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Review

Sustainability of Building Materials: Embodied Energy and Embodied Carbon of Masonry

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Abstract: The growing attention to sustainability and life cycle issues by European and international policies has recently encouraged the adoption, in the construction sector, of environmental labels able to quantify the impacts on environment associated with the fabrication of several building materials, e.g., their embodied energy and carbon. Within this framework, since walls represent a large percentage of building mass and therefore of embodied impacts, this article collects and analyzes nearly 180 Environmental Products Declarations (EPDs) of wall construction products such as masonry blocks and concrete panels. The data related to the primary energy (renewable and non-renewable) and the global warming potential extracted from the EPDs were compared firstly at the block level (choosing 1 kg as functional unit), enabling designers and manufacturers to understand and reduce the impacts from wall products at the early design stage. As the design progresses, it is therefore necessary to evaluate the environmental impacts related to the entire wall system. For this purpose, this paper proposes a further investigation on some simple wall options having similar thermal performance and superficial mass (the functional unit chosen in this case was equal to 1 m^2 with $R \approx 5\ m^2K/W$, $Ms \approx 260\ kg/m^2$). The outcomes showed how the durability of the materials and the potential of disassembly of the wall stratigraphies can play a crucial role in reducing the environmental impact. This paper provides a methodological reference both for manufacturers to reduce impacts and for designers committed to the application of environmental labeling in the design process since they will now be able to compare their products with others.

Keywords: life cycle assessment (LCA); embodied energy; embodied carbon; environmental product declarations (EPD); masonry materials; sustainable buildings; early design stage

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1. Introduction

To address the challenges of climate change, the construction sector has traditionally focused on reducing carbon emissions from operational energy consumptions [1,2]. However, since buildings are becoming more and more energy efficient (and electricity generation has decarbonized), the operating energy and carbon of new buildings has already dropped significantly [3–5]. This means that embodied carbon can represent a greater part in the entire life cycle than in the past, e.g., up to 40–70% of the whole life cycle carbon in a new building [6–9].

Striving to reduce embodied impacts requires an increase in the renewable energy content of construction materials [10,11] as well as a transition from linear-based models to circular ones [12,13]. This is particularly important since the construction industry requires vast amounts of resources and accounts for about 50% of all extracted minerals and materials [14]: the total greenhouse gas emissions from materials extraction, manufacturing of construction products, and construction and renovation of buildings can account for

5–12% of the total national GHG emissions [14]. Moreover, the production of some building materials, such as bricks and concrete, is highly energy intensive and consequently, in case of fossil-based production chains, also responsible for a vast amount of greenhouse gas emissions [15,16].

Increasing energy efficiency in buildings, enhancing circular economy strategies, and reducing the carbon footprint of construction materials are some of the key strategies to achieve the 2030 EU targets [14,17]. Different policy recommendations and directives have already been published by the EU, aiming at reducing the environmental impact of the construction sector: the Energy Performance of Buildings Directive, the Energy Efficiency Directive, the Waste Management Directive, the Green Product Procurement Directive, the Ecodesign Directive, and the Taxonomy Directive are only some examples of the commitment of the Commission on this topic. Inevitably, the effort involves the analysis of all the life cycle stages of buildings and of their components. Level(s) [18], that is the new EU framework for the evaluation of sustainable buildings, adopts such a life-cycle-based thinking and circular approach to guide the construction sector to environmental sustainability goals.

The different amounts of embodied and operating carbon in the total life cycle carbon of buildings may vary considerably depending on the type and function of the building [19–22], as well as factors including location, climate, fuel type used, orientation of building, mass of building, construction nature, etc. [23–25]. Many authors have demonstrated that some building parts (foundation, columns, floor slabs, and envelope) provide the highest opportunities to reduce environmental impacts, and thus should be the focus of embodied carbon reductions [19,26,27]. The envelope is a dominant building element for both embodied and operational energy [28] and, especially in tall buildings, walls make up the greatest area of the building envelope and hence make the greatest contribution to embodied energy [29].

Different typologies of commercial products can be found for the construction of building walls: Figure 1 shows a classification based on:

(a) the construction technique used for the assembly of the wall;
(b) the kind of the element characterizing the product.

