPDs for performing LCA studies or for carrying out comparisons [6]. Table 1 shows the impact categories covered by this method.

The ReCiPe 2016 Endpoint (Hierarchist) is a method that evaluates both midpoint (problem oriented) and endpoint (damage oriented) impact categories [66]. The relationship between the 18 midpoint impact categories and the three endpoint categories of protection is summarized in Fig. 7. The two approaches are complementary since the midpoint level is more strongly related to environmental flows with lower uncertainty, while the endpoint level is easier to interpret in terms of the relevance of the environmental flows [38]. Only the most relevant impact categories are considered taking into consideration the context of this LCA study and the similarities with the impact categories of the EPD method. It should also be noted that this method, based on different sources of uncertainty and value choices, is divided into three groups: Individualist (I), Hierarchist (H) and Egalitarian (E) [66]. The model adopted for this LCA was the Hierarchist since it is considered the default model and is widely used in scientific models [12,67].

5. Results and discussion

5.1. EPD (2018) method

Based on the LCI and the LCIA phases, a comparative LCA is carried out using SimaPro. The results for the EPD (2018) method are presented in Fig. 8. For comparison purposes, the system with the highest contribution in each category is set with the highest score in percentage (i.e., 100 %). The results (characterization) for the contribution of the different life cycle stages to the environmental impact of system 1, 2, 3 and 4 are shown in Figs. 9, 10, 11 and 12, respectively.

As Fig. 8 shows, the ETICS-EPS retrofit solution has higher contribution in most categories (five categories), compared to ETICS-ICB (three categories). However, the difference between certain categories, e.g., acidification, eutrophication or abiotic depletion - elements, is quite small.

Table 1
Overview of the impact categories included in EPD (2018) method, related characterization factors and units [25].

Impact category	Characterization factor (CF)	Unit
Acidification (fate not incl.)	Acidification potential (AP)	kg SO_2-eq
Eutrophication	Eutrophication potential (EP)	kg PO_4-eq
Global warming	Global warming potential (GWP100a)	kg CO_2-eq
Photochemical oxidation	Photochemical oxidant creation potential (POCP)	kg NMVOC
Abiotic depletion, elements	Abiotic depletion potential – elements (ADPe)	kg Sb-eq
Abiotic depletion, fossil fuels	Abiotic depletion potential - fossil fuels (ADPff)	MJ
Water Scarcity	Water scarcity footprint (WSF)	m^3 water-eq
Ozone layer depletion	Ozone depletion potential (ODP) (optional)	kg CFC-11-eq

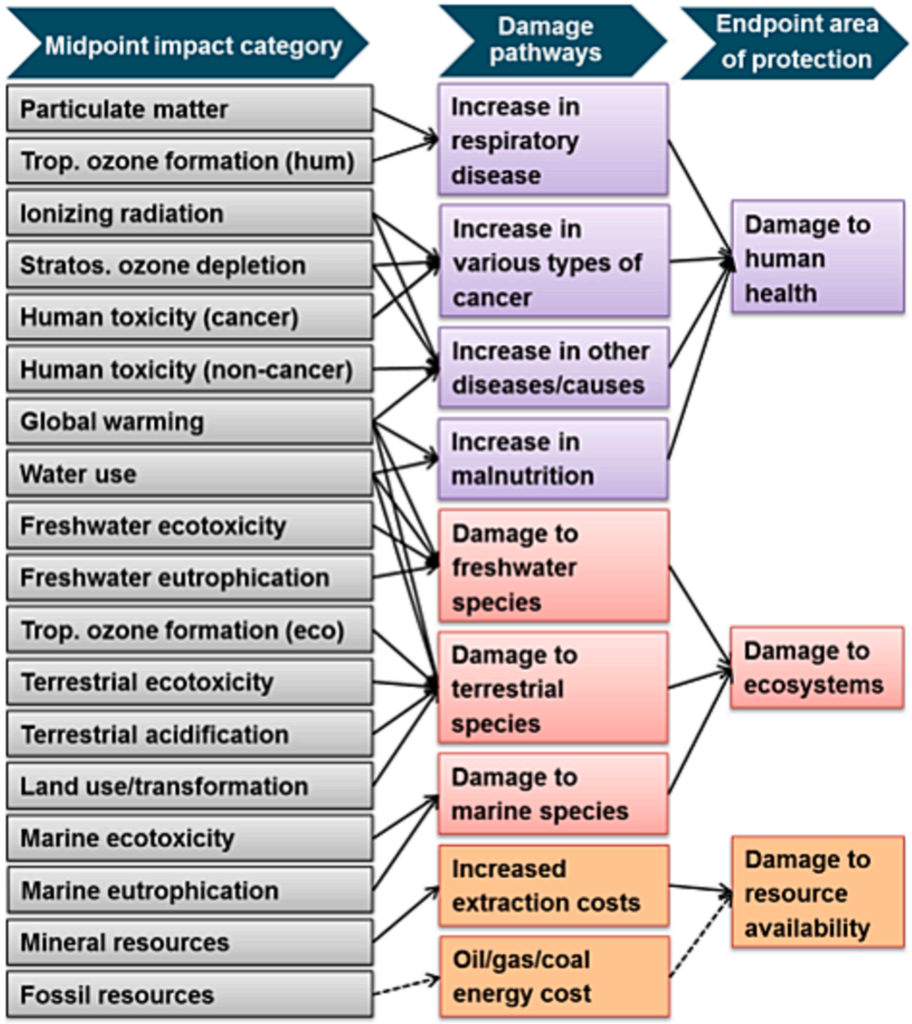


Fig. 7. Overview of the midpoint impact categories included in ReCiPe 2016 and their relation to the areas of protection (endpoint categories) adapted from [66]. The dotted line means there is no constant mid-to-endpoint factor for fossil resources [39].

As shown in Figs. 9 and 10, the major contributor for the environmental impact of both ETICS solutions, in all categories, is the maintenance stage, which includes jet cleaning and repainting operations every 10 years, until the end of the life cycle (40 years). By considering the amount of paint necessary for the primer and, especially, for the finish coat, it can only be concluded that the largest contribution to the environmental impact of these systems is attributed to the acrylic paint (see Table 2 from Appendix A. Supplementary data). That means that the environmental impact of the ETICS solutions is not so affected by the thermal insulation material but by the paint used as a finish. It should also be noted, in Fig. 8, the higher environmental impact of ETICS-ICB in the ozone layer depletion category, compared to ETICS-EPS. This comes as a surprise because the ICB is commercialized as being a sustainable product since is produced using a renewable natural resource (cork) through a more ecological industrial process. The reason for this can be justified by the difference between the density assumed for each insulation material. For the production of these materials, the unit processes used from the Ecoinvent database are related to the production of EPS boards with a density of 30 kg/m^3, and ICB boards with a density of 100 kg/m^3 (see Table 2 from Appendix A. Supplementary data). The density is considered in the calculation of the output mass quantity required for each life cycle stage, according to the functional unit adopted (see 3.2 "Functional unit" subsection). In addition to the mass quantity of ICB being almost four times greater than that of EPS, the transportation amount, measured in t.km (ton-kilometers), is also greater (see Table 2 from Appendix A. Supplementary data), which translates in a larger environmental impact, not only for the production and EoL, but for the transportation stage of the ICB as well.

