*sustainability*

MDPI

*Article*

# Eco-Efficiency of Concrete Sandwich Panels with Different Insulation Core Materials

**Bruna Moura [1], Tiago Ramos da Silva [1], Nelson Soares [2] and Helena Monteiro [1,*]**

[1] Low Carbon & Resource Efficiency, R&Di, Instituto de Soldadura e Qualidade, R. do Mirante 258, 4415-491 Grijó, Portugal; bcmoura@isq.pt (B.M.); tasilva@isq.pt (T.R.d.S.)
[2] University of Coimbra, ADAI, Department of Mechanical Engineering, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal; nelson.soares@dem.uc.pt
* Correspondence: himonteiro@isq.pt

**Abstract:** Given the current need to improve the thermal and energy performance of buildings, special attention has been given to the building envelope and materials. Concrete sandwich panels (CSPs) are versatile composite construction elements whose popularity is increasing given their properties, e.g., good thermal and acoustic insulation, durability, and fire resistance. Nevertheless, besides their properties, it is important to evaluate the sustainability of composite panels under development. This work aims to assess the eco-efficiency of six CSPs with distinct insulation materials: lightweight concrete (LWC), cork, glass wool, and expanded polystyrene (EPS). Coupling both life cycle assessment (LCA) and life cycle costing (LCC) analysis, this study derives eco-efficiency indicators to inform decisions regarding CSP environmental and economic performances. The results of the LCA and LCC showed that the high-performance concrete (HPC) layer was the main hotspot of the CSPs in all scenarios. Moreover, the best scenario changed when different environmental impact categories were considered. Thus, using multiple environmental indicators is recommended to avoid problem-shifting. Considering the final cost, the CSP with cork is the most expensive panel to produce, with the other five options having very similar manufacturing prices. On average, raw material inputs, labour, and material delivery account for 62.9%, 18.1%, and 17.1% of the total costs, respectively. Regarding the eco-efficiency results, the most eco-efficient scenario changed with the environmental indicator used. Cork seems to be the best option when considering the carbon footprint of the panels, whereas when considering other environmental indicators, the recycled EPS scenario has the best eco-efficiency and the CSP with cork the worst.

**Keywords:** construction material; sustainability; LCA; LCC; environmental impacts; economic performance

check for updates

Academic Editor: Antonio Caggiano

Received: 25 October 2024
Revised: 28 January 2025
Accepted: 14 February 2025
Published: 18 February 2025

**Citation:** Moura, B.; Ramos da Silva, T.; Soares, N.; Monteiro, H. Eco-Efficiency of Concrete Sandwich Panels with Different Insulation Core Materials. *Sustainability* **2025**, *17*, 1687. https://doi.org/10.3390/su17041687

**Copyright:** © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The building industry accounts for approximately 40% of worldwide final energy, of which 80% is used by heating and climatisation systems [1], releasing about 40% of anthropogenic $CO_2$ emissions in the European region [2]. Thermal energy losses through poorly insulated building envelopes worsen this issue, increasing the need for high-performance insulation materials to improve energy efficiency and, ultimately, to reduce energy consumption during the operational phase. The production of construction materials also incorporates significant primary energy that should be considered from a life cycle perspective. Therefore, the careful selection of walls with adequate thermal insulation properties

allows for control of both the incorporated energy and the associated environmental burdens of construction [1,3–5].

Given this, by assessing alternative insulation materials, components, and constructive solutions, life cycle assessment (LCA) can help identify sustainable design alternatives that balance embodied energy, operational energy efficiency, and overall environmental impact. Commonly, environmental impacts are understood as the direct implications of activities in both natural and built environments that may affect different parts of the ecosystem, such as land, water, air, animals, or people.

Concrete sandwich panels (CSPs) may be utilised as an option for exterior walls, consisting of two concrete layers enclosing an insulating core. Even though CSPs have been used in the construction industry for the last 60 years [6], they have been increasing in popularity in the last decades due to advantages such as fire retardancy, enhanced thermal and sound insulation, robustness, and suitability for prefabricated or modular construction [7]. Concrete and concrete-based materials are among the most-used construction materials worldwide, which means that lowering their environmental impacts will contribute to more sustainable development [8]. Moreover, as suggested by Wang et al. (2016) [9], the concrete industry can improve the sustainable management of resources in many economies because it can make use of a large amount of industrial and municipal waste as a substitute for raw materials. Thus, the assessment of the production cost, material flow, and environmental impact of concrete-based materials over their life cycle is vital to provide indicators that can be combined to evaluate the eco-efficiency of products with different performances. This will assist in defining the most adequate ones for a given construction application [10]. Given the diversity of insulation and concrete compositions that can be integrated into CSPs, further research is required to determine the most sustainable configurations that minimise embodied energy while maintaining structural performance.

Some LCA studies have analysed the environmental performance of different external walls, such as lightweight steel framing (LSF) walls [11], wooden, double and single brick masonry, and concrete block walls [12,13], but few studies have evaluated the environmental performance of CSPs. On the other hand, some works only focused on sandwich panels for floors [14,15] or roofs. However, these panels do not have the same function as CSPs for walls, and consequently, the results can only be carefully extrapolated to external walls. More recently, some authors have analysed some composite wall panels. Santos et al. (2021) [16] assessed the environmental impacts of 1 $m^2$ of cross-insulated timber (CIT) and cross-laminated timber (CLT) panels with different insulation materials, namely insulation cork boards (ICBs), extruded polystyrene (XPS), polyurethane foam (PUR), and rock wool. They concluded that for the CLT panels, the rock wool and the XPS sandwich panels were the alternatives with the best environmental performance on a *cradle-to-gate* boundary. Tighnavard et al. 2022 [17] evaluated the environmental and economic performance of different floor slab alternatives made by (i) lightweight steel, (ii) concrete, (iii) cofradal slab, and (iv) glued laminated timber. For 1 $m^2$ of floor with a lifetime of 50 years and a *cradle-to-grave* approach, the glued laminated timber floor had the best environmental performance in all the categories studied. Nonetheless, from the economic point of view, this scenario showed great construction costs. These costs could be reduced depending on the end-of-life (EoL) scenario considered, reducing the total costs of the glue-laminated timber floor. Sahmenko et al. (2021) [3] performed an LCA study to assess the global warming potential (GWP) of 1 $m^2$ of different walls with thermal transmittance (U-value) ranging from 0.17 to 0.20 $W/m^2 \cdot K$. The sandwich walls considered by the authors included a CSP and three hemp composite walls: (i) external foam concrete layers with foam polystyrene as the inner core; (ii) external average density hemp layers with an inner lightweight hemp layer; (iii) interior high-density hemp layer with lightweight

hemp inner core and average density hemp as exterior layer; and (iv) external high-density hemp layers and a lime-based hemp composite core. The authors concluded that the last alternative has the best environmental performance (having a carbon footprint of −9.5 kg of $CO_2$-eq/$m^2$), which was due to the carbon emissions captured during the hemp plant growing and the lime binder layer drying. On the other hand, the sandwich panel with concrete and polystyrene presented higher carbon emissions (82.4 kg of $CO_2$-eq/$m^2$). The authors concluded that the use of bio-based materials may result in lower environmental impacts despite the panels' low thermal inertia. Finally, Yılmaz et al. (2022) [1] evaluated the environmental burdens of 1 $m^2$ of aluminium (Al) sandwich panels with different thicknesses of rock wool (50, 60, and 80 mm), considering a *cradle-to-gate* approach. The authors concluded that the panel with the 50 mm thick insulation material had the best environmental performance (70 kg of $CO_2$-eq). Otherwise, the panel with the 80 mm thick rock wool presented the worst environmental performance in terms of GWP (75 kg of $CO_2$-eq). The aluminium sheets accounted for more than 70% of the impacts in all the scenarios, followed by the rock wool (9.5% to 14% in the panels with 50 mm and 80 mm thick rock wool, respectively). On the other hand, energy was responsible for less than 1% of the impacts in all the evaluated scenarios.

Recently, companies have been searching for some differentiation that gives them advantages when competing with other organisations within the same sector. This differentiation may be achieved by assessing not only the techno-economic feasibility but also through the evaluation of environmental aspects. Thus, the decision-making process is becoming dependent on evaluating different sustainability dimensions, which may also be booted by future policies and fiscal incentives. In general, sustainability is perceived as the balance of three dimensions—like environmental, economic, and social (e.g., equity)—integrated with each other to make resilient and healthy communities over generations.

The life cycle cost (LCC) and LCA methodologies are known to provide reliable information about both economic and environmental aspects of sustainability and may be used as the basis for the adoption of the most eco-efficient strategies [18]. The study of eco-efficiency has increased in the literature on sustainable development [19] since eco-efficiency indicators can condense and relate important information about the economic value of a product and/or service and its environmental pressure. In the buildings sector, eco-efficiency can be seen as a very practical tool to promote the sustainable use of energy and natural resources, reduce pollutant emission trends, and increase the value of products and/or services [20]. Indeed, eco-efficiency can help construction companies to achieve greater value with lower adverse environmental impacts. At the same time, it can be used for comparison purposes and to support engineers, architects, and building practitioners in decision-making tasks towards a more sustainable built environment. In a time of increasingly stringent building thermal efficiency standards, rising energy costs, and worldwide awareness of the need to reduce natural resources and energy consumption, there is an increasing need for more eco-efficient construction materials and techniques that can contribute to improving the thermal performance of the building's envelope. This will lead to reduced heating and cooling energy demand during the operational phase of buildings.