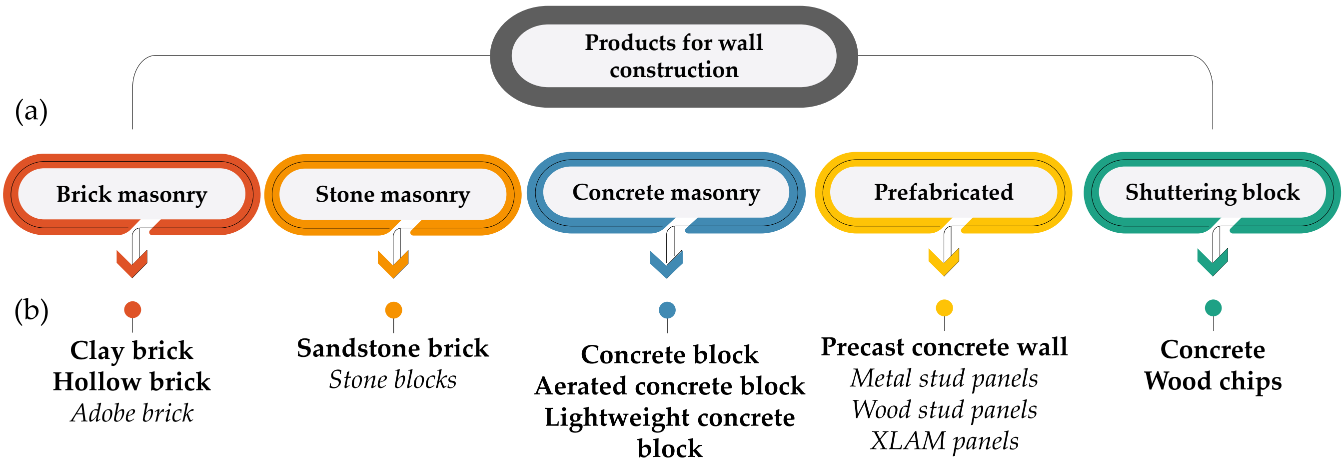


Figure 1. Classification of products for wall construction (those in italic are not considered in this study). (**a**) Construction technique, (**b**) construction element/product.

It was possible to identify five main categories of products: brick masonry, stone masonry, concrete masonry, prefabricated walls, and shuttering blocks in concrete or wood chips. The identified subcategories are mainly based on the kind of the material characterizing the construction element and on its mechanical and density properties.

Masonry can be done with natural stones or artificial elements (such as bricks or concrete blocks); alternatively, different kinds of prefabricated panels can be considered for the construction of walls. For the latter, in this study, only precast concrete panels were selected, since lightweight solutions, such as metal stud or wood-based panels, are technologies which are hardly comparable with masonry.

Masonry walls consist of modular building blocks bonded together with mortar at the construction site to form walls that are durable, fire-resistant, and structurally efficient in compression [30]. They can be both bearing and non-bearing walls of variable thickness, depending on compression resistance values and the reinforcing system adopted. Clay-bricks are one of the most ancient building materials, tracked to the ancient Egyptians and Mesopotamians, and they are still largely used both in modern buildings and in works of repairment of historic buildings with load-bearing wall structures. Already in Roman times, production took place in ante litteram factories, called *figlinae* or *figline*, located near clay quarries and rivers, thus facilitating the transport of materials. Bricks derived from the firing of clay blend contain different percentages of sand, iron oxides, and calcium carbonate. The dough has a plastic consistency and, before the firing, it can be shaped to create different kinds of products including bricks, hollow bricks, brick blocks, tiles, etc.

Precast concrete wall panels, on the other hand, are manufactured in a plant off-site, later to be transported to the construction site and finally assembled in place as rigid components with cranes. The off-site production allows to have a consistent quality in strength, durability, and aesthetics [30].

Another solution is the use of disposable formworks that can be made of a mixture of different materials (e.g., wood chips in a concrete matrix). These disposable formworks, particularly if they are filled with concrete and steel rebars, can have similar mechanical characteristics and functions to the ones of masonry. If the information about the filling of the disposable formwork was not available in the environmental declaration, we decided not to include it as data to be considered in this study.