By comparing the results for the ventilated facade solutions shown in Fig. 8, the VENT-TMW retrofit solution presents a higher contribution in every environmental impact category, except for the abiotic depletion – elements category. The same type of wood was considered for both timber claddings (pine wood), with similar densities adopted, 420 kg/m^3 for the thermally modified wood and 440 kg/m^3 for the untreated wood. Considering that the timber cladding adopted for the VENT-UPW retrofit solution also has a paint finish, it was not expected that the thermal treatment applied to the wood in the case of VENT-TMW solution would be the main responsible for such results. As shown in Figs. 11 and 12, although the thermally modified wood (VENT-TMW) requires less maintenance than an opaque painted untreated wood (VENT-UPW), and the heat treatment process does not use any chemicals (only steam) [48], it does require a higher consumption of energy, especially from fossil fuels (see Table 6 from Appendix A. Supplementary data). Furthermore, it requires a high amount of raw material (10,920 kg) according to the defined functional unit. For the transportation, the amount considered for the thermally treated wood (4,049 t.km) is almost five times higher than the one considered for the painted wood (0,874 t.km), which also contributes to a higher environmental impact. In the case of VENT-UPW, the contribution of the maintenance stage is more pronounced not only due to the application of the wood

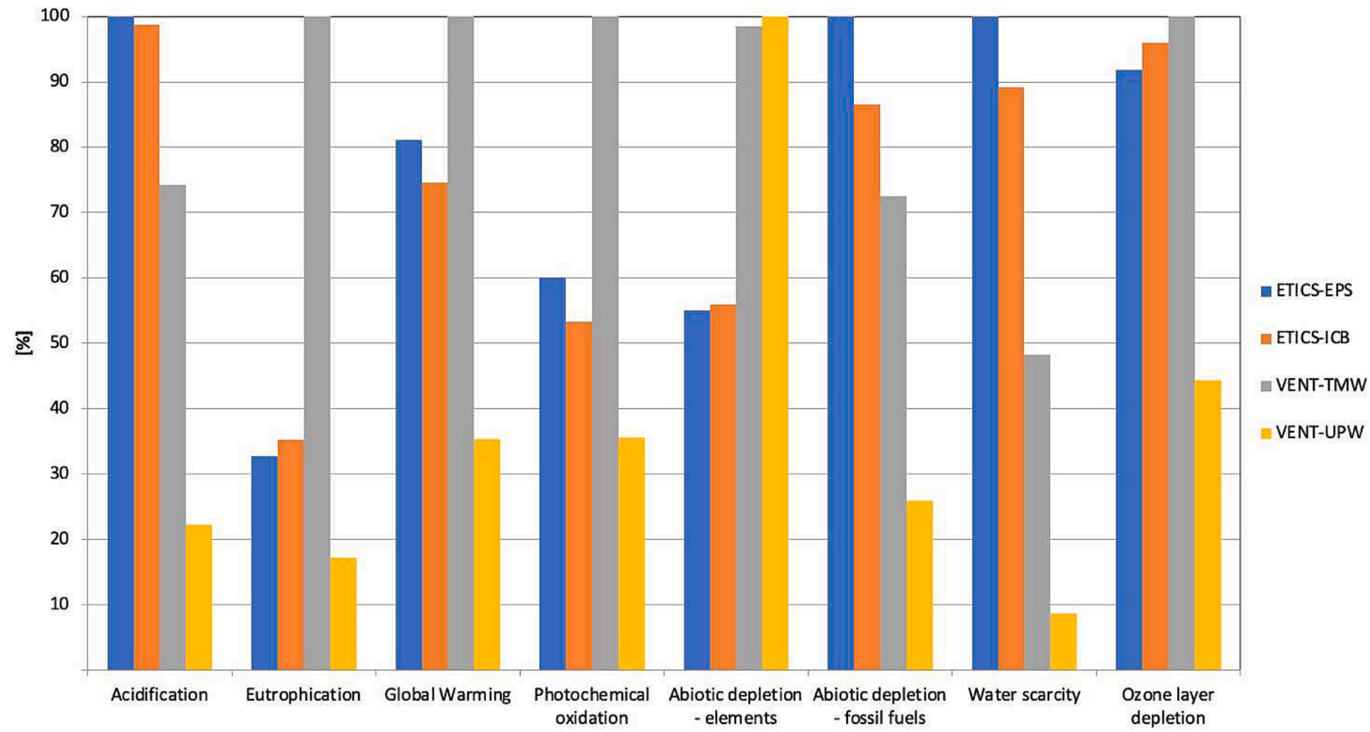


Fig. 8. Comparative LCA results of the EPD (2018) method (Characterization).

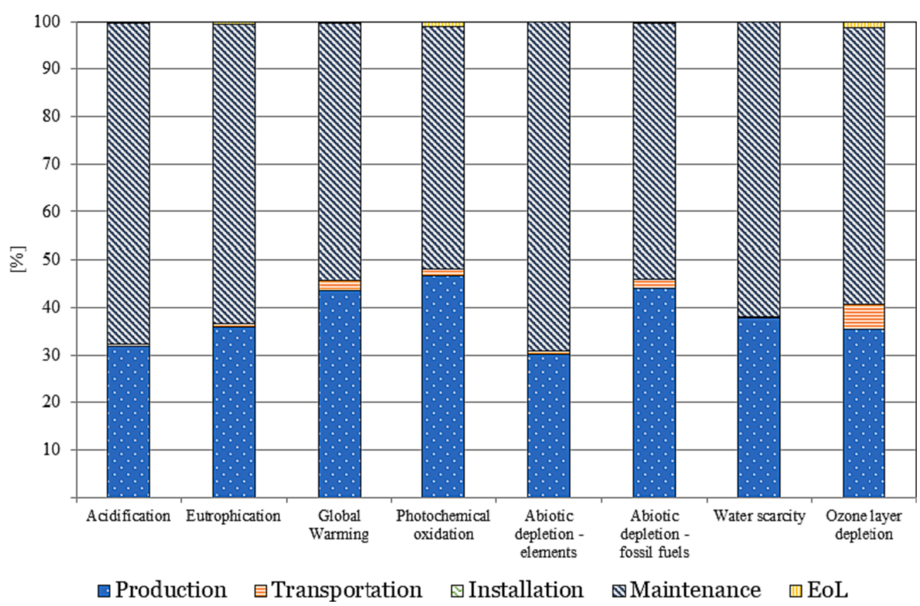


Fig. 9. EPD (2018) method results for the contribution of the different life cycle stages to the environmental impact of ETICS-EPS retrofit solution (Characterization).

preservative product, but also the paint.

Overall, the retrofit solution with the highest environmental impact is VENT-TMW, with the largest contribution in four categories, whereas VENT-UPW shows the lowest contribution in all categories, except for that concerning mineral resources consumption (abiotic decrease - elements).

The characterization results of the EPD (2018) method are also presented in table format in Appendix A. Supplementary data section.

5.2. ReCiPe 2016 Endpoint (H) method

For this study, the impact assessment using the ReCiPe 2016 Endpoint (H) method includes the characterization and normalization phases. The results for the characterization are shown in Fig. 13. Given the context of this study and the lower relevance of some categories, only fifteen (15) of a total of twenty-two (22) impact categories are shown. It should also be noted that for the characterization phase, this method allows for a more detailed analysis by discriminating the impact of certain categories, e.g., global warming, in terms of areas of protection (see 3.6 “Life cycle impact assessment” subsection).

By comparing ETICS retrofit solutions, it is possible to see in Fig. 13 that ETICS-EPS has a higher environmental impact in a larger number of categories (eight) than ETICS-ICB. However, this greater contribution only translates into one more category compared to ETICS-ICB (seven

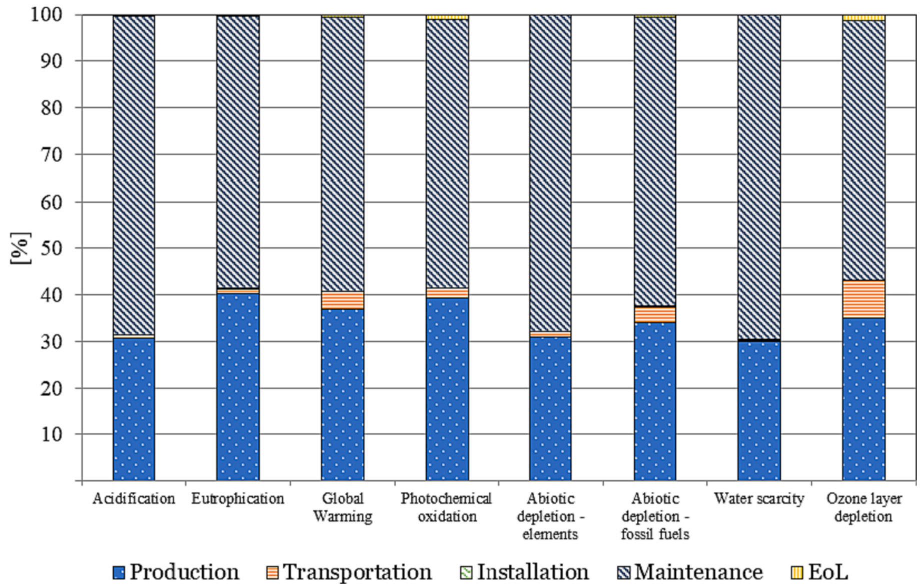


Fig. 10. EPD (2018) method results for the contribution of the different life cycle stages to the environmental impact of ETICS-ICB retrofit solution (Characterization).