The eco-efficiency is known as a measure of sustainability in which the economic and the environmental performances of a product or a service are integrated. Previous works comparing the eco-efficiency of CSPs have been published. Overall, they focus on panels with different characteristics that do not consider concrete for the outer layers [14,21] or that compare CSPs with entirely different construction methods, like reinforced concrete frames or steel frames [22]. Although there is a study that estimates the eco-efficiency of CSPs built throughout an alternative production route, further research is needed to

fully evaluate the economic and environmental performance of CSPs with other insulation materials (e.g., cork and glass wool). Furthermore, LCA studies devoted to the assessment of the environmental burdens of CSPs are still scarce in the literature.

In this context, the main goal of this work is to assess the ecoefficiency of novel CSPs with similar thermal transmittance but different insulation materials, i.e., lightweight concrete (LWC), expanded cork panel (cork), glass wool, and expanded polystyrene (EPS)—100% virgin, 55% virgin, and 100% recycled. To do so, LCA and LCC methodologies were performed to assess the environmental impacts and the life cycle costs associated with each scenario. Then, using different environmental indicators, some ecoefficiency indicators were obtained and compared. Also, a sensitivity analysis was undertaken to assess the influence of distance and means of transport when transporting heavy materials to produce both the inner and outer layers of the panel. Additionally, the obtained carbon footprint results were compared with the results existing in the literature. The paper is structured as follows: Section 2 describes the case study and the assessment methodologies carried out, i.e., LCA, LCC, and ecoefficiency analysis; and Section 3 presents the environmental, economic, and ecoefficiency results and their discussion (including sensitivity and comparison analyses). Finally, the main conclusions of the study and ideas for further research are highlighted in Section 4.

## 2. Materials and Methods

### *2.1. Case Study and System Boundary Definition*

This study investigates six sandwich panels with different insulation materials (LWC, EPS, cork, and glass wool) and identical thermal transmittance (U-value) of 0.33 $W/m^2 \cdot K$. This was accomplished by considering the thermal conductivity of each insulation element and varying the thickness of the intermediate layer. The exterior layers of the CSPs studied were built using high-performance concrete (HPC) reinforced by steel fibres with a thickness of 75 mm (outer) and 35 mm (inner). All scenarios analysed are presented in Table 1. In general, a total of six scenarios were evaluated considering the following insulation elements: glass wool, lightweight concrete (LWC), cork, and EPS. Regarding the last element, three potential scenarios were considered, i.e., EPS made by (i) 100% virgin, (ii) 55% virgin, and (iii) 100% recycled materials. The three EPS variants and the glass wool were chosen as they are some of the most common insulator materials applied to CSPs [23] and widely available on the market, representing common benchmarks. The LWC variant was chosen for its novelty value, fully mineral characteristics, on-site preparation possibility, and increasingly more commonplace application in these types of panels [23]. Finally, cork was selected, as it is a product with high relevance for the Portuguese export and manufacturing industry [24]; it has good thermal, acoustic, and electrical insulation [25]; and its biogenic carbon uptake characteristics give it the possibility of improving the environmental profile of CSPs. It should be noted that although thermal transmittance is identical for all panel variants, the durability and long-term performance of the insulation layers may vary across the different options, thereby potentially affecting the durability and performance of the complete CSP. Since no long-term experimental data are available for these panels, this parameter could not be evaluated, which is a limitation of the present work.

Figure 1 depicts the production flowchart for each scenario under study. The outer layers of the CSPs are manufactured on-site, whereas the other materials are made off-site and carried to the project location. In general, the manufacturing process begins by producing the fresh HPC blend in a concrete mixer, according to a mixture previously evaluated by other authors [26–28]. Afterward, the HPC inner layer is cast, followed by the placing of the insulation material in the middle layer, and finally, the casting of the

HPC outer layer. The different CSP layers are held together by transversely laid out glass fibre-reinforced polymer connectors. Regarding the first scenario that considers the LWC insulation material, an additional manufacturing process is needed to obtain the fresh LWC mix, as it is also produced on-site. This manufacturing process starts with foam production in a foam generator, followed by the batch mix in a concrete mixer, similar to HPC production. This mix is then cast between the two HPC layers. In total, six insulation core materials with the thermophysical properties presented in Table 1 were considered.

**Table 1.** Thermophysical properties and thickness of the insulation layer for each panel, and HPC layers.

| Scenario | Insulation Core Material/External Layers | Density [kg/m$^3$] | Thermal Conductivity [W/m·K] | Thickness [mm] |
|---|---|---|---|---|
| A | LWC | 137 | 0.045 | 120 |
| B | Cork | 115 | 0.040 | 107 |
| C | Glass Wool | 40 | 0.034 | 91 |
| D | EPS, virgin | 30 | 0.035 | 93 |
| E | EPS, 55% virgin | 30 | 0.035 | 93 |
| F | EPS, recycled | 30 | 0.035 | 93 |
| All | HPC | 2357 | 0.707 | 35–75 |

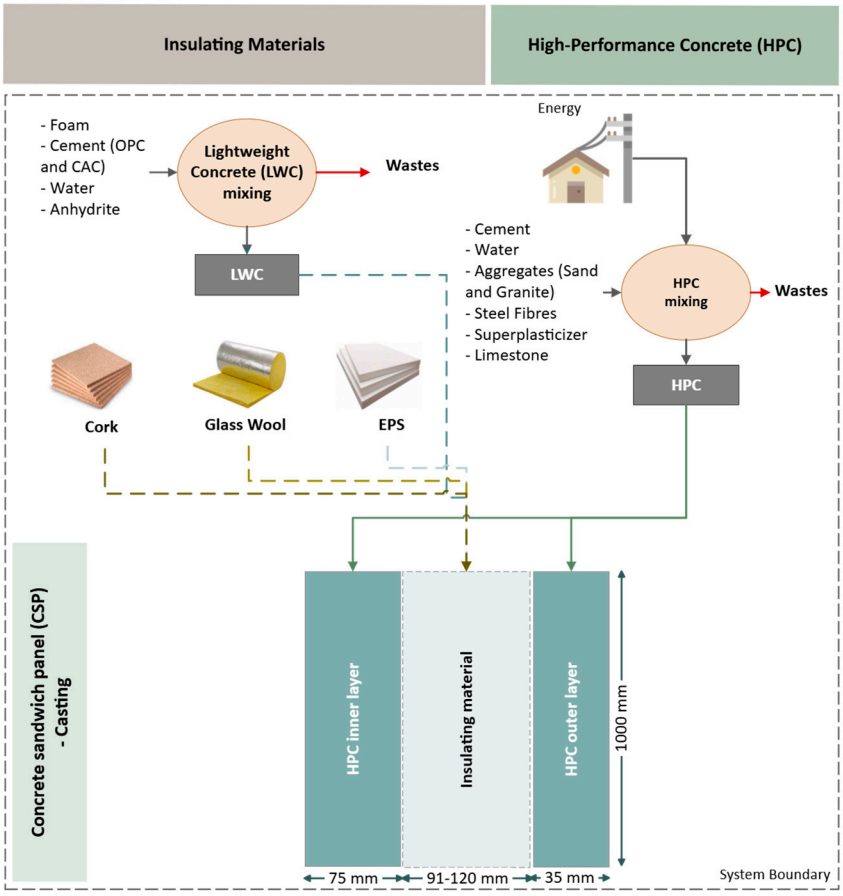


**Figure 1.** Flowchart and key characteristics of CSP production that are being analysed. Note that CAC stands for Calcium Aluminate Cement and OPC for Ordinary Portland Cement.

### *2.2. Life Cycle Assessment*

The LCA is a widely used methodology to assess the environmental impacts associated with a product or a service throughout its entire life cycle or part of it. In this work, this

approach was carried out following the ISO 14040 [29] and ISO 14044 [30] standards. The main steps are described in the following sub-sections.

#### 2.2.1. Goal and Scope Definition

As aforementioned, the present study aimed to evaluate and compare the environmental impacts of six different scenarios of CSPs. To calculate the environmental burdens of the several scenarios, 1 $m^2$ of CSP was defined as the functional unit (FU) in a *cradle-to-gate* system. As such, every step from the raw material acquisition and extraction process up to the manufacturing of the CSPs on-site was considered.

#### 2.2.2. Life Cycle Inventory (LCI)

Table 2 provides a summary of the LCI, which was compiled using information from the literature [26,27,31]. This was then supplemented with secondary datasets from the Ecoinvent v3.9 database [32] within SimaPro software (v9.4) [33]. Transportation distances were standardised at 25 km (typical for the Portuguese setting), assuming diesel-powered lorries as the primary mode of delivery. When specific background data were unavailable, environmental product declarations (EPDs) [34,35] were consulted to estimate embodied impacts.

**Table 2.** LCI for the CSPs under evaluation; FU: 1 $m^2$ of CSP.

| Layer | Scenario | Element | Amount [kg/$m^2$] |
|---|---|---|---|
| Inner | A to F | HPC | 180.0 |
| Insulation | A | LWC | 30.0 |
| | B | Cork | 12.3 |
| | C | Glass wool | 1.4 |
| | D | EPS, virgin | 2.8 |
| | E | EPS, 55% virgin | 2.8 |
| | F | EPS, recycled | 2.8 |
| Outer | A to F | HPC | 84.0 |
| | A to F | Glass fibres | 1.2 |

#### 2.2.3. Life Cycle Impact Assessment (LCIA)

The EN 15804 + A2 European standard [36] aims to give key product category rules associated with environmental declarations Type III (i.e., EPDs) for construction products. This document lists mandatory (or core) and optional impact categories that must be reported. So, to assess the potential environmental impacts of the six CSPs scenarios, the core impact categories of the EN 15804 + A2 method (v1.03) [33,37] were considered (Table 3).