From the designer's point of view, there are several criteria for choosing the type of masonry, keeping in mind that mechanical strength still remains the first requirement for choosing a product as it guarantees the safety and stability of the masonry; lately, other requirements related to the environment, energy, and technology have also become important to face the increasingly stringent regulatory constraints. Hence, the project must be approached in a complex and integrated way to meet all demands. Thanks to the information made available by manufacturers, designers can easily calculate and optimize the thermal characteristics of masonry, while it is much rarer to have data on the environmental performance of a particular building material.

To the best of the authors' knowledge, few papers have systematically dealt with the embodied energy and carbon of construction blocks. This paper aims at assessing the environmental performance of different wall construction technologies, analyzing nearly 180 datasets (based on EPDs) derived mainly from the European construction market. Moreover, this study is also addressed to designers and developers to compare the environmental impacts with the main physical and technological requirements of a construction system. For that purpose, a case study has been considered.

The work is structured as follows: Section 2 provides a state of the art about the environmental studies on construction blocks, focusing particularly on bricks; Section 3 describes the adopted methodology; Section 4 presents the results and a discussion on the most important findings; Section 5 illustrates a case study; and Section 6 concludes the study.

2. State of the Art

2.1. Standards Related to Building Products

The European standards on the requirements of building materials are primarily consistent with the CE marking (logo CE) for products and goods within the European market (EU No. 305/2011 [31]). The CE label identifies the general requirements and performances to be met in terms of mechanical resistance and stability, safety in case of fire, hygiene, noise protection, energy saving, and sustainable use of natural resources for the construction of buildings.

Hence, it is essential that the performance of building materials meets both environmental demands and requirements for safety and structural functionality.

Since the year 2000, the International Organization for Standardization (ISO) has published standards for environmental labelling practices within the ISO 14000 framework. ISO proposed three categories of environmental labels depending on the specific aspects and the required procedures to obtain the declaration: type I in ISO 14024; type II in ISO 14021; and type III in ISO 14025. Concerning type III labels, at the start of January 2022, there were over 12,000 Verified Environmental Product Declarations (EPDs) to EN 15804 for construction products registered globally [32].

Environmental Product Declarations (EPDs) provide a common way of declaring the environmental impacts related to the life cycle of a product through the life cycle assessment (LCA).

EPDs for construction products in Europe use the European standard (EN 15804) or specific product category rules (PCR) to ensure that information is provided using the same LCA rules with the same environmental indicators. The EPD should always be independently verified by an expert whose expertise is familiar with the product category.

Furthermore, there are standards related to other specific requirements and performances that different types of masonry must satisfy (e.g., EN 711 series). Hence, designers must make sure that the masonry guarantees minimum mechanical and thermo-physical values, considering also technological aspects such as dimensions, weight, and drilling percentages for the correct use of the building material.

2.2. Literature Review on Envelope Materials

An increasing interest in the evaluation of the embodied impacts of buildings construction elements was argued from a review of literature studies. Different authors [33,34] have already proposed a review of the embodied energy and GWP of insulating materials considering EPD data and recalculating the impacts after the definition of a uniform functional unit able to normalize the operational energy performance of these materials. Asdrubali et al. [35] reported a data analysis about the same EPD impact categories for windows; Rasmusssen et al. [36] proposed a review of EPD data of structural wood products. The aim of the works previously cited was to define some reference values starting from the analysis of EPD data and to evaluate the main sources of variability of data in the declarations.

The literature about the environmental impact of bricks and construction blocks usually makes use of LCA as a support for an objective evaluation. The purposes of LCA application in this field can be listed as follows:

- Evaluation of the stages with the highest environmental impacts in the entire life cycle of the considered material.
- Proposal of potential improvements of the environmental performances through the entire life cycle.

The literature focuses on production stages because the operational energy of construction blocks is difficult to determine due to the many different operational scenarios.

As far as the embodied impacts, different studies have already shown that brick production is an energy-intensive process and that most of the impacts are linked to the energy use at the fabrication site [10,37]. The two main impacting processes are the firing and the drying that together can represent 87% of the total energy employed in the manufacturing process [38].