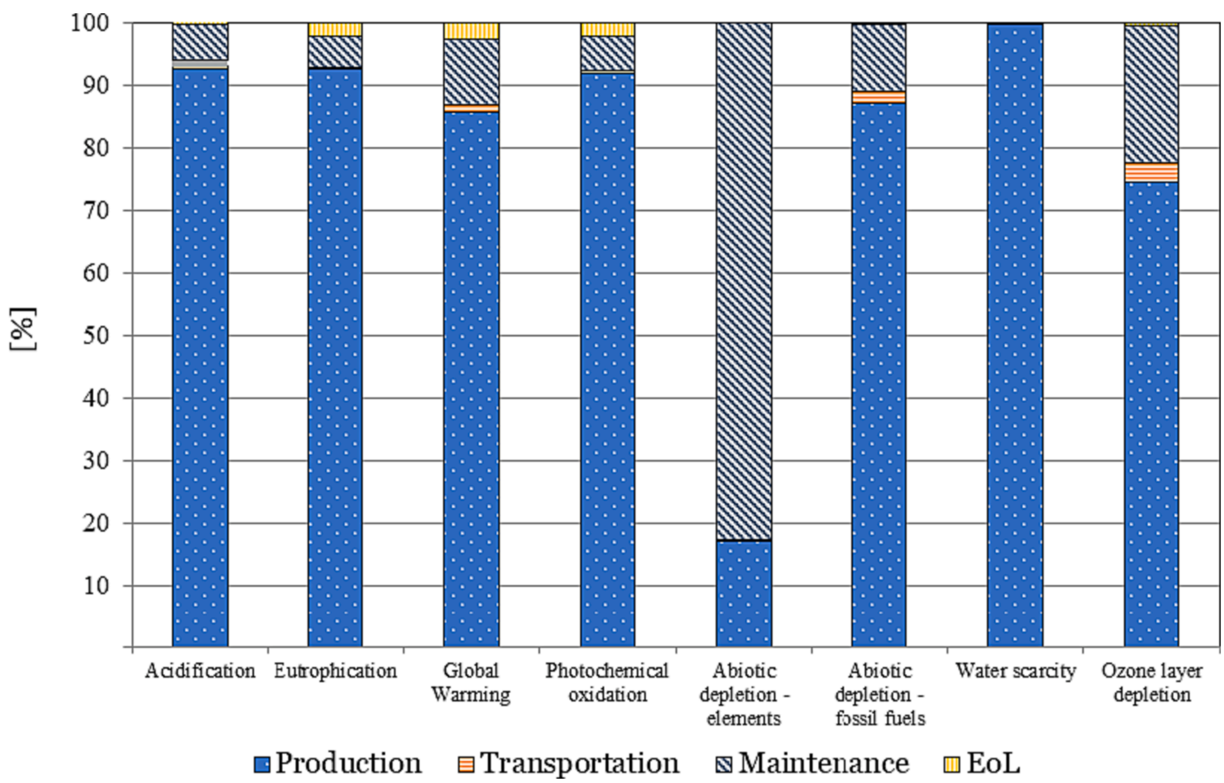


Fig. 11. EPD (2018) method results for the contribution of the different life cycle stages to the environmental impact of VENT-TMW retrofit solution (Characterization). The installation stage is not included because no related inputs are considered for this solution.

categories). Also, their contribution for certain categories is very similar, e.g., ETICS-ICB is responsible for the highest environmental impact for the mineral resource scarcity category (100 %), whereas ETCS-EPS comes close with 99,82 % of contribution. This only reinforces the interpretation concerning the characterization phase results of the EPD method (2018), i.e., the environmental impact of the ETICS solutions is mainly associated with the paint adopted as finish and its maintenance. For this study, the choice of the insulation material was not a determining factor for the results.

When comparing the ventilated retrofit solutions, again, VENT-TMW is the solution with the largest contribution in every category, except for the mineral resource scarcity category. The same remark can be made when comparing all solutions, i.e., VENT-TMW retrofit solution has the highest environmental impact, whereas VENT-UPW is the solution with the lowest impact.

The characterization results of the ReCiPe 2016 Endpoint (H) method are also presented in table format in Appendix A. Supplementary data section (see Table 12). Depending on the type of damage, the

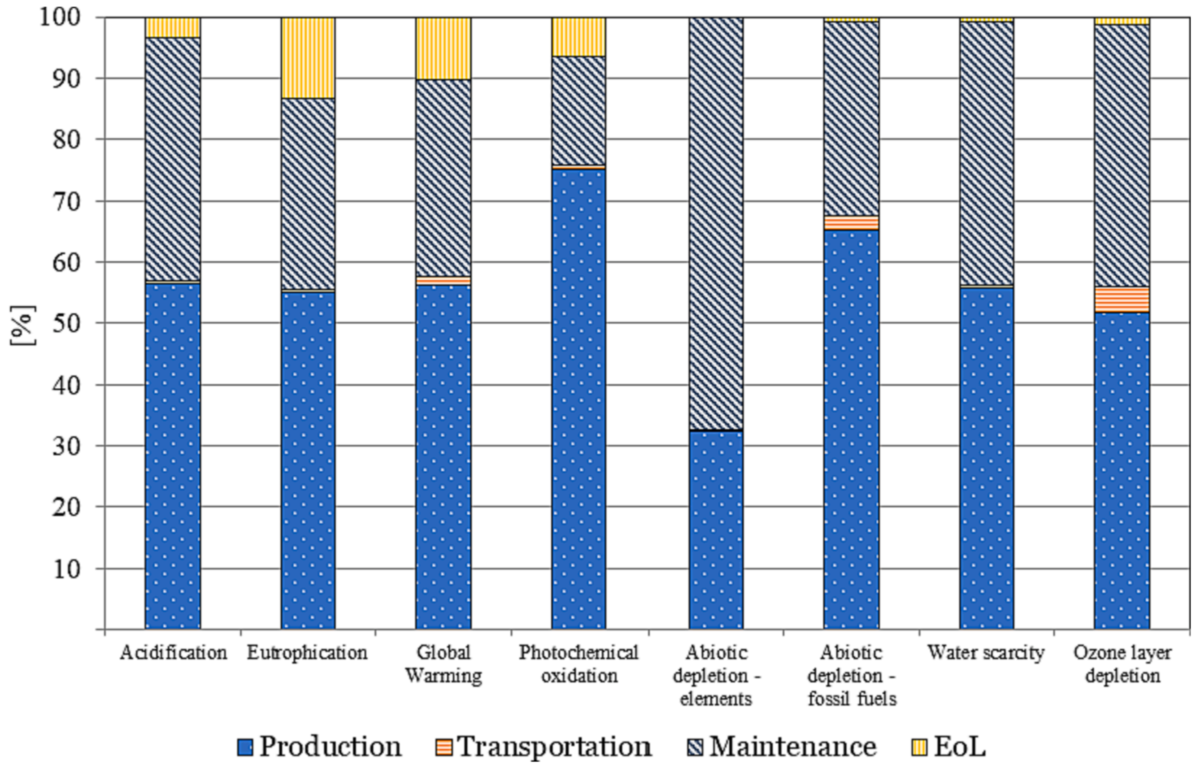


Fig. 12. EPD (2018) method results for the contribution of the different life cycle stages to the environmental impact of VENT-UPW retrofit solution (Characterization). The installation stage is not included because no related inputs are considered for this solution.