**Table 3.** Impact categories under study.

| Impact Category | Abbreviation | Unit |
|---|---|---|
| Climate change | CC | kg $CO_2$-eq |
| Ozone depletion | OD | kg CFC-11-eq |
| Photochemical ozone formation | POF | kg NMVOC-eq |
| Acidification | AC | mol H+ -eq |
| Eutrophication, freshwater | EF | kg P-eq |
| Eutrophication, marine | EM | kg N-eq |
| Eutrophication, terrestrial | ET | mol N-eq |
| Water use | WU | $m^3$ depriv. |
| Resource use, fossils | RU(F) | MJ |
| Resource use, minerals, and metals | RU(E) | kg Sb-eq |

### 2.3. Life Cycle Costing

LCC is a cost management approach used to quantify the sum of all expenses, revenues, and the corresponding cash flows throughout the entire life cycle of a product [38,39]. In this work, the life cycle costs of six CSPs were evaluated using the Material Flow Cost Accounting (MFCA) methodology (ISO 14051 [40]). It is focused on material and energy flows, and it aims at pinpointing and quantifying waste and losses of production processes in monetary terms [41]. This method differentiates from other traditional costing methods, where costs are attributed only to saleable or usable goods. In the MFCA approach, both the finished product and the undesirable outputs are allocated to the manufacturing expenses [41]. It is worth mentioning that the same boundaries of the LCA study were considered for the LCC study. In other words, the life cycle costs include all costs from the raw material production to the on-site assembly of the CSP sandwich panels, including the transport of goods.

#### 2.3.1. Flow Model and Material Balance

The production processes within the system boundary were divided into several quantity centres (QCs). Indeed, in the flow model construction, a QC is assigned for each part of the production process where the transformation of materials occurs or other input costs, like electricity and labour, are invested. Figure 2 shows the flow model of this work. In each QC, input materials are compared with the obtained products to account for material losses through the following relation presented in Equation (1) [42]:

$$\text{Material loss} = \text{Input} - \text{Products} \quad (1)$$

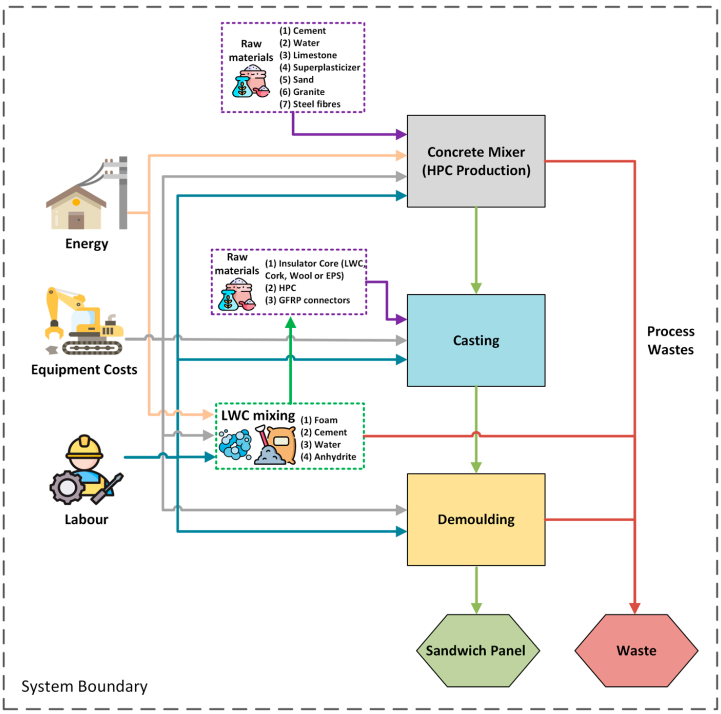


**Figure 2.** Flow model based on the MFCA methodology.

#### 2.3.2. Monetary Value Attribution

Following ISO 14051 [40] standards, all costs associated with the entry and exit of material flows in each QC must be assessed and attributed to those material flows [42]. In MFCA, these costs are divided into four different categories, which are listed in Table 4: (i) material costs; (ii) energy costs; (iii) system costs; and (iv) waste management costs. The

allocation criteria to assign production costs to the saleable products and to the wastes were based on mass distribution [42]. Raw material and equipment costs, as well as equipment energy usage, were gathered from industry partners and online supplier estimates [43–56]. Likewise, for labour costs, the mean time to task completion and number of personnel needed were provided by industry partners, and the labour hourly rate was assumed as 6 €/h according to the Portuguese Labour Ministry construction sector statistics [57]. All the compiled costs are VAT-free.

**Table 4.** MFCA cost categories.

| Category | Description | Example |
|---|---|---|
| Material Costs | Cost of the materials used in production. | Water, cement, aggregates, etc. |
| Energy Costs | Costs with all energy inputs. | Electricity, fuel, etc. |
| System Costs | Expenses associated with the production processes that do not fit into the other categories. | Labour and equipment costs. |
| Waste Management Costs | Costs of handling and disposing of the process wastes. | Labour for waste handling, recycling, and cleaning. |

### *2.4. Eco-Efficiency Analysis*

Eco-efficiency analysis is a methodology used to assess the environmental impact in proportion to the cost-effectiveness of a product. The assessment of the life cycle costs and the aggregation to an overall eco-efficiency indicator is based on ISO 14045 [58]. In this standard, the eco-efficiency indicator (EI) is obtained through the ratio between the product system value and its environmental impact, as represented in Equation (2).

$$\text{Eco-efficiency} = \frac{\text{Product System Value}}{\text{Environmental Impact}} \quad (2)$$

In this work, the EI was taken as the ratio between the economic value (EV) of each CSP scenario (i.e., the profit margin per $m^2$ [€/$m^2$]) and its environmental pressure. Aiming to reduce the environmental impacts of different alternatives and, at the same time, increase their value, high EIs are preferable. So, for comparison purposes, the higher the eco-efficiency indicator, the better the CSP scenario. Given the fact that opposite results were obtained in different impact categories, different environmental indicators were considered, namely CC, POF, and RU(F) (Table 3). Therefore, to conclude about the most eco-efficient panel, several EIs were obtained and compared. Since all panels are expected to be functionally equivalent, it was assumed that a final customer would pay the same retail price for each alternative. Moreover, it was considered that the retail price of the CSPs is equal to the production cost of the more expensive alternative, with an overhead price increase of 25% to account for the profit margin and other non-disclosed expenses. Consequently, the panel with the highest profit margin will be the one with the lowest production cost.

## 3. Results and Discussion

### *3.1. LCA Results*

Regarding the LCA results, Figure 3 depicts the potential environmental impacts for all categories under study. Overall, the HPC layers (both inner and outer) are responsible for most of the burdens obtained, amounting to more than 70% of the impacts in all scenarios. This happens due to the use of Portland Cement (OPC), which accounts for more than 50% of the environmental impacts of the concrete mixture.