The firing of the raw material, which occurs at high temperatures (800–2000 °C) and with direct flame, is usually the most impacting process in the fabrication of bricks [39,40], in the stages A1–A3 according to the PCR (Table 1) [41]. According to Bribián et al. [39], this stage is responsible for 80% of the primary energy consumption at the production plant. The energy mix or fuel employed at the fabrication site strongly influences the overall environmental impact with a generally high amount of CO_2, SO_2, and NO_x emissions released into the atmosphere, especially in case of fossil or low-grade fuel: the resulting environmental impacts are linked to climate change, acidification, photochemical oxidation, and eutrophication. According to Koroneos and Dompros [10], if pet-coke is used as fuel in the fabrication process, acidification accounts for more than 50% of the total ecopoints when using the Eco Indicator 95 methodology [42]; this is due to the high sulfur content in the fuel used, which results in acidification at most. The industrial brick ovens are fed by natural gas in more than 90% of cases [43] and, considering the energy intensity of the process, the use of renewable energy sources is unlikely. The use of petroleum coke in place of natural gas further worsens the environmental profile of the brick production process [40]. Biomass is a competitive alternative compared with natural gas, but it requires large storage spaces and causes high amounts of particle emissions: therefore, the use of natural gas in the ceramic industry is still considered the best available solution [43]. Finally, considering the installation of cogeneration units, Bribián et al. [39] calculated a 10% reduction in the primary power required by the factory.

Table 1. Complete phases of the LCA analysis [41]. M = mandatory; O = optional.

LCA Phases																			
A1–A3			A4–A5		B1–B7							C1–C4				D			
Product Stage			Construction Stage		Use							End of Life				Benefits and Loads Beyond the System Boundary			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D			
M	M	M	O	O	O	O	O	O	O	O	O	M	M	M	M	M	M	M	O
Raw Materials Supply	Transport	Manufacturing	Transport	Construction	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational Energy	Operational Water	De-Construction/Demolition	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling	Exported Energy

The drying process can be performed using heat recovered from the ovens; this solution is able to significantly reduce the impact connected to the above-mentioned process. The substitution of natural gas with biomass as the fuel used in the drying process can reduce some of the environmental burdens linked to the brick production phase (abiotic depletion, global warming, ozone layer depletion, and non-renewable fossil energy) but it involves high investment costs for the reorganization of production spaces [40,43].

Certainly, the production of adobe bricks is more environmentally friendly since firing is excluded and drying is performed directly under the sun. Christoforou et al. [44] reported an embodied energy value between 0.033 and 0.17 MJ/kg of adobe bricks and an embodied carbon between 0.0017 and 0.0129 kg CO_2eq/kg; these values are much lower than the ones displayed by traditional fired bricks having an embodied energy of 1.2–4.1 MJ/kg and an embodied carbon of about 0.24 kg CO_2eq/kg. However, the performance and maintenance requirement of the two products during the operational use are very different and a comprehensive evaluation is very difficult. Other authors [45] have also evaluated the omission of the firing through different stabilizing processes using cement and aggregates. These kinds of production techniques should be accurately evaluated from an environmental point of view since the production of these additives, especially in the case of Portland cement, entails several environmental challenges.

The use of additives or fossil aggregates in the dough can significantly increase the environmental footprint of the final product both in the production stage and in the end-of-life one. In some cases, however, the use of additives can increase the thermal resistance of the material resulting in an overall environmental benefit due to the reduction of energy consumption of buildings during the phase of use [46,47]. The substitution with additives of natural origin could result in a significant improvement for the embodied components [48]. Bories et al. [49], for example, manufactured, at a laboratory scale, some clay bricks incorporating bio-based, pore-forming agents and evaluated their resulting environmental performances through LCA methods; the addition of additives increases the porosity of 7.2% and reduces the thermal conductivity of 7%. A decrease of about 15–20% in all the considered embodied impact categories was observed in comparison with the scenario without poring agents but a collapse of the mechanical performances was the resulting effect. Similar results confirming the environmental advantages of organic waste addition in brick clay dough were also found by Lozano-Miralles et al. [50]. Beal et al. [51] showed that the addition of vermiculite or sawdust in the brick matrix (about 25% in weight) increases porosity and reduces the thermal conductivity of the final material but decreases compression strength that can be lowered to about 4 MPa (in case of vermiculite) or 2 MPa (in case of sawdust) in comparison to the 22 MPa obtained from the base clay brick.