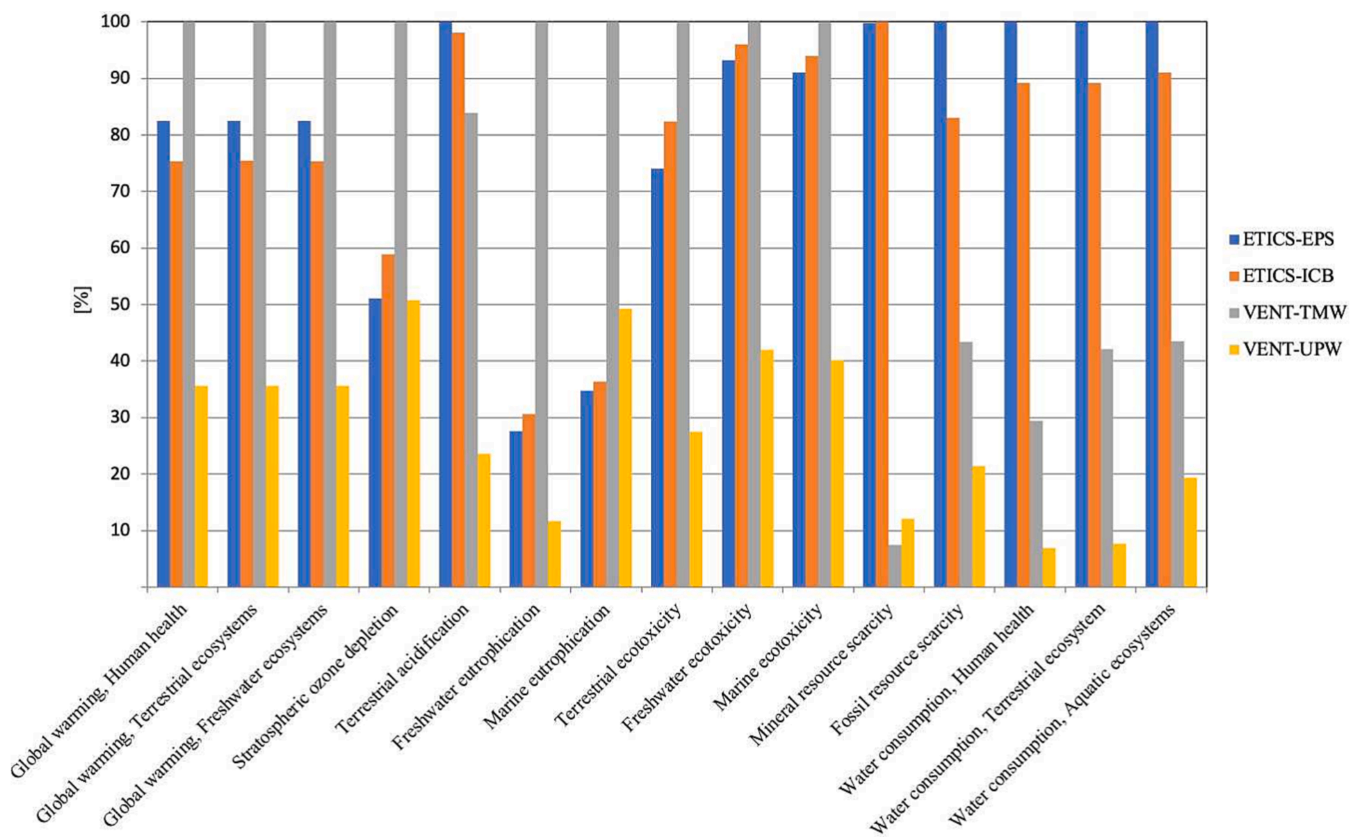


Fig. 13. Comparative LCA results of the ReCiPe 2016 Endpoint (H) method (Characterization).

midpoint category units are related to the three areas of protection: human health, ecosystems and resources. In the human health category, DALYs (disability adjusted life years) are used as a unit to indicate the number of years a person loses or is disabled due to a disease or accident. For the ecosystems category, the unit is species.year, which measures the local species loss over time. In the resource scarcity category, the unit is USD2013 (US dollar for the reference year), which represents the additional costs associated with future mineral and fossil resource extraction [38].

For the normalization step covered by the ReCiPe method, at the endpoint level, all the midpoint categories are grouped in the three areas of protection (see 3.6 "Life cycle impact assessment" subsection). Fig. 14 shows the results (dimensionless) of the contribution of the different systems for each endpoint category.

The Fig. 14 makes clear that ETICS retrofit solutions exhibit similar results, as also demonstrated above. However, ETICS-EPS solution shows a higher impact in the categories human health and resources, in comparison with ETICS-ICB. The reason for that is related to the production stage of EPS thermal insulation where several chemical processes are required to obtain the polystyrene as raw material, a polymer made from styrene monomer mostly through suspension polymerization [89]. On the other hand, ETICS-ICB shows a larger contribution in the ecosystems category, which was expected considering the contribution of ICB to the related midpoint categories in the characterization analysis (freshwater ecotoxicity, marine eutrophication, marine ecotoxicity, terrestrial ecotoxicity, and freshwater eutrophication).

With respect of the ventilated retrofit facade solutions, again, VENT-TMW exhibits a larger contribution for the three categories. However, it was not expected that the thermally wood modified-based retrofit solution would be responsible for such a significant environmental impact in the human health category, which encompasses the characterization categories related to, e.g., global warming and stratospheric ozone depletion. Although the thermal treatment does not require the use of chemicals, as it was mentioned before, it is a demanding process in terms of energy consumption that, combined with the amount of wood to be used as raw material, explains the major contribution to the referred category.

As for the comparison of all four retrofit solutions, VENT-TMW shows the highest environmental impact in the human health and ecosystems categories, especially in the first one, while VENT-UPW has the lowest environmental impact in the three categories. It is also worth mentioning that ventilated retrofit solutions, by incorporating timber claddings, contribute less to the resources scarcity category compared to ETICS-based retrofit solutions, since wood is a renewable natural resource.

Overall, the largest contribution of every system is to the human health category, in comparison with the results for the other categories, which is not clear from the previous analysis. In short, the environmental impact of these solutions can lead, above all, to consequences for human health.

The normalization results related to the ReCiPe 2016 Endpoint (H) method are also presented in table format in Appendix A. Supplementary data section (see Table 13). The environmental impact for each category is quantified by points.

In addition to EPD and ReCiPe methodologies, the global warming potential (in kg CO2 eq.) and cumulative energy requirement for all four systems were also calculated using Intergovernmental Panel on Climate Change (IPCC) 2007 20a and Cumulative Energy Demand (CED) V 1.11 methodologies, respectively in the SimaPro software (refer to Fig. 15). A similar trend in results was observed in these two methodologies. The VENT-TMW solution was seen to be the most carbon and energy intensive option while the VENT-UPW solution was observed to be the most carbon and energy efficient choice.