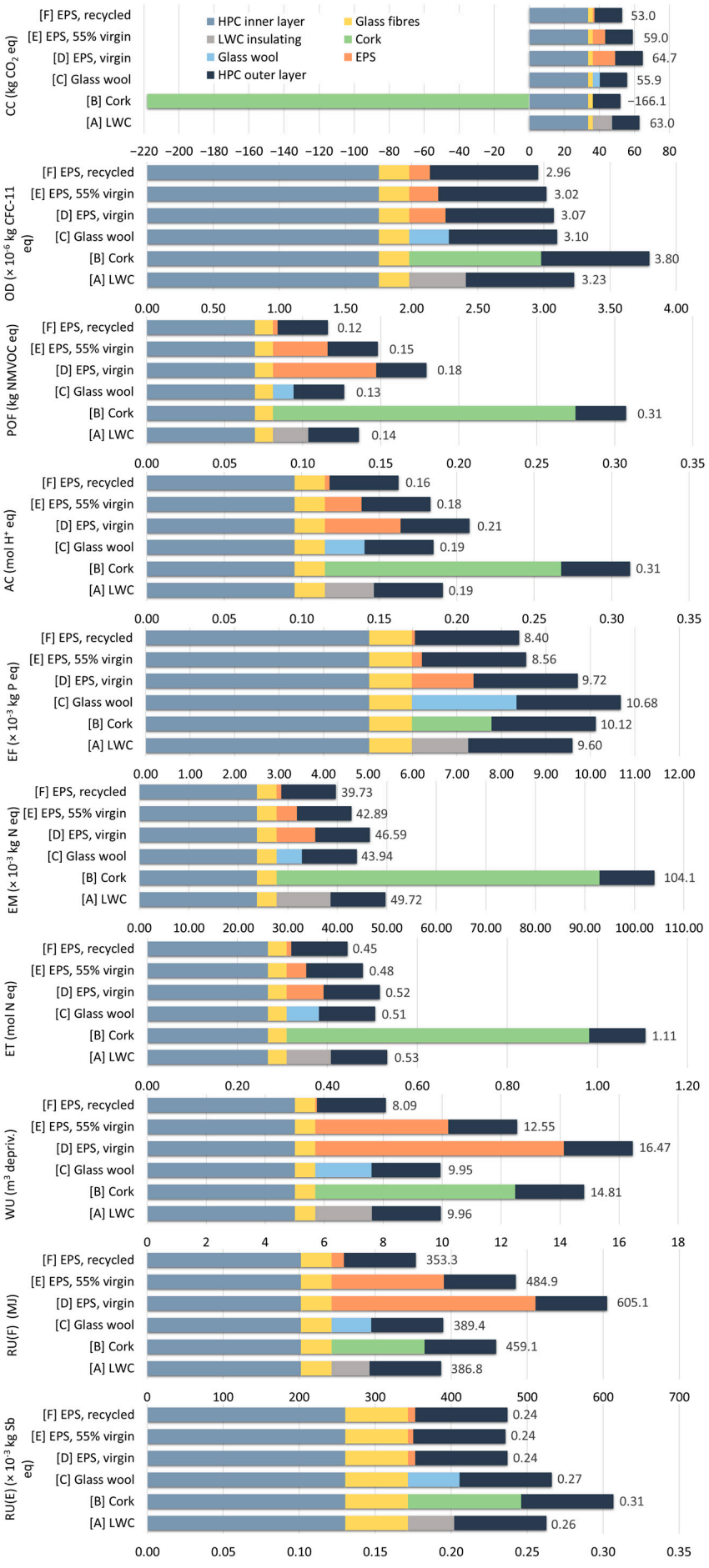


**Figure 3.** Potential environmental impacts obtained for the six scenarios under study.

Examining each impact category in greater detail reveals that the alternative with a lower impact depends on the chosen impact category. For example, when considering the CC category, Figure 3 shows that the CSP configuration incorporating cork as insulation material is the scenario with the best global warming potential, with a positive contribution to the environment. Due to biogenic $CO_2$ uptake that turns cork oak into a carbon sink while existing in the forest, this scenario presents the lowest carbon footprint. As is evidenced in Figure 3, when subtracting the $CO_2$ uptake provided by the cork from the $CO_2$ emissions of the remaining panel components, we get a net carbon capture of up to −166 kg of $CO_2$-eq/$m^2$. Regarding the other scenarios, the CSP with virgin EPS is responsible for the highest carbon emissions (65 kg of $CO_2$-eq/$m^2$). Nevertheless, instead of using virgin raw material, the decision-maker can select a more environmentally friendly alternative, such as EPS with 45% recycled material (59 kg of $CO_2$-eq/$m^2$) or even an EPS that is 100% recycled (53 kg of $CO_2$-eq/$m^2$). Thus, compared with Scenario D, these alternatives reduce carbon emissions by about 9% and 18%, respectively. In this context, the scenario with recycled EPS has the second lowest carbon emissions, followed by glass wool (56 kg of $CO_2$-eq/$m^2$) and the LWC (63 kg of $CO_2$-eq/$m^2$) scenarios.

Considering other impact categories, such as POF, AC, EM, ET, WU, and RU(F), the best alternative varied, showing that the CSP with cork was not the best alternative in any of them, and other alternatives like glass wool and lightweight concrete had less environmental burdens than the scenario with cork as the insulating material. Indeed, for the RU(E), AC, ET, EM, POF, and OD categories, Scenario B proved to be the worst to consider, given the production process of the expanded insulation corkboard. Moreover, when compared with the CSP using virgin EPS, the recycled EPS CSP showed up as a scenario with a good environmental performance (since it reduced the panel environmental impacts, on average, by 21%), which reveals the potential that material recovery and recycling can have to lower building construction embodied impacts.

Overall, the obtained results support the importance of assessing more than one environmental impact indicator since the conclusions about the best option for the insulation material to be used on a CSP may change accordingly. Thus, from an environmental point of view, the choice of which insulation material should be used must be carefully analysed.

As expected, in every scenario under study, the HPC layers are the main hotspot in both impact categories, representing from 49% to 76% of the environmental burdens. Therefore, reducing their impacts is very important. During the local production stage of the HPC mix, the electricity did not show an influence on the impacts, accounting for less than 1% of the total environmental impacts. Nevertheless, the materials and their transport are responsible for most of the impacts. Thus, to understand the influence of the transport stage, namely the distances and means of transport, a sensitivity analysis was performed regarding the transport of the heaviest materials (the coarse river sand and crushed granite used), considering the theoretical scenarios presented in Table 5.

To allow comparability among different studies, the sensitivity analysis results are presented for the CC category because most of the literature studying CSPs assesses the carbon footprint of their alternatives. Since background data are not available in the ecoinvent database yet, to assess the environmental impact of electric trucks compared to diesel ones, a reduction of 38% in carbon emissions was considered based on a Scania report [59].

The results of the sensitivity analysis are presented in Figure 4, showing the increment or reduction in CC that the new transport scenarios have when compared to the base case one (25 km, diesel truck). Figure 4 illustrates that replacing the trucks powered by diesel with electric ones allows carbon emissions to be reduced (−1.1 kg of $CO_2$-eq/$m^2$). Nevertheless, if the distance increases, the GWP also rises. For example, transporting the

aggregates 100 km in a diesel lorry emits more than 4.9 kg of $CO_2$-eq/$m^2$. Moreover, in this analysis, except for the cork CSP, the scenarios with lower GWP (e.g., glass wool CSP, EPS, recycled CSP) are more sensible to the transport scenario than the others.

**Table 5.** Scenarios under study in the sensitivity analysis.

| Transport Distance [km] | Scenario | Mean of Transport Used |
|---|---|---|
| 25 | Baseline | Lorry powered by diesel |
| | E-lorry25 | Electrical lorry |
| 50 | D-lorry50 | Lorry powered by diesel |
| | E-lorry50 | Electrical lorry |
| 100 (or 75 km by train and 25 km by lorry) | D-lorry100 | Lorry powered by diesel |
| | E-lorry100 | Electrical lorry |
| | E-T + L100 | Electrical train and lorry |
| | D-T + L100 | Train and lorry powered by diesel |
| | E-T + D-L100 | Electrical train and lorry powered by diesel |
| | D-T + E-L100 | Train powered by diesel and electrical lorry |

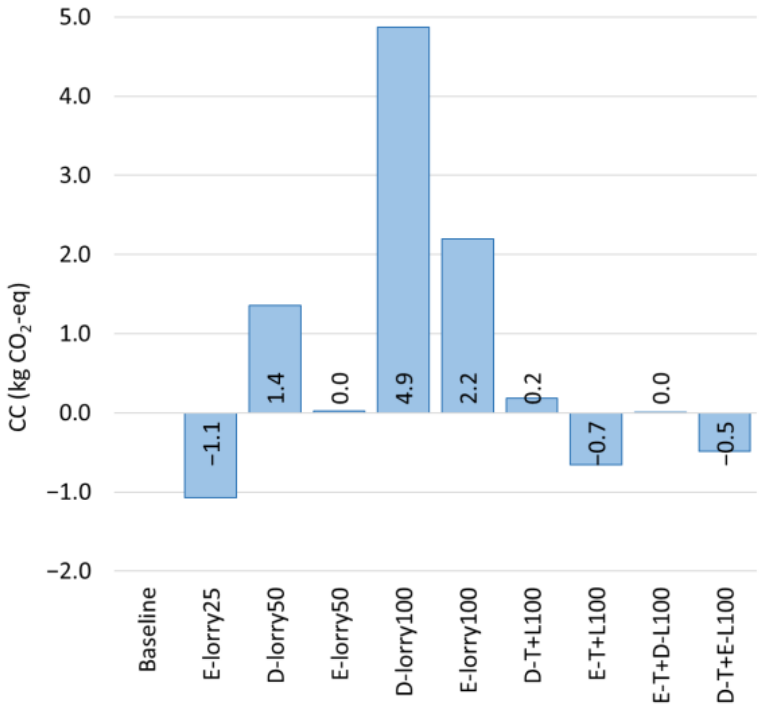


**Figure 4.** Sensitivity analysis results on transportation scenarios for the CSPs; FU: 1 $m^2$ of CSP.

Overall, this analysis supports the idea that the heaviest and most bulky construction materials (i.e., the aggregates) should, whenever possible, be acquired and transported from nearby suppliers to reduce transportation energy requirements and emissions. Furthermore, the electrical means of transport (train and lorry) were shown to be preferable to conventional diesel transport in terms of carbon emissions.

Figure 5 compares the carbon footprint of the CSP scenarios under evaluation with some previous results found in the literature.

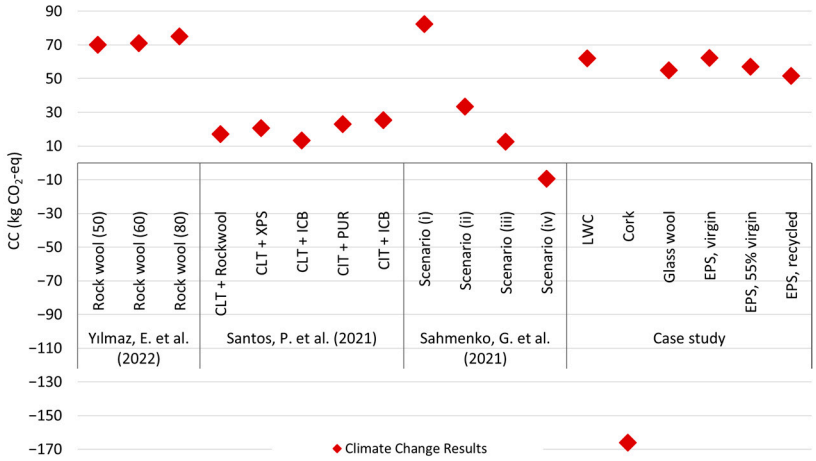


**Figure 5.** Comparison of the results obtained in this work with the ones available in the literature (CC); *Cradle-to-gate* approach; FU of 1 $m^2$ of panel [1,3,16]. Note that in Sahmenko's [3] study, the following scenarios were considered: (i) external foam concrete layers with foam polystyrene as the inner core; (ii) external average density hemp layers with an inner lightweight hemp layer; (iii) interior high-density hemp layer with lightweight hemp inner core and an average-density hemp as exterior layer; and (iv) external high-density hemp layers and a lime-based hemp composite core.