Ramos Huarachi et al. [45] proposed a review of literature about the environmental impacts of traditional and alternative bricks with organic (mainly agricultural waste) or inorganic additives (construction and demolition waste). These alternative solutions, which involve the use of recovery or reused waste materials, have shown to be the right pathway to make the brick industry a more sustainable one. The percentage of recovered material that can enter the fabrication process and the related consequences on the mechanical performances of bricks or construction blocks is still under study. Table 2 reports some literature references about the mechanical and thermophysical properties of bricks with additives, showing how these components can have a significant influence on the operational performance.

Table 2. Characteristics of bricks with additives.

Additive/Reference	Density Range [kg/m^3]	Additive [% of Weight]	Compression (c)/ Bending (b) Resistance [MPa]	Thermal Conductivity [W/mK]
Reference (no additives) [51]	1660	-	22 (c)	0.29
Vermiculite [51]	1030	25	4 (c)	0.24
Wood ash [51]	1430	25	20 (c)	0.32
Sawdust [51]	839	25	2 (c)	0.16
Reference (no additives) [49]	1900	-	10.4 (b)	0.57
Wheat straw [49]	1860	1	10.0 (b)	0.53
Olive stone flour [49]	1790	2	6.5 (b)	0.46
Glycerol carbonate [49]	1830	2	7.0 (b)	0.53
Dimethyl carbonate [49]	1880	2	7.5 (b)	0.47

However, the impact of use stage (B1–B4 modules, Table 1) is neglected by the EPDs, and this effect is very difficult to quantify objectively through these certifications. Almeida et al. [40] proposed a methodology to establish first PCR for the development of a "cradle to grave" EPD specific for ceramic bricks, so still neglecting the contribution of operational stages. The functional unit (FU) suggested by the PCR is 1 ton or 1 m^3 for the "cradle to gate" studies and 1 m^2 of brick masonry in some "cradle to grave" analysis. In some cases, the results also make reference to different products of the same manufacturer and factory.

Regarding concrete, numerous literature studies [52–54] have emphasized the huge potential for reducing environmental impacts by replacing some of its components with by-products or recycled materials; cement, for instance, is well-known as an energy and carbon-intensive material and its substitution with other compounds can significantly improve the environmental profile of concrete products [55,56]. Manjunatha et al. [57] showed that the integration of industrial waste by-product materials, such as PVC powder and ground-granulated blast furnace slag (15–20% in weight), can help to improve the environmental performance of concrete materials as well as their structural and durability properties.

3. Materials and Methods

This work is developed starting with the recollection of available EPDs about construction blocks. The selected EPDs are all realized in accordance with EN 15804 [58] or its update in 2019 [59] that extended the life cycle impacts to be declared in the final report with the inclusion of end-of-life stage ones. The data extracted from the EPDs were compared and the outputs developed in this paper can be a useful reference for designers and manufacturers to interpret, understand, and reduce the impacts from wall construction blocks without compromising performance requirements. A comparative assertion on a population of alternatives, that is one of the scopes of this work, is in fact essential for early-stage designers working on building sustainability as underlined in other literature studies [54,60,61].

A cradle-to-gate approach was adopted because the largest part of the EPDs is based on EN1584 (2012) that does not consider the end-of-life of the products; stages A1–A3 of Table 1 were considered and, in particular, the extraction of the raw material (stage A1), the transportation to the manufacturing site (stage A2), and the manufacturing process itself, including the packaging of the final product (stage A3). To compare all the products, stage A5 was also considered for the shuttering blocks that required infilled reinforced concrete as a mandatory complementary material for laying the wall element. Stage A4, which includes the impacts linked to the transportation of the final product to the construction site, was instead always neglected because the related impacts depend on factors that are exogenous to the scopes of this study.

According to the sub-PCR published by the International EPD (2020) "bricks, blocks, tiles, flagstone of clay and siliceous earths (construction product)", the environmental impacts of the Module B (product use), which covers environmental aspects and impacts arising from the product during its normal use, are not relevant for the product category. The only exception is linked to the inclusion of carbonation of concrete that is associated with stage B1 and that represents a negative contribution to the GWP indicator. The effect of carbonation is, however, negligible in comparison with the GWP generated during the cradle-to-gate stages and it is not considered in this study. No data related to stages B2–B5 were found in the EPDs selected because, generally, the construction blocks do not require any maintenance, repair, or replacement during their reference service life. Stages B6–B7 are considered not relevant by PCR, and they are always discarded. Concerning the end-of-life modules (C1–C4), they are mandatory and thus taken into account by the EPDs based on the EN 15804:2012 + A2:2019, whereas they were not always included in the others [62]. For this reason, the end-of-life burdens are not included in this work.