5.3. Discussion

The results obtained in this study could help decision-makers in finding out which stages of the retrofit solution's life cycle have the most

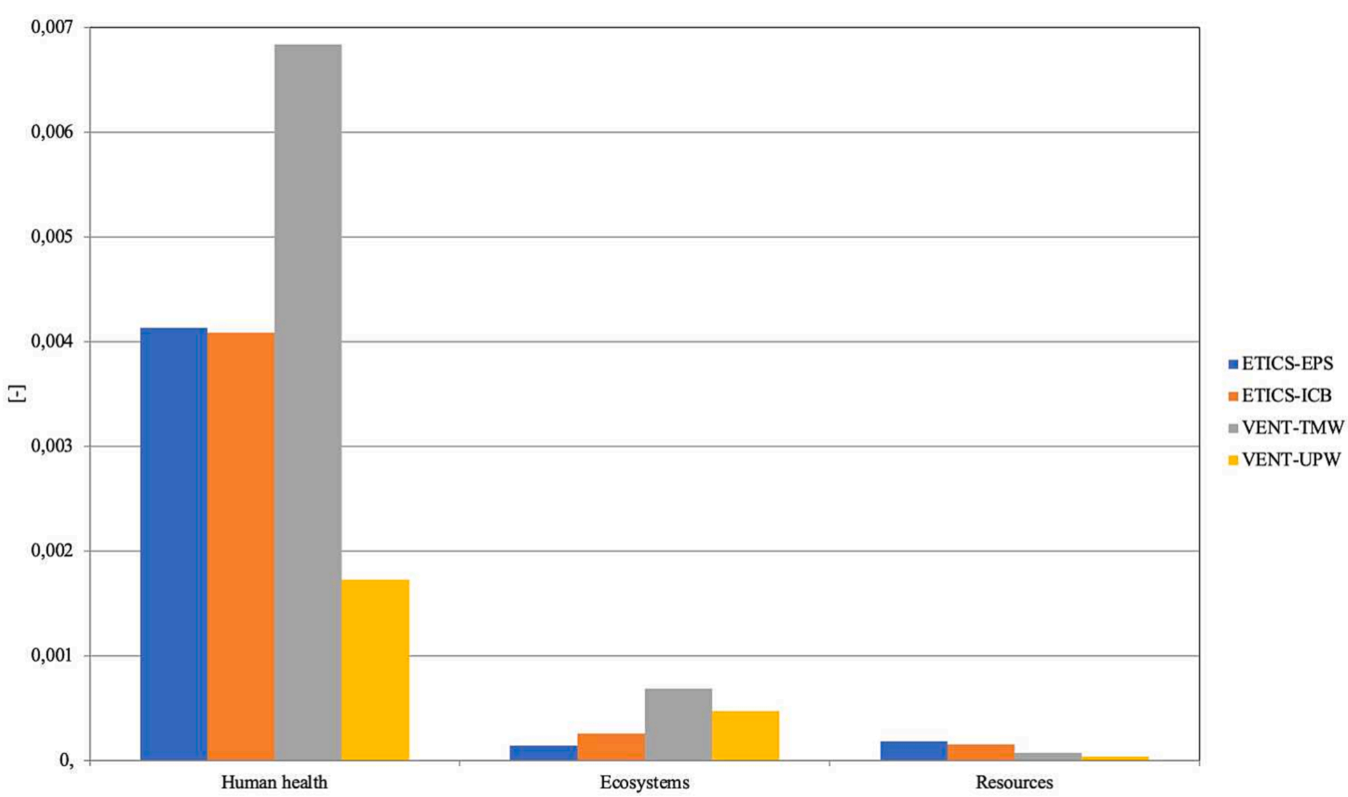


Fig. 14. Comparative LCA results of the ReCiPe 2016 Endpoint (H) method (Normalization).

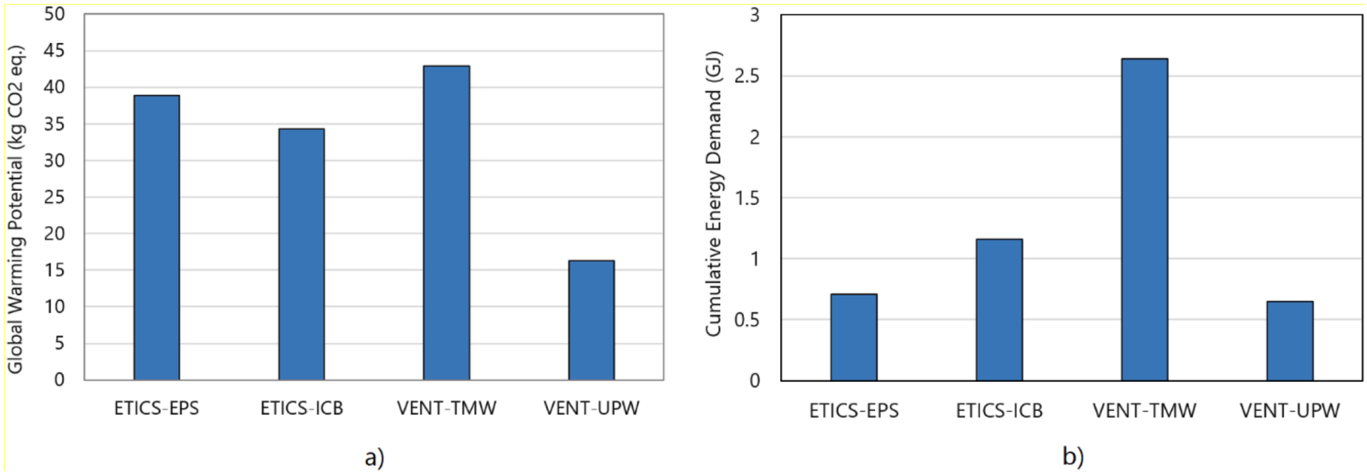


Fig. 15. Comparative LCA result based on a) IPCC method b) CED method.

substantial environmental impact. As previously shown, material density and transportation have a significant role in the environmental impact of distinct solutions for building facade retrofitting. When deciding which materials to use for their projects, decision-makers should take into account these factors. Materials with a lower density and more environmentally friendly transportation options, for example, can contribute to reducing the impact on the environment.

The results have also shown that companies investing in research and development can reduce the environmental impact of their products, such as switching to paints that have lower impact on the environment or employing low-energy production methods for insulation materials. Using these results, decision-makers can align their products with customer preferences and obtain advantages over their competitors. Additionally, decision-makers can also use these results for ensuring that environmental standards and regulations are met [74].

For example, throughout the Western Mediterranean, the cork oak tree thrives [80]. Europe accounts for 80 % of global cork production [57] and Portugal accounts for approximately 50 % of the world's cork supply [54]. As such, cork is abundant in Portugal, and can be used as a building material [84]. It has many useful properties for a Mediterranean climate, such as being possible to be considered a hydrophilic material from a molecular perspective, while at the macroscopic level, it can be considered a hydrophobic material [11], as well as being thermally insulating and impermeable [84]. Therefore, since these four solutions are the most likely to occur in deep renovation retrofitting, knowing the environmental impacts of ETICS retrofit solutions, especially how ETICS-ICB fares in comparison with other solutions. This can help decision makers to decide the most suitable option, from an environmental perspective, not just economical. Even though in this case ETICS-ICB was not the most environmentally friendly option, decision makers can also take into account the social dimension of their choice, such as the number of jobs created, working hours or health and safety [82] or through the group of social indicators obtained through Social Life Cycle Assessment, such as the satisfaction of basic needs and quality of life, social coherence and social justice [59].

As for limitations, some simplifications were adopted in the study due to the restrictions imposed by the scope of this LCA and a lack of research data. The simplifications implemented are the exclusion of some system components (wall structure, fixing devices and accessories) and recycling as an end-of-life treatment.

6. Conclusions

A comparative life cycle assessment of ETICS and ventilated facade systems incorporating natural-based solutions (Expanded Insulation Corkboard - and wood), in addition of the so-called "traditional" Expanded Polystyrene, was performed in this paper in order to establish which solution is better from an environmental point of view. Furthermore, this study analyses the life cycle stages and materials that contribute the most for the overall environmental impact of each solution. The results show that both ETICS solutions, ICB-based and EPS-based have similar results for both impact assessment methods in the characterization phase, meaning that the choice of the thermal insulation material does not significantly affect the environmental impact of each solution, but rather the paint used as finish coat. However, the EPS-based solution (ETICS-EPS) shows a higher environmental impact compared to ICB-based solution (ETICS-ICB), due to its contribution to a greater number of categories in both methods. The life cycle stage with the largest contribution for the environmental impact of both ETICS solutions, in all categories, is maintenance, which includes jet cleaning and repainting operations. The amount of acrylic paint necessary for the primer and, especially, for the finish coat, is the major contributor to the environmental impact of these systems.