The CSPs analysed in this study showed less carbon emissions than the Al panels evaluated by Yılmaz et al. (2022) [1], and the scenario (i) from Sahmenko et al. (2021) [3]. Compared with the CLT and ICB panels studied by Santos et al. (2021) [16], the scenarios under evaluation in this study have a higher carbon footprint. Moreover, Figure 5 shows that the CLT with ICB is the best scenario considering only the GWP due to the capture of $CO_2$. Nonetheless, the authors highlighted that considering other impact categories, this scenario presents the worst environmental performance. Specifically for cork products, other questions arose when considering the estimation of carbon emissions. For example, at the moment, opinions on the best suitable approach to calculate temporary carbon storage capacity and emissions of biogenic carbon are divided [60]. In the literature, several studies assessed the carbon footprint of different cork products, namely stoppers [61], insulation cork boards [62], and expanded cork slabs [60]. These studies agree on the advantages of cork concerning carbon emissions, highlighting that cork oak forests may help mitigate climate change because these trees can sequestrate $CO_2$ from the atmosphere and store it in different parts as organic matter, i.e., perennial tissues and soil [61].

Regarding the carbon uptake during the use phase and emissions during EoL scenarios, the global warming potential may vary slightly depending on the lifespan considered during the use step. Nevertheless, considering the carbon sequestrated while existing in the cork oak forest may decrease the carbon footprint dramatically [60]. When assessing the carbon emissions of the cork oak sector with and without biogenic carbon emissions and their uptake at the forest step, Demertzi et al. (2016) [61] obtained meaningful variation of the results, showing total carbon emissions (including forest, manufacturing, use, and EoL steps) varying from about 200,000 t of $CO_2$-eq (without carbon capture) to −1,000,000 t of $CO_2$-eq (with carbon capture). Significant differences were also obtained by Silvestre et al. (2016) [62] while comparing the global warming potential obtained by two different methods, i.e., CML (without $CO_2$ sequestration) and considering $CO_2$ uptake and biogenic emissions. From a *cradle-to-gate* perspective (raw material extraction to production and packaging of the material), the authors obtained a carbon footprint of 40.2 kg of $CO_2$-eq/$m^3$ of ICB and −435 kg of $CO_2$-eq/$m^3$ of ICB for scenarios with and without carbon sequestration, respectively. Therefore, results existing in the literature seem to agree that the consideration of the biogenic carbon sequestration in the forest may affect the results

significantly [60]. Furthermore, Demertzi et al. (2017) [60] concluded that the choice of mass or economic allocation, as well as the lifespan and EoL scenarios, should be carefully considered since they may lead to different results. Thus, different environmental impact results may be found in the available literature and EPDs associated with cork-based products, depending on the assumptions made by the authors, which explains the variability of the obtained results.

Other solutions, including the bio-based ones assessed by Sahmenko et al. (2021) [3], have better environmental performance and are pointed out by the authors as more sustainable alternatives despite their lower thermal inertia. Moreover, it is worth noting that the structural role of each sandwich panel may not be the same. Thus, a carbon index considering other properties (e.g., compressive strength, etc.) should also be considered in future studies because, depending on the panel function, the best option can differ.

### *3.2. LCC Results*

Figure 6 depicts the life cycle cost of the six panels under evaluation. In addition to being the main environmental hotspot, the HPC mix for the inner and outer layers is also the major production cost driver for all the scenarios (47.7 €/m$^2$). The production costs of the CSPs with EPS, LWC, and glass wool insulation layers are closely aligned, with the LWC, glass wool, and EPS 55% virgin panels presenting almost identical results in terms of cost. The CSP with cork is the most expensive panel to produce (124.7 €/m$^2$), followed by the CSPs with fully virgin EPS (101.4 €/m$^2$) and 55% virgin EPS (96.8 €/m$^2$), then the panel with the glass wool layer (96.2 €/m$^2$), the CSP with LWC (96 €/m$^2$), and finally, the CSP with fully recycled EPS (91.3 €/m$^2$). Therefore, to produce panels with similar thermal performance, the cork sandwich panel costs 37% more than the one with fully recycled EPS. Waste costs are not very expressive; they represent, on average, 2.3% of the production cost across the six scenarios.

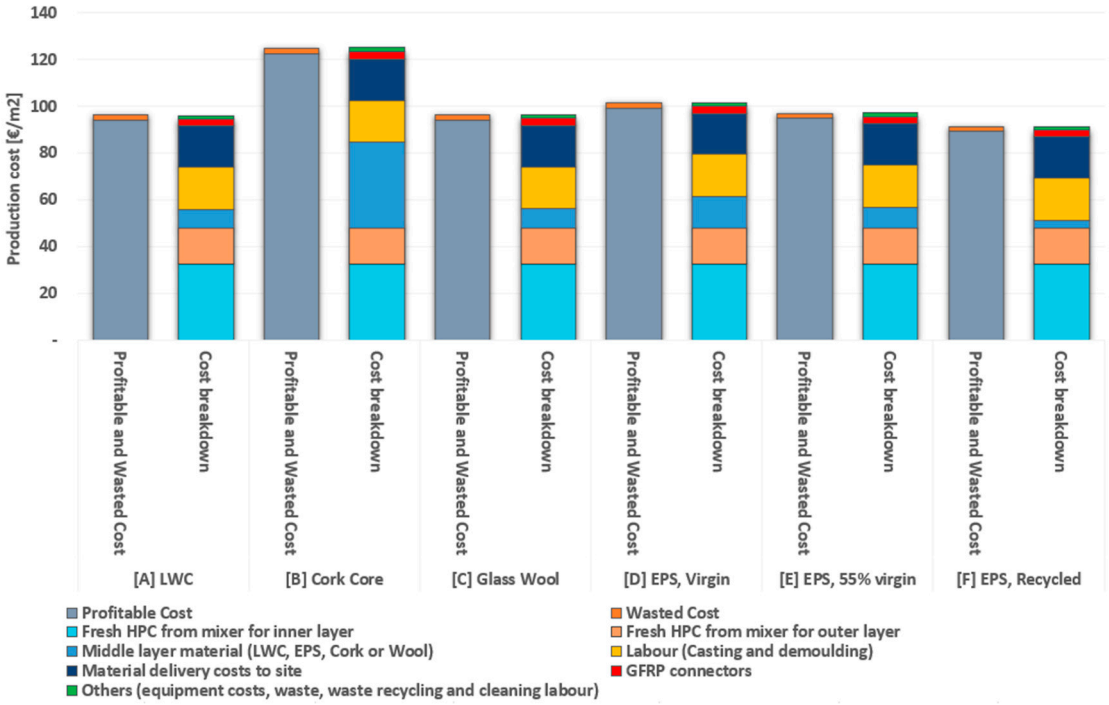


**Figure 6.** Life cycle costs per m$^2$ of panel for the six CSP scenarios under evaluation.

The combination of all the raw material inputs represents the majority of the production cost for the six scenarios, at an average of 62.9% of the total expense. However, labour is also an important input in terms of final cost variation, representing 19.4%, 17.8%, 18.6%,

19.7%, 14.4%, and 18.7% of the total production costs of the CSPs with LWC, virgin EPS, 55% virgin EPS, recycled EPS, cork, and glass wool, respectively. This is a consequence of the type of batch/on-site manufacturing considered, where reduced automation and equipment simplicity lead to a necessary increase in labour input. An industrial production with a more automated casting and demoulding process would see these labour costs drop expressively (as opposed to a natural increase in equipment and running costs). Another important input is the delivery cost of the materials to the construction site, representing 17.1%, on average, of the total production cost. However, the considered purchase quantities were small, enough for the fabrication of 13 $m^2$ of panels. It was found that some suppliers offer delivery costs for purchases above a certain value, so a construction company buying in bulk quantities and with higher production volumes could see significant reductions in these costs per $m^2$ of panel.

To assess the influence of raw material price and labour rates on CSP production costs, a sensitivity analysis for these two cost categories was conducted (Figure 7). When varying the inflation rate from −20% (deflation scenario) up to +50% (inflation scenario), results showed that the raw material inflation rate (RMIR) had a significantly greater impact on the final production cost of CSPs compared to the labour inflation rate (LIR). This is coherent with the fact that the sum of all the raw materials employed in the panel represents a much larger cost driver than the labour rate itself. On average, an increase of just 8% in the RMIR will lead to a similar production cost rise of an increase of 50% in the LIR. As such, this indicates that strategies targeting reductions in raw material costs (like bulk purchasing) will yield greater cost savings and have a higher impact on the cost structure than those focused solely on labour. For a socially conscious CSP manufacturer, it can even demonstrate that a small reduction in raw material costs allows for a considerable pay increase to its labour force without affecting profitability.