The life cycle impacts generally most considered in the literature and which were extracted from the EPDs for this study are:

- Global Warming Potential (GWP): it is the indicator that evaluates the impact on climate change in kg CO_2eq. The time horizon that is usually used is equal to 100 years to account for the degradation of some gases in the atmosphere. Biogenic carbon removals are also considered as a negative contribution if the EN 15804 is taken as a reference.
- Non-Renewable Primary Energy (PENR): it expresses the amount of non-renewable energy (in MJ) both as input energy and input materials necessary in every life cycle stage of the product. It is usually calculated employing the single issues indicator: cumulative energy demand [63].
- Renewable Primary Energy (PER): it represents the renewable energy use (in MJ) characterizing every life cycle stage of the product input as energy or materials flow. As for PENR, it is determined using the cumulative energy demand method.

The embodied energy was considered to be the sum of the PENR and PER associated with stages A1 through A3. Similarly, embodied carbon is defined as the GWP of the products tested for stages A1 to A3 and excluding biogenic carbon.

The right choice of a uniform FU is fundamental to achieve a comparison of the environmental performances of different kinds of products. This study adopted the kg as the reference unit to compare different construction blocks; if the considered EPDs selected a different FU, some simple conversions were made. In particular, the FUs that are often adopted by the EPDs as an alternative to kg are tons, cubic meters, and square meters of wall. The density of the material, which is always declared, allows the conversion between the various units.

However, when construction blocks are integrated into wall assemblies, this FU is not able to take into account the different thermal behaviors that different materials provide, both in terms of resistance and in terms of attenuation or phase shift [64]. To tackle this issue, in Section 5, we demonstrated a comparison of different wall options that were proposed, changing the thickness of the construction blocks and of the insulation layer they are composed of. Even if this hypothesis is not always realistic, particularly for some construction blocks that are produced with a standard size, in this way, the wall models selected have very similar operational performances (e.g., in terms of thermal behavior).

For this case study, we considered as a FU 1 m^2 of an external infill wall without a load-bearing function, having a thermal resistance of about 5 m^2K/W and a superficial mass close to 260 kg/m^2.

3.1. Origin of the Dataset

The EPDs were retrieved from free online databases, and they were all developed by European Program Operators and in compliance with the EN 15804 [58]. The selected Program Operators and consulted databases are described in Table 3.

Table 3. Databases consulted for the present study [41].

Database	Abbreviation	Description	N. EPDs
Baubook [65]	Bau	It is a European administrator of EPD and LCA data contained within the online tool Ecosoft that was supported by the Austrian government.	55
EPD Danmark [66]	Den	It is a database containing a lot of EPDs developed in accordance with EN 15804 and verified by independent third-party verifiers.	16
EPD international AB [67]	Env	It is a collection of EPDs managed by the European administrator named International EPD System, a Sweden-settled company; the database includes the environmental declarations of a wide range of products manufactured in different countries.	16
EPD Italy [68]	Ita	It is the Italian EPD database that has been developed since 2016; the declarations refer to a lot of construction products of Italian manufacturers.	26
EPD Norge [69]	Nor	It is an EPD database managed by the "The Norwegian EPD Foundation", a non-profit organization founded in 2002.	15
IBU [70]	Ibu	It is a German association that appoints EPD verifiers and manages an online database that makes public the information contained in the declarations in XML format.	28
VUPS [71]	Vups	It is a Czech Accreditation Institute that verify EPDs.	14
BRE GLOBAL [72]	Bre	It is a center for building science settled in the United Kingdom that develops EPDs.	3
OCL [73]	Ocl	It is a website managed by a Finnish group that gathers many verified data from public and private sources.	2
OEKOBAUDAT [74]	Oek	It is the mandatory database for the Assessment System for Sustainable Building, handled by the German Federal Ministry of the Interior, Building and Community.	2

Table 3. *Cont.*

Database	Abbreviation	Description	N. EPDs
AENOR [75]	Aen	It is a founding member of ECO Platform, the European Association of Environmental Declarations Verification Programmes.	1
EPD TURKEY [76]	Tur	It is a fully aligned regional program of The International EPD System run by the Turkish Centre for Sustainable Production Research and Design–SÜRATAM.	1

Figure 2 shows the percentage of each program operator with respect to the total analyzed data.