For ventilated-based retrofit solutions featuring thermally modified timber and painted timber as cladding, the difference in the results is quite significant. The solution with the thermally modified timber (VENT-TMW) shows a much higher environmental impact than the solution with painted timber (VENT-UPW), in almost every category, for both methods in the characterization phase. The reason for a poorer environmental performance is related to the thermal treatment applied to the wood for external cladding, which requires a higher consumption of energy, especially from fossil fuel. Although painted timber solution (VENT-UPW) has a lower environmental impact, the maintenance stage has a larger contribution not only due to the application of the wood preservative product, but also the paint.

Of all studied solutions, the thermally modified timber shows the highest environmental impact and the solution with painted timber shows a higher environmental impact in the characterization phase of both systems. From the analysis carried out for the ReCiPe 2016 Endpoint (H) normalization step, this study also concludes that the solution with the thermally modified timber compares negatively with the others due the largest contribution to the human health category.

This type of analysis by environmental damage categories can be useful for decision makers since it provides an overview of the environmental impact associated with buildings. As such, decision-makers could benefit from a thorough cost-benefit analysis that considers not only the immediate financial costs but also the long-term environmental costs associated with their retrofit solutions.

This study shows that some apparently eco-friendly materials increase the embodied energy in buildings because of their energy-intensive manufacturing. Therefore, as for future studies, a natural step would be studying the implementation of industrial processes with a higher percentage of energy consumption from renewable resources in the manufacturing of building products.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2023.113842.

References

[1] A. Andaloro, E. Gasparri, S. Avesani, M. Aitchison. *Market survey of timber prefabricated envelopes for new and existing buildings*, 2019.
[2] M.K. Ansah, X. Chen, H. Yang, L. Lu, P.T.I. Lam, An integrated life cycle assessment of different façade systems for a typical residential building in Ghana, Sustain. Cities Soc. 53 (2020), 101974, https://doi.org/10.1016/j.scs.2019.101974.
[3] V. Apostolopoulos, P. Giourka, G. Martinopoulos, K. Angelakoglou, K. Kourtzanidis, N. Nikolopoulos, Smart readiness indicator evaluation and cost estimation of smart retrofitting scenarios—A comparative case-study in European residential buildings, Sustain. Cities Soc. 82 (2022), 103921, https://doi.org/10.1016/j.scs.2022.103921.
[4] N. Ata-Ali, V. Penadés-Plà, D. Martínez-Muñoz, V. Yepes, Recycled versus non-recycled insulation alternatives: LCA analysis for different climatic conditions in Spain, Resour. Conserv. Recycl. 175 (2021), 105838, https://doi.org/10.1016/j.resconrec.2021.105838.
[5] J. Ayoub, L. Aelenei, D. Aelenei, A. Scognamiglio, F. Garde, Solution Sets for Net Zero Energy Buildings: Feedback from 30 Buildings Worldwide, 1st ed., Ernst & Sohn, 2017.
[6] H. AzariJafari, G. Guest, R. Kirchain, J. Gregory, B. Amor, Towards comparable environmental product declarations of construction materials: Insights from a probabilistic comparative LCA approach, Build. Environ. 190 (2021), 107542, https://doi.org/10.1016/j.buildenv.2020.107542.
[7] H. Bikas, P. Stavropoulos, G. Chryssolouris, Additive manufacturing methods and modelling approaches: a critical review, Int. J. Adv. Manuf. Technol. 83 (1) (2016) 389–405, https://doi.org/10.1007/s00170-015-7576-2.
[8] K. Biswas, S.S. Shrestha, M.S. Bhandari, A.O. Desjarlais, Insulation materials for commercial buildings in North America: An assessment of lifetime energy and environmental impacts, Energ. Buildings 112 (2016) 256–269, https://doi.org/10.1016/j.enbuild.2015.12.013.
[9] S. Brito-Coimbra, D. Aelenei, M. Gloria Gomes, A. Moret Rodrigues, Building façade retrofit with solar passive technologies: a literature review, *Energies* 14 (6) (2021) Article 6, https://doi.org/10.3390/en14061774.
[10] D. Búryová, P. Sedlák, Life cycle assessment of coated and thermally modified wood façades, Coatings 11 (12) (2021) Article 12, https://doi.org/10.3390/coatings11121487.
[11] J. Chanut, Y. Wang, I. Dal Cin, E. Ferret, R.D. Gougeon, J.-P. Bellat, T. Karbowiak, Surface properties of cork: Is cork a hydrophobic material? J. Colloid Interface Sci. 608 (2022) 416–423, https://doi.org/10.1016/j.jcis.2021.09.140.
[12] A. Charpentier Poncelet, A. Beylot, P. Loubet, B. Laratte, S. Muller, J. Villeneuve, G. Sonnemann, Linkage of impact pathways to cultural perspectives to account for multiple aspects of mineral resource use in life cycle assessment, Resour. Conserv. Recycl. 176 (2022), 105912, https://doi.org/10.1016/j.resconrec.2021.105912.
[14] DAPHabitat, *DAPHabitat, Product Category Rules: Thermal Insulation- Version 1.3/ 2022*, Civil Engineering Department – University of Aveiro, 2022.
[15] A. de Gracia, L. Navarro, A. Castell, D. Boer, L.F. Cabeza, Life cycle assessment of a ventilated facade with PCM in its air chamber, Sol. Energy 104 (2014) 115–123, https://doi.org/10.1016/j.solener.2013.07.023.
[16] DH 918. (2012). *DH 918—VIPLÁS 50, VIPLÁS 100, VIPLÁS ar 95, VIPLÁS 167 and VIPLÁS 275 Redes para Reforço De Revestimentos de Paredes*. LNEC.
[17] DIERA. *DIERA – Coating Factory, Adhesives and Paints, Ltd, Technical Datasheet: DIERA RV Plascryl – Thick Plastic Coating*. DIERA – Coating Factory, Adhesives and Paints, 2022.