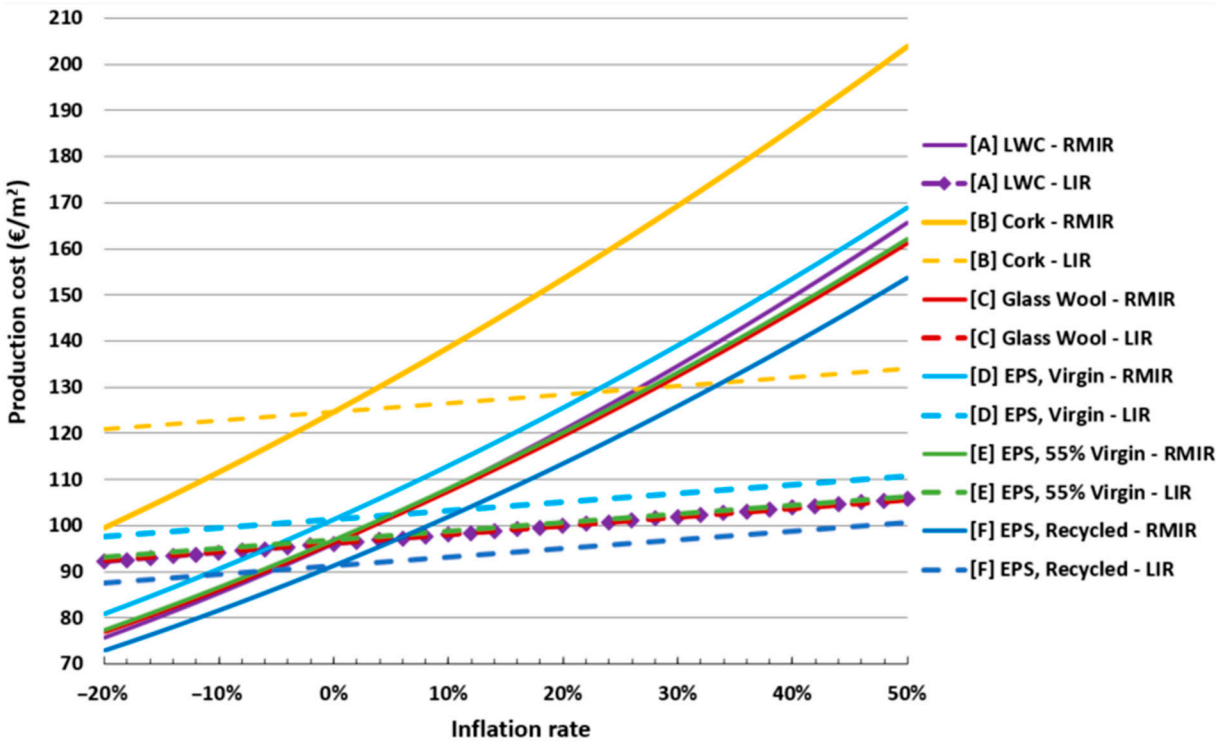


**Figure 7.** Sensitivity analysis on the effect of the raw material inflation rate and labour rate on the production cost of the six CSP scenarios under evaluation. RMIR—raw material inflation rate; LIR—labour inflation rate.

### 3.3. Eco-Efficiency Results

The results of the eco-efficiency assessment are shown in Table 6. In Figure 8, the eco-efficiency matrixes are presented, depicting the EV (€/m$^2$) vs. CC (kg $CO_2$-eq), POF (kg NMVOC-eq), and RU(F) (MJ) results for each CSP scenario.

**Table 6.** Economic and environmental indicators and respective eco-efficiency indexes for the six CSP scenarios under evaluation.

| Scenario | Insulation Material | EV [€/m$^2$] | CC [kg $CO_2$-eq] | POF [kg NMVOC-eq] | RU(F) [MJ] | EI—CC | EI—POF | EI—RU(F) |
|---|---|---|---|---|---|---|---|---|
| A | LWC | 59.80 | 62.97 | 0.14 | 386.82 | 0.95 | 439.97 | 0.15 |
| B | Cork | 31.16 | −166.14 | 0.31 | 459.14 | −0.19 | 101.43 | 0.07 |
| C | Glass wool | 59.60 | 55.92 | 0.13 | 389.38 | 1.07 | 470.88 | 0.15 |
| D | EPS, virgin | 54.42 | 64.74 | 0.18 | 605.12 | 0.84 | 303.32 | 0.09 |
| E | EPS, 55% virgin | 58.98 | 59.03 | 0.15 | 484.87 | 1.00 | 397.88 | 0.12 |
| F | EPS, recycled | 64.54 | 52.99 | 0.12 | 353.33 | 1.22 | 555.21 | 0.18 |

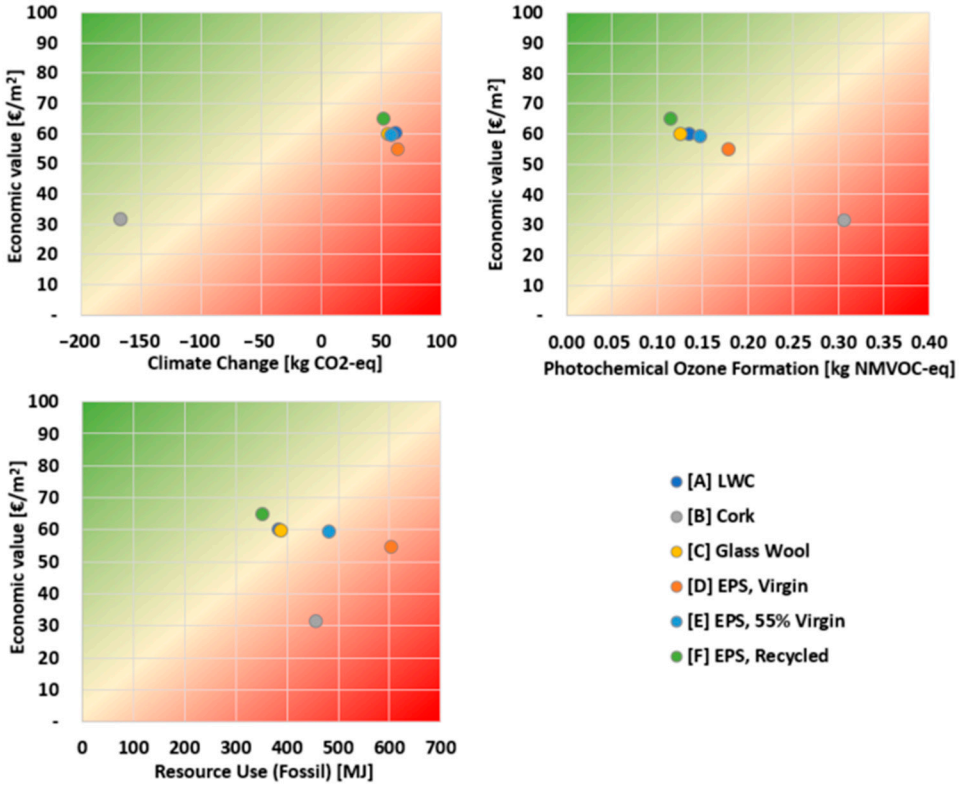


**Figure 8.** Eco-efficiency matrixes for the CC, POF, and RU(F) environmental indicators.

Starting with the eco-efficiency results for the CC environmental indicator, a rather uncommon scenario is presented. Since the CSP with cork exhibits negative results for this indicator due to the cork oak's biogenic $CO_2$ uptake prior to production, a direct EI comparison with the other scenarios through Equation (2) is not possible. However, the matrix of Figure 8 and the fact that the production of this scenario has a positive impact on the environment in terms of carbon emissions (instead of a negative one like the other settings) leads to the logical conclusion that this is the most eco-efficient scenario in terms of EV vs. CC. Similar matrix approaches were used by other authors when assessing the economic and environmental benefits of different products [63,64]. The CSP with cork is followed by the recycled EPS CSP (EI of 1.22), glass wool CSP (1.07), 55% virgin EPS CSP (1.00), and LWC CSP (0.95). The least eco-efficient scenario for the CC environmental

indicator is the virgin EPS CSP (EI of 0.84), as it couples the second lowest economic value of all the studied options with the highest carbon emissions.

Advancing to the eco-efficiency comparisons with the POF indicator, the cork CSP is now by far the least eco-efficient option, presenting the worst economic value and the highest emission levels with an EI of 101.43. The remaining scenarios follow an almost identical order to the analysis with the CC indicator: the recycled EPS CSP leads in terms of eco-efficiency, showcasing the highest economic value and the lowest environmental burden (EI of 555.21); the glass wool CSP is the second-best option (470.88); the LWC CSP switches positions with the 55% virgin EPS CSP, being respectively the third and fourth most eco-efficient options (439.97 vs. 397.88, correspondingly); and the second-to-last scenario is the fully virgin EPS CSP, with an EI of 303.32.

Considering the results for the RU(F) environmental indicator, the CSP with fully recycled EPS again leads in eco-efficiency, combining the lowest fossil fuel resource use with the highest economic value, with an EI of 0.18. The next most eco-efficient options are the LWC CSP and glass wool CSP, with almost identical results in both the economic and environmental dimensions, both presenting an EI of 0.15. They are followed by the 55% virgin EPS CSP (EI of 0.12) and fully virgin EPS CSP (0.09). So, for this environmental indicator, the cork CSP once again shows the worst results in terms of eco-efficiency. Although both the 55% virgin and fully virgin EPS CSPs employ higher fossil resource use on a *cradle-to-gate* analysis, the high costs of the cork CSP outweigh this environmental advantage.

Following on from what was discussed in the LCA results, this highlights the importance of also considering several environmental impact indicators for an eco-efficiency analysis. Indeed, although the cork CSP demonstrates very positive results when calculating eco-efficiency through the CC environmental indicator, the opposite was shown for the analyses using the POF and RU(F) indicators. Thus, the definition of the most relevant environmental criteria for each service or product being assessed must be carefully thought out, as this can heavily impact the final eco-efficiency results.

When analysing the data across the three eco-efficiency indicators, the fully recycled EPS CSP consistently displays the highest eco-efficient results; thus, it seems to be the overall most eco-efficient option. The difference in eco-efficiency results between the fully recycled EPS and the fully mineral EPS CSPs is also quite stark. While the recycled EPS CSP is the leader in eco-efficiency for two of the indicators and second place in the other, the virgin EPS CSP is the penultimate scenario in two of the analyses and last place in the other.

As was seen in the sensitivity analysis of Section 3.2, both the LIR and RMIR (especially the latter) have a definite effect on the production cost of the CSPs. However, since the profile and slope of the production cost curves are almost identical across the different panel variants, it can be concluded that these parameters do not affect the eco-efficiency rankings of Table 6. If we are comparing the panels across identical inflation rate conditions, the fully recycled EPS CSP remains the most eco-efficient alternative.