[18] C.A.P. Dos Santos, R. Rodrigues. Thermal Transmittance of Building Envelope Opaque Elements. Construction Solutions for Old Buildings. Construction Solutions Adopted in the Autonomous Regions of Portugal—ITE 54 (6th ed.), 2012. LNEC.
[19] L. Ducoulombier, Z. Lafhaj, Comparative study of hygrothermal properties of five thermal insulation materials, Case Stud. Thermal Eng. 10 (2017) 628–640, https://doi.org/10.1016/j.csite.2017.11.005.
[20] V. Durão, J.D. Silvestre, R. Mateus, J. de Brito, Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes, Resour. Conserv. Recycl. 156 (2020), 104703, https://doi.org/10.1016/j.resconrec.2020.104703.
[22] EN 15978:2011. (2011). EN 15978:2011—Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method. CEN.
[23] EOTA. (2008). *European Organisation for Technical Approvals—ETAG 08/ 0172—WKRET-MET-LTXΦ10 and WKRET-MET-LMXΦ10—Nailed-in plastic anchors for fixing of external thermal insulation composite systems with rendering in concrete and masonry*.
[24] EOTA. (2012). *ETAG 034—Guideline for European Technical Approval of Kits for External Wall Claddings—Part I: Ventilated Cladding Kits Comprising Cladding Components and Associated Fixings*. European Organisation for Technical Approvals (EOTA).
[25] EPD. (2022). *Environmental performance indicators*. EPD International AB.
[26] ETA 14/0363. (2014). *ETAssessment 14/0363*. EOTA. https://www.eota.eu/etassessments/1544.
[27] ETAG 004, Guideline for European Technical Approval of External Thermal Insulation Composite Systems (ETICS) with Rendering, EOTA, 2013.
[28] European Commission. Directorate General for Climate Action. (2019). *Going climate-neutral by 2050: A strategic long term vision for a prosperous, modern, competitive and climate neutral EU economy*. Publications Office. https://data.europa.eu/doi/10.2834/02074.
[29] European Commission. Joint Research Centre. (2018). *Competitive landscape of the EU's insulation materials industry for energy-efficient buildings: Revised edition*. Publications Office. https://data.europa.eu/doi/10.2760/750646.
[30] Eurostat. (2010). *Eurostat—European Commission, Guidance on classification of waste according to EWC-Stat categories: Supplement to the Manual for the Implementation of the Regulation (EC) No 2150/2002*. Eurostat - European Commission.
[31] J. Ferreira, B. Esteves, L. Nunes, I. Domingos, Life Cycle Assessment as a tool to promote sustainable Thermowood boards: A Portuguese case study, Int. Wood Products J. 7 (3) (2016) 124–129, https://doi.org/10.1080/20426445.2016.1160592.
[32] Finnish ThermoWood Association, Executive Summary –Thermowood®: Life Cycle Assessment (LCA) of Finnish Thermally Modified Wood Cladding, Publishing House Koivuniemi, Finnish ThermoWood Association, 2008.
[33] S. García-Pérez, J. Sierra-Pérez, J. Boschmonart-Rives, Environmental assessment at the urban level combining LCA-GIS methodologies: A case study of energy retrofits in the Barcelona metropolitan area, Build. Environ. 134 (2018) 191–204, https://doi.org/10.1016/j.buildenv.2018.01.041.
[34] R. Giordano, F. Gallina, B. Quaglio, Analysis and assessment of the building life cycle. Indicators and tools for the early design stage, Sustainability 13 (11) (2021) Article 11, https://doi.org/10.3390/su13116467.
[35] C.A.S. Hill. *Wood Modification: Chemical, Thermal and Other Processes* (1st ed.). Wiley, 2006. 10.1002/0470021748.
[36] C. Hill, A. Norton, J. Dibdiakova, A comparison of the environmental impacts of different categories of insulation materials, Energ. Buildings 162 (2018) 12–20, https://doi.org/10.1016/j.enbuild.2017.12.009.
[37] L. Huang, G. Krigsvoll, F. Johansen, Y. Liu, X. Zhang, Carbon emission of global construction sector, Renew. Sustain. Energy Rev. 81 (2018) 1906–1916, https://doi.org/10.1016/j.rser.2017.06.001.
[38] M.A.J. Huijbregts, Z.J.N. Steinmann, P.M.F. Elshout, G. Stam, F. Verones, M.D. M. Vieira, A. Hollander, M. Zijp, R. van Zelm, ReCiPe 2016 v1.1: A harmonized life cycle impact assessment method at midpoint and endpoint level—Report I: Characterization, National Institute for Public Health and the Environment, National Institute for Public Health and the Environment, 2016.
[39] M.A.J. Huijbregts, Z.J.N. Steinmann, P.M.F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander, R. van Zelm, ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level, Int. J. Life Cycle Assess. 22 (2) (2017) 138–147, https://doi.org/10.1007/s11367-016-1246-y.
[40] S. Ilomets, D. Heim, I. Chodak, D. Czarny, T. Kalamees, A method to develop energy activated ETICS, E3S Web Conf. 172 (2020) 21006, https://doi.org/10.1051/e3sconf/202017221006.
[41] ISO. (2006). *ISO 14044:2006-Environmental management—Life cycle assessment—Requirements and guidelines*.
[44] I. Jahan, G. Zhang, M. Bhuiyan, S. Navaratnam, Circular economy of construction and demolition wood waste—a theoretical framework approach, Sustainability 14 (17) (2022) Article 17, https://doi.org/10.3390/su141710478.
[45] K.-A. Kertsmik, K. Kuusk, K. Lylykangas, T. Kalamees, Evaluation of renovation strategies: Cost-optimal, CO_2e optimal, or total energy optimal? Energ. Buildings 287 (2023), 112995 https://doi.org/10.1016/j.enbuild.2023.112995.
[46] K.-H. Kim, A comparative life cycle assessment of a transparent composite façade system and a glass curtain wall system, Energ. Build. 43 (12) (2011) 3436–3445, https://doi.org/10.1016/j.enbuild.2011.09.006.
[47] M. Kołaczkowski, A. Byrdy, FEM analysis and experimental research into carrier brackets in ventilated facades, Periodica Polytechnica Civ. Eng. 64 (3) (2020) Article 3, https://doi.org/10.3311/PPci.13822.

[48] T. Lahtela, I.L. Oy, ThermoWood Handbook, International Thermowood Association, 2021.
[49] R. Landolfi, M. Nicolella, Durability assessment of ETICS: comparative evaluation of different insulating materials, Sustainability 14 (2) (2022) 980, https://doi.org/10.3390/su14020980.
[50] L.I. Librelotto, M. Kekez, H.M.G. Bártolo (2020). The environmental impact of an etics layer: a case of study with life cycle assessment (LCA) from environmental product declaration (EPD) IN PORTUGAL. *MIX Sustentável*, *6*(2), 139–148. 10.29183/2447-3073.MIX2020.v6.n2.139-148.
[51] C. Llatas, B. Soust-Verdaguer, A. Passer, Implementing Life Cycle Sustainability Assessment during design stages in Building Information Modelling: From systematic literature review to a methodological approach, Build. Environ. 182 (2020), 107164, https://doi.org/10.1016/j.buildenv.2020.107164.
[52] R.A. Lopes, P. Magalhães, J.P. Gouveia, D. Aelenei, C. Lima, J. Martins, A case study on the impact of nearly Zero-Energy Buildings on distribution transformer aging, Energy 157 (2018) 669–678, https://doi.org/10.1016/j.energy.2018.05.148.
[53] Y. Lou, Y. Ye, Y. Yang, W. Zuo, Long-term carbon emission reduction potential of building retrofits with dynamically changing electricity emission factors, Build. Environ. 210 (2022), 108683, https://doi.org/10.1016/j.buildenv.2021.108683.
[54] A. Lum. A Comparative Life Cycle Assessment of Cork versus Traditional Shoe Insole Material. *Independent Study Project (ISP) Collection*, 2023. https://digitalcollections.sit.edu/isp_collection/3588.
[55] X.J. Luo, Retrofitting existing office buildings towards life-cycle net-zero energy and carbon, Sustain. Cities Soc. 83 (2022), 103956, https://doi.org/10.1016/j.scs.2022.103956.
[56] N. Majdalani, D. Aelenei, R.A. Lopes, C.A.S. Silva, The potential of energy flexibility of space heating and cooling in Portugal, Util. Policy 66 (2020), 101086, https://doi.org/10.1016/j.jup.2020.101086.
[57] S. Malanho, R. Veiga, C.B. Farinha, Global performance of sustainable thermal insulating systems with cork for building facades, Buildings 11 (3) (2021) Article 3, https://doi.org/10.3390/buildings11030083.
[58] A. Martinez, M. Patterson, A. Carlson, D. Noble, Fundamentals in façade retrofit practice, Procedia Eng. 118 (2015) 934–941, https://doi.org/10.1016/j.proeng.2015.08.534.
[59] G. Mazzucco, M. Canepa, K. Perini, Application of Social-Life Cycle Assessment in Urban Settings: Social Impact Assessment of Green Roofs, Buildings 13 (7) (2023) 1659, https://doi.org/10.3390/buildings13071659.
[60] B. Michałowski, J. Michalak, Sustainability-oriented assessment of external thermal insulation composite systems: A case study from Poland, Cogent Eng. 8 (1) (2021) 1943152, https://doi.org/10.1080/23311916.2021.1943152.
[61] I.V. Muralikrishna, V. Manickam. Life Cycle Assessment. In *Environmental Management* (pp. 57–75). Elsevier, 2017. 10.1016/B978-0-12-811989-1.00005-1.
[63] P. Palma, J.P. Gouveia, R. Barbosa, How much will it cost? An energy renovation analysis for the Portuguese dwelling stock, Sustain. Cities Soc. 78 (2022), 103607, https://doi.org/10.1016/j.scs.2021.103607.
[64] F. Pardo-Bosch, C. Cervera, T. Ysa, Key aspects of building retrofitting: Strategizing sustainable cities, J. Environ. Manage. 248 (2019), 109247, https://doi.org/10.1016/j.jenvman.2019.07.018.
[65] Petrovski, A., Petrovska-Hristovska, L., Ivanovic-Sekularac, J., & Sekularac, N. (2020). Assessment of the sustainability of façade refurbishment. *Thermal Sci.*, *24*(2 Part A), 991–1006. 10.2298/TSCI190218307P.
[66] PRé Sustainability. (2020). *SimaPro database manual Methods library*. PRé Sustainability B.V.
[67] S. Pushkar, A. Yezioro, C. Hershcovich, Y.J. Grobman, Life-cycle assessment of sculptured tiles for building envelopes in mediterranean climate, Buildings 12 (2) (2022) Article 2, https://doi.org/10.3390/buildings12020165.
[68] H. Radhi, S. Sharples, Global warming implications of facade parameters: A life cycle assessment of residential buildings in Bahrain, Environ. Impact Assess. Rev. 38 (2013) 99–108, https://doi.org/10.1016/j.eiar.2012.06.009.
[69] M. Rahiminejad, D. Khovalyg, Review on ventilation rates in the ventilated air-spaces behind common wall assemblies with external cladding, Build. Environ. 190 (2021), 107538, https://doi.org/10.1016/j.buildenv.2020.107538.
[70] T. Santos, J. Almeida, J.D. Silvestre, P. Faria, Life cycle assessment of mortars: A review on technical potential and drawbacks, Constr. Build. Mater. 288 (2021), 123069, https://doi.org/10.1016/j.conbuildmat.2021.123069.
[71] E. Saretta, P. Caputo, F. Frontini, A review study about energy renovation of building facades with BIPV in urban environment, Sustain. Cities Soc. 44 (2019) 343–355, https://doi.org/10.1016/j.scs.2018.10.002.
[72] S. Sattler, D. Österreicher, Assessment of sustainable construction measures in building refurbishment—life cycle comparison of conventional and multi-active façade systems in a social housing complex, Sustainability 11 (16) (2019) Article 16, https://doi.org/10.3390/su11164487.
[73] K. Schabowicz, Ł. Zawiślak, P. Staniów, Efficiency of ventilated facades in terms of airflow in the air gap, Studia Geotech. Mech. 43 (3) (2021) 224–236, https://doi.org/10.2478/sgem-2021-0014.
[74] M. Scherz, E. Hoxha, D. Maierhofer, H. Kreiner, A. Passer, Strategies to improve building environmental and economic performance: An exploratory study on 37 residential building scenarios, Int. J. Life Cycle Assess. 28 (7) (2023) 828–842, https://doi.org/10.1007/s11367-022-02073-6.
[75] S. Schiavoni, F. D'Alessandro, F. Bianchi, F. Asdrubali, Insulation materials for the building sector: A review and comparative analysis, Renew. Sustain. Energy Rev. 62 (2016) 988–1011, https://doi.org/10.1016/j.rser.2016.05.045.
[76] R. Siebers, B. Hauke, M. Helmus, A. Meins-Becker, 21.16: Sustainability considerations for the construction phase of steel structures, Ce/papers 1 (2–3) (2017) 4630–4639, https://doi.org/10.1002/cepa.524.
[77] J. Sierra-Pérez, J. Boschmonart-Rives, X. Gabarrell, Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions, J. Clean. Prod. 113 (2016) 102–113, https://doi.org/10.1016/j.jclepro.2015.11.090.
[79] J.D. Silvestre, A.M.P. Castelo, J.J.B.C. Silva, J.M.C.L. de Brito, M.D. Pinheiro, Retrofitting a building's envelope: sustainability performance of ETICS with ICB or EPS, Appl. Sci. 9 (7) (2019) 1285, https://doi.org/10.3390/app9071285.
[80] I.H. Sørensen, M. Torralba, J. Muñoz-Rojas, L.S. Kristensen, T. Plieninger, Embedding plural values in value chains to enhance sustainability in the management of cork oak landscapes, Landsc. Ecol. (2023), https://doi.org/10.1007/s10980-023-01730-x.
[82] B. Soust-Verdaguer, J.A. Gutiérrez, C. Llatas, Development of a plug-in to support sustainability assessment in the decision-making of a building envelope refurbishment, Buildings 13 (6) (2023) Article 6, https://doi.org/10.3390/buildings13061472.
[83] X. Su, Z. Luo, Y. Li, C. Huang, Life cycle inventory comparison of different building insulation materials and uncertainty analysis, J. Clean. Prod. 112 (2016) 275–281, https://doi.org/10.1016/j.jclepro.2015.08.113.
[84] P. Talhinhas, J.C. Ferreira, V. Ferreira, A.L. Soares, D. Espírito-Santo, T.A. Paço, do., In the search for sustainable vertical green systems: an innovative low-cost indirect green façade structure using Portuguese native ivies and cork, Sustainability 15 (6) (2023) Article 6, https://doi.org/10.3390/su15065446.
[85] A.S. Tártaro, T.M. Mata, A.A. Martins, J.C.G. Esteves da Silva, Carbon footprint of the insulation cork board, J. Clean. Prod. 143 (2017) 925–932, https://doi.org/10.1016/j.jclepro.2016.12.028.
[86] H. Teixeira, M. Glória Gomes, A. Moret Rodrigues, D. Aelenei, Assessment of the visual, thermal and energy performance of static vs thermochromic double-glazing under different European climates, Build. Environ. 217 (2022), 109115, https://doi.org/10.1016/j.buildenv.2022.109115.
[87] T. Townsend, T. Tolaymat, H. Solo-Gabriele, B. Dubey, K. Stook, L. Wadanambi, Leaching of CCA-treated wood: Implications for waste disposal, J. Hazard. Mater. 114 (1) (2004) 75–91, https://doi.org/10.1016/j.jhazmat.2004.06.025.
[88] Q. Tushar, G. Zhang, M.A. Bhuiyan, S. Navaratnam, F. Giustozzi, L. Hou, Retrofit of building façade using precast sandwich panel: an integrated thermal and environmental assessment on BIM-based LCA, Buildings 12 (12) (2022) Article 12, https://doi.org/10.3390/buildings12122098.
[89] A.N. Uttaravalli, S. Dinda, B.R. Gidla, Scientific and engineering aspects of potential applications of post-consumer (waste) expanded polystyrene: A review, Process Saf. Environ. Prot. 137 (2020) 140–148, https://doi.org/10.1016/j.psep.2020.02.023.
[90] L. Van Gulck, L. Wastiels, M. Steeman, How to evaluate circularity through an LCA study based on the standards EN 15804 and EN 15978, Int. J. Life Cycle Assess. 27 (12) (2022) 1249–1266, https://doi.org/10.1007/s11367-022-02099-w.
[91] C. Vandervaeren, S.M. Fufa, J. Kallaos, Level(s) compared to European and Norwegian standards for life cycle assessment of buildings, IOP Conf. Series: Earth Environ. Sci. 1078 (1) (2022), 012056, https://doi.org/10.1088/1755-1315/1078/1/012056.
[92] S. Varela Luján, C. Viñas Arrebola, A. Rodríguez Sánchez, P. Aguilera Benito, M. González Cortina, Experimental comparative study of the thermal performance of the façade of a building refurbished using ETICS, and quantification of improvements, Sustain. Cities Soc. 51 (2019), 101713, https://doi.org/10.1016/j.scs.2019.101713.
[93] P. Villoria Sáez, M. Osmani, A diagnosis of construction and demolition waste generation and recovery practice in the European Union, J. Clean. Prod. 241 (2019), 118400, https://doi.org/10.1016/j.jclepro.2019.118400.
[94] P. Vitale, N. Arena, F. Di Gregorio, U. Arena, Life cycle assessment of the end-of-life phase of a residential building, Waste Manag. 60 (2017) 311–321, https://doi.org/10.1016/j.wasman.2016.10.002.
[95] C. Zhang, M. Hu, X. Yang, A. Amati, A. Tukker, Life cycle greenhouse gas emission and cost analysis of prefabricated concrete building façade elements, J. Ind. Ecol. 24 (5) (2020) 1016–1030, https://doi.org/10.1111/jiec.12991.