A comparison with some results obtained in previous literature devoted to the assessment of the eco-efficiency of sandwich panels is hard to establish. Shanmugam et al. (2019) [21] used different FUs and environmental indicators. Demertzi et al. (2020) [14] neither provided the U-values of the panels nor the densities of the materials, and the considered panels were destined for floors rather than walls, making it difficult to establish if they are functionally equivalent to the alternatives evaluated in this work. Finally, Pérez-García et al. (2014) [22] only presented results for the combined performance of the entire residential structures and not for the specific building elements.

## 4. Conclusions

This work applied eco-efficiency analysis to support decisions towards more sustainable building choices. The approach followed included LCA, LCC, and eco-efficiency studies to compare six CSPs with the same thermal function and alternative insulation materials (cork, glass wool, EPS, and LWC). Key findings include the following: (i) HPC layers were the main environmental and cost hotspots for all CSP variants; thus, further studies are advised to reduce OPC layers or improve the HPC recipe, mainly to reduce OPC incorporation. (ii) Recycled EPS CSP was generally the most eco-efficient option across LCA, LCC, and eco-efficiency indicators (i.e., it reduced the panel environmental impacts, on average, by 21% when compared to virgin EPS CSP), which shows the potential that material recovery and recycling may have to reduce building embodied impacts. (iii) Incorporating a bio-based material, cork CSP had the lowest carbon footprint (due to cork carbon capture assumed). However, it performed poorly in other environmental categories, and it had the highest cost. To overcome these drawbacks, improvements in the cork insulation production process are still required. (iv) Compared with the literature, the proposed CSPs seem to have a better carbon footprint than Al sandwich panels but worse than CLT (cross-laminated timber) panels, and, as CSPs are heavier, transportation (means and distances) is a relevant factor to consider. (v) Raw material costs are the most significant cost driver (63%), strongly linking the final production cost of the CSPs to raw material market prices and the inflation rate. Labour expenses (18%) and the material delivery costs (17%) to the construction site were also shown to be important cost drivers. (vi) The research also highlights the importance of a multi-criteria approach in eco-efficiency analysis, as performance varies significantly depending on the environmental impact categories considered. This shows that focusing solely on carbon emissions or a single category may provide an incomplete picture of a product's overall environmental impact.

These findings positively contribute to decision-making in the construction sector, enlarging current knowledge by showcasing the potential for environmental footprint reduction and careful material selection via eco-efficiency analysis for CSPs. This insight is crucial for designers, project managers, and policymakers aiming to align the building sector with global and regional sustainability goals, such as those in the Paris Agreement.

On the other hand, the LCC results emphasise that while some materials may have higher upfront costs (e.g., cork), their long-term benefits could justify the investment, particularly in projects prioritising carbon footprint reduction. This can be helpful in assisting construction companies to align with green building certifications like LEED or BREEAM.

Additionally, with this research, the authors expect to encourage circular economy practices and strategic planning in the sector. For example, by highlighting the environmental and economic advantages of using recycled vs. virgin materials (as showcased by the different EPS panel variants), optimising material use (e.g., potentially finding ways to reduce HPC layer thickness, as it is the main environmental and cost hotspot), locally sourcing materials, or adopting cleaner transport solutions like electric mobility.

Based on this study, further research areas are also suggested to strengthen the knowledge in the field and overcome some identified limitations: (1) to analyze other panels with different insulation options or concrete blends, especially those incorporating recycled materials since offsetting virgin fossil based materials may have reduced impacts; (2) to evaluate CSPs' performance and service-life estimation through long-term performance and durability tests, as the environmental and cost profile of the panels per year of service may significantly alter the results when alternatives have different life spans; (3) to include potential differences in functionality beyond thermal U-vales (ex. compressive strength) of the panels; (4) to consider end-of-life scenarios; (5) to assess the eco-efficiency for increased

production volumes and off-site manufacturing since considering the small production volumes assessed in this work, the labour and material delivery costs probably contribute more significantly to the final production cost of the panels than the economy of scale of the manufactured panels.

**Author Contributions:** Conceptualisation, B.M., T.R.d.S. and H.M.; methodology, B.M., T.R.d.S. and H.M.; software, B.M. and T.R.d.S.; validation, B.M., T.R.d.S., H.M. and N.S.; formal analysis, B.M. and T.R.d.S.; writing—original draft preparation, B.M., T.R.d.S. and H.M.; writing—review and editing, B.M., T.R.d.S., H.M. and N.S.; visualisation, B.M., T.R.d.S., H.M. and N.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the base funding component of the Center for Technology and Innovation—ISQ, under the terms defined in AAC nº 03/C05-i02/2022.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Yılmaz, E.; Aykanat, B.; Çomak, B. Environmental life cycle assessment of rockwool filled aluminum sandwich facade panels in Turkey. *J. Build. Eng.* **2022**, *50*, 104234. [CrossRef]
2. Torres-rivas, A.; Pozo, C.; Palumbo, M.; Ewertowska, A.; Jiménez, L.; Boer, D. Systematic combination of insulation biomaterials to enhance energy and environmental efficiency in buildings. *Constr. Build. Mater.* **2021**, *267*, 120973. [CrossRef]
3. Sahmenko, G.; Sinka, M.; Namsone, E.; Korjakins, A.; Bajare, D. Sustainable Wall Solutions Using Foam Concrete and Hemp Composites. *Environ. Clim. Technol.* **2021**, *25*, 917–930. [CrossRef]
4. Monteiro, H.; Cruz, P.L.; Oliveira, M.C.; Iten, M. Technical and economical assessment of waste heat recovery on a ceramic industry. In *Wastes: Solutions, Treatments and Opportunities III*; CRC Press: Boca Raton, FL, USA, 2019; pp. 524–530. [CrossRef]
5. Monteiro, H.; Soares, N. Integrated life cycle assessment of a southern European house addressing different design, construction solutions, operational patterns, and heating systems. *Energy Rep.* **2022**, *8*, 526–532. [CrossRef]
6. Losch, E.D.; Hynes, P.W.; Andrews Jr, R.; Browning, R.; Cardone, P.; Devalapura, R.; Donahey, R.; Freedman, S.; Gleich, H.A.; Goettsche, G.; et al. State of the Art of Precast/Prestressed Concrete Sandwich Wall Panels. *PCI J.* **2011**, *56*, 131–176.
7. Resende, P.; May, M.; Hallak, T.; Hiermaier, S. Bio-based/green sandwich structures: A review. *Thin-Walled Struct.* **2022**, *177*, 109426. [CrossRef]
8. Monteiro, H.; Moura, B.; Soares, N. Advancements in nano-enabled cement and concrete: Innovative properties and environmental implications. *J. Build. Eng.* **2022**, *56*, 104736. [CrossRef]
9. Wang, W.; Jiang, D.; Chen, D.; Chen, Z.; Zhou, W.; Zhu, B. A Material Flow Analysis (MFA)-based potential analysis of eco-efficiency indicators of China's cement and cement-based materials industry. *J. Clean. Prod.* **2016**, *112*, 787–796. [CrossRef]
10. de Souza, A.M.; de Lima, G.E.S.; Nalon, G.H.; Lopes, M.M.S.; Júnior, A.L.d.O.; Lopes, G.J.R.; Olivier, M.J.d.A.; Pedroti, L.G.; Ribeiro, J.C.L.; de Carvalho, J.M.F. Application of the desirability function for the development of new composite eco-efficiency indicators for concrete. *J. Build. Eng.* **2021**, *40*, 102374. [CrossRef]
11. Tavares, V.; Soares, N.; Raposo, N.; Marques, P.; Freire, F. Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials. *J. Build. Eng.* **2021**, *41*, 102705. [CrossRef]
12. Monteiro, H.; Freire, F. Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods. *Energy Build.* **2012**, *47*, 572–583. [CrossRef]
13. Monteiro, H.; Freire, F.; Soares, N. Life cycle assessment of a south European house addressing building design options for orientation, window sizing and building shape. *J. Build. Eng.* **2021**, *39*, 102276. [CrossRef]
14. Demertzi, M.; Silvestre, J.D.; Durão, V. Life cycle assessment of the production of composite sandwich panels for structural floor's rehabilitation. *Eng. Struct.* **2020**, *221*, 111060. [CrossRef]
15. Demertzi, M.; Silvestre, J.; Garrido, M.; Correia, J.R.; Durão, V.; Proença, M. Life cycle assessment of alternative building floor rehabilitation systems. *Structures* **2020**, *26*, 237–246. [CrossRef]
16. Santos, P.; Correia, J.R.; Godinho, L.; Dias, A.M.P.G.; Dias, A. Life cycle analysis of cross-insulated timber panels. *Structures* **2021**, *31*, 1311–1324. [CrossRef]

17. Tighnavard, A.; Sher, W.; Yeoh, D.; Koushfar, K. LCA & LCC analysis of hybrid glued laminated Timber—Concrete composite floor slab system. *J. Build. Eng.* **2022**, *49*, 104005. [CrossRef]
18. França, W.T.; Barros, M.V.; Salvador, R.; de Francisco, A.C.; Moreira, M.T.; Piekarski, C.M. Integrating life cycle assessment and life cycle cost: A review of environmental-economic studies. *Int. J. Life Cycle Assess.* **2021**, *26*, 244–274. [CrossRef]
19. Schaltegger, S.; Synnestvedt, T. The link between "green" and economic success: Environmental management as the crucial trigger between environmental and economic performance. *J. Environ. Manag.* **2002**, *65*, 339–346. [CrossRef]
20. UN.ESCAP. Eco-efficiency Indicators: Measuring Resource-use Efficiency and the Impact of Economic Activities on the Environment. *Green. Econ. Growth Ser.* 2009. Available online: https://hdl.handle.net/20.500.12870/1598 (accessed on 13 February 2025).
21. Shanmugam, K.; Jansson, S.; Gadhamshetty, V.; Matsakas, L.; Rova, U.; Tysklind, M.; Christakopoulos, P.; Upadhyayula, V.K.K. Ecoefficiency of Thermal Insulation Sandwich Panels Based on Fly Ash Modified with Colloidal Mesoporous Silica. ACS Sustain. *Chem. Eng.* **2019**, *7*, 20000–20012. [CrossRef]
22. Pérez-García, A.; Víllora, A.G.; Pérez, G.G. Building's eco-efficiency improvements based on reinforced concretemultilayer structural panels. *Energy Build.* **2014**, *85*, 1–11. [CrossRef]
23. O'Hegarty, R.; Kinnane, O. Review of precast concrete sandwich panels and their innovations. *Constr. Build. Mater.* **2020**, *233*, 117145. [CrossRef]
24. Fonseca, T.J.F.; Parresol, B.R. A new model for cork weight estimation in Northern Portugal with methodology for construction of confidence intervals. *For. Ecol. Manag.* **2001**, *152*, 131–139. [CrossRef]
25. Lakreb, N.; Şen, U.; Toussaint, E.; Amziane, S.; Djakab, E.; Pereira, H. Physical properties and thermal conductivity of cork-based sandwich panels for building insulation. *Constr. Build. Mater.* **2023**, *368*, 130420. [CrossRef]
26. Lameiras, R.; Barros, J.; Valente, I.B.; Azenha, M. Development of sandwich panels combining fibre reinforced concrete layers and fibre reinforced polymer connectors. Part I: Conception and pull-out tests. *Compos. Struct.* **2013**, *105*, 446–459. [CrossRef]
27. Lameiras, R.; Barros, J.; Azenha, M.; Valente, I.B. Development of sandwich panels combining fibre reinforced concrete layers and fibre reinforced polymer connectors. Part II: Evaluation of mechanical behaviour. *Compos. Struct.* **2013**, *105*, 460–470. [CrossRef]
28. Fenollera, M.; Míguez, J.L.; Goicoechea, I.; Lorenzo, J. Experimental Study on Thermal Conductivity of Self-Compacting Concrete with Recycled Aggregate. *Materials* **2015**, *8*, 4457–4478. [CrossRef] [PubMed]
29. *ISO 14040:2006/Amd 1:2020*; Environmental management–Life cycle assessment–Principles and framework–Amendment 1. ISO: Geneva, Switzerland, 2020.
30. *ISO 14044:2006/Amd 2:2020*; Environmental management–Life cycle assessment–Requirements and guidelines–Amendment 2. ISO: Geneva, Switzerland, 2020.
31. Thomas, A.; Anya, V.; Johannes, H.; Linda, H.; Sigrid, B.-C. Ultra-lightweight foamed concrete for an automated facade application. *Mag. Concr. Res.* **2018**, *71*, 424–436. [CrossRef]
32. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *9*, 1218–1230. [CrossRef]
33. PRé Sustainability, B.V. Simapro Database Manual—Methods Library. 2020. Available online: https://simapro.com/wp-content/uploads/2022/07/DatabaseManualMethods.pdf (accessed on 13 February 2025).
34. *EPD EN 15804+A2/ISO 14025/ISO 21930*; Expanded Insulation Corkboard (ICB). Amorim Cork Insulation: Mozelos, Portugal, 2023.
35. *EPD-IES-0003101:002*; Recycled Aggregate Products. Argent Materials Inc.: Oakland, CA, USA, 2021.
36. *EN 15804:2012+A2:2019*; Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products. CEN: Brussels, Belgium, 2019.
37. European Comission. European Platform on LCA | EPLCA—EN15804. Available online: https://eplca.jrc.ec.europa.eu/LCDN/EN15804.html (accessed on 13 December 2024).
38. Kloepffer, W. Life cycle Sustainability Assessment of Products (with Comments by Helias A. Udo de Haes, p. 95). Int. *J. Life Cycle Assess.* **2008**, *13*, 89–95. [CrossRef]
39. Swarr, T.E.; Hunkeler, D.; Klöpffer, W.; Pesonen, H.-L.; Ciroth, A.; Brent, A.C.; Pagan, R. Environmental life-cycle costing: A code of practice. *Int. J. Life Cycle Assess.* **2011**, *16*, 389–391. [CrossRef]
40. *ISO 14051:2011*; Environmental management—Material flow cost accounting—General framework. ISO: Geneva, Switzerland, 2011.
41. Bierer, A.; Götze, U.; Meynerts, L.; Sygulla, R. Integrating life cycle costing and life cycle assessment using extended material flow cost accounting. *J. Clean. Prod.* **2015**, *108*, 1289–1301. [CrossRef]
42. *ISO 14051*; Manual on Material Flow Cost Accounting. Asian Productivity Organization: Tokyo, Japan, 2014.
43. EDP Comercial. Tarifários de Eletricidade e Gás Natural para Particulares. Available online: https://www.edp.pt/particulares/energia/tarifarios/ (accessed on 12 August 2022).
44. Agere. TARIFÁRIO 2023. Available online: https://agere.pt/wp-content/uploads/2023/01/TARIFARIO-AGERE-2023.pdf (accessed on 13 February 2025).

45. Haufler Composites GmbH & Co. KG, Haufler Composites—Online Store. Available online: https://www.compositeshop.de/xoshop/ (accessed on 12 August 2022).
46. Obras360 by Sotecnisol. Obras360 by Sotecnisol | Loja de Materiais de Construção e Energia. Available online: https://www.obras360.pt/ (accessed on 12 August 2022).
47. Coelho, A.; De Brito, J. Economic viability analysis of a construction and demolition waste recycling plant in Portugal—Part I: Location, materials, technology and economic analysis. *J. Clean. Prod.* **2013**, *39*, 338–352. [CrossRef]
48. Master Ferro. Master Ferro–Comércio de Produtos Siderúrgicos. Available online: https://www.masterferro.pt/pt (accessed on 12 August 2022).
49. Aercrete Technology AB. Aercrete FG-6TM—Aercrete. Available online: https://www.aercrete.se/en/aercrete-fg-6-2/ (accessed on 12 September 2022).
50. Chave Vertical—Máquinas & Ferramentas Profissionais. Betoneira Hidráulica Brh1200 Eléctrica C/PÁ SIRL'. Available online: https://chavevertical.com/produto/betoneira-hidraulica-brh1200-electrica-c-pa-sirl/ (accessed on 12 August 2022).
51. Davidnunuo. CHAPA PILAR 2500X500. Available online: https://www.davidnuno.com/(S(bshhtbtq5axggx4bf2ml0113))/artigo.aspx?code=19030305 (accessed on 12 August 2022).
52. Portugal, S. 2022–TABELA DE PREÇOS–CONSTRUÇÃO. Available online: https://www.almacla.pt/wp-content/uploads/2021/10/tabela-precos-sika.pdf (accessed on 12 August 2022).
53. Backstein Engineering GmbH. Moertelshop Online store. Available online: https://www.moertelshop.eu/ (accessed on 12 August 2022).
54. Armazéns Reis. Armazéns Reis—Online Store. Available online: https://www.armazensreis.pt/pt/ (accessed on 12 August 2022).
55. Maria Granel. Maria Granel—Online store. Available online: https://www.mariagranel.com/ (accessed on 12 August 2022).
56. CYPE Ingenieros, S.A. Gerador de preços para construção civil—Portugal. Available online: http://www.geradordeprecos.info (accessed on 12 August 2022).
57. Gabinete de Estratégia e Planeamento do Ministério do Trabalho Solidariedade e Segurança Social Estatísticas de Salários por Profissão na Construção—Janeiro 2021. 2021. Available online: www.gep.mtsss.gov.pt (accessed on 16 June 2022).
58. *ISO 14045*; Environmental management—Eco-efficiency assessment of product systems—Principles, requirements and guidelines. ISO: Geneva, Switzerland, 2012.
59. Burul, D.; Algesten, D. *Battery Electric Vs Diesel Driven*, SCINIA: Södertälje, Sweden, 2021.
60. Demertzi, M.; Sierra-Pérez, J.; Paulo, J.A.; Arroja, L.; Dias, A.C. Environmental performance of expanded cork slab and granules through life cycle assessment. *J. Clean. Prod.* **2017**, *145*, 294–302. [CrossRef]
61. Demertzi, M.; Paulo, J.A.; Arroja, L.; Dias, A.C. A carbon footprint simulation model for the cork oak sector. *Sci. Total Environ.* **2016**, *566–567*, 499–511. [CrossRef] [PubMed]
62. Silvestre, J.D.; Pargana, N.; De Brito, J.; Pinheiro, M.D.; Durão, V. Insulation Cork Boards—Environmental Life Cycle Assessment of an Organic Construction Material. *Materials* **2016**, *9*, 394. [CrossRef] [PubMed]
63. Rodrigo-Bravo, A.; Calderón, V.; Cuenca-Romero, L.A.; Arroyo, R.; Gutiérrez-González, S. Eco-efficiency and economic assessment of gypsum-based precast with polymeric waste: A case study. *Case Stud. Constr. Mater.* **2024**, *20*, e03052. [CrossRef]
64. Lévesque, J.; Perreault, V.; Mikhaylin, S. Eco-efficiency as a prioritization tool in the reduction of food waste in restaurants. *Sci. Total Environ.* **2024**, *927*, 171515. [CrossRef] [PubMed]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.