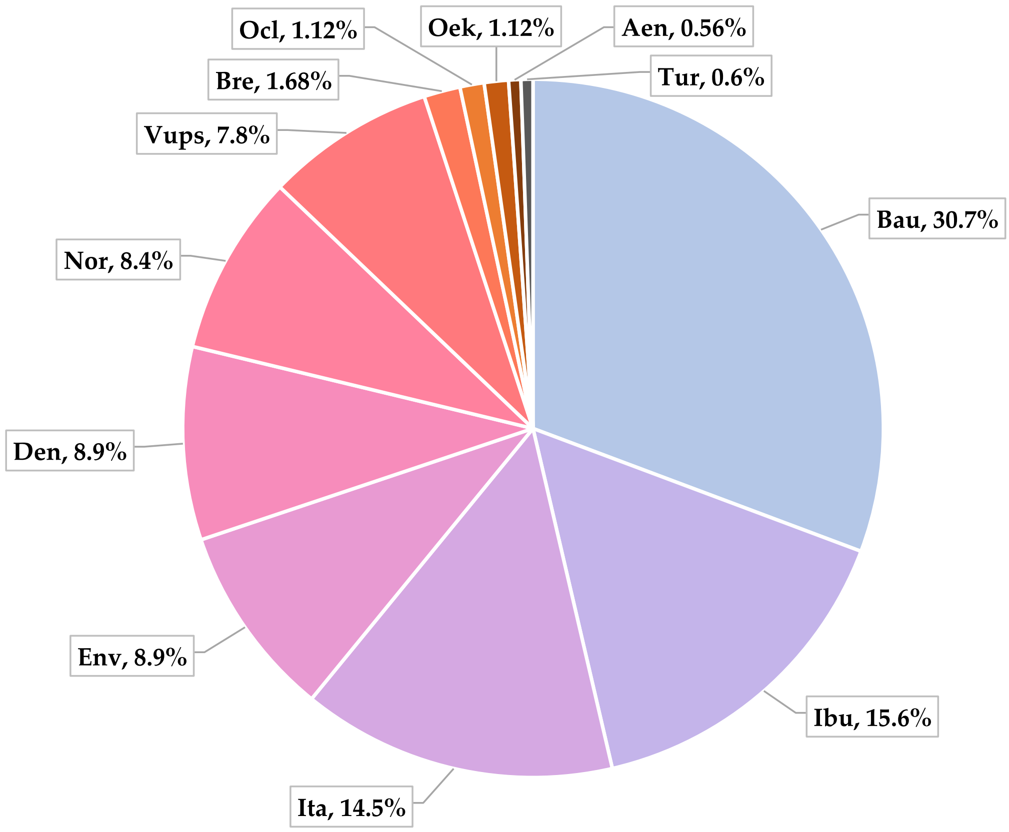


Figure 2. Share of the various program operators in the total amount of analyzed data.

The Baubook (30.7%), IBU (15.6%), EPD Italy (14.5%), Environdec (8.9%), and EPD Denmark (8.9%) databases represent the major data sources, making up approximately 78.6% of the whole sample.

By also adding the contributions of the EPD Norge (8.4%) and VUPS (7.8%) databases, almost all of the sample (94.8%) is covered; the remaining contribution is offered by minor program operators.

3.2. Description of the Dataset

The collected data are composed of a total number of 179 EPDs of wall building materials, from which the relative impact categories of PENR, PER, and GWP have been assessed. As can be observed from Figure 3, the collected wall materials are mainly made of concrete blocks (20% with 36 EPDs), prefabricated panels (12%), bricks (12%), and, above all, hollow bricks (44% with 78 EPDs); a lower amount of data are available for sandstone bricks (3%) and wood-chips concrete shuttering blocks (9%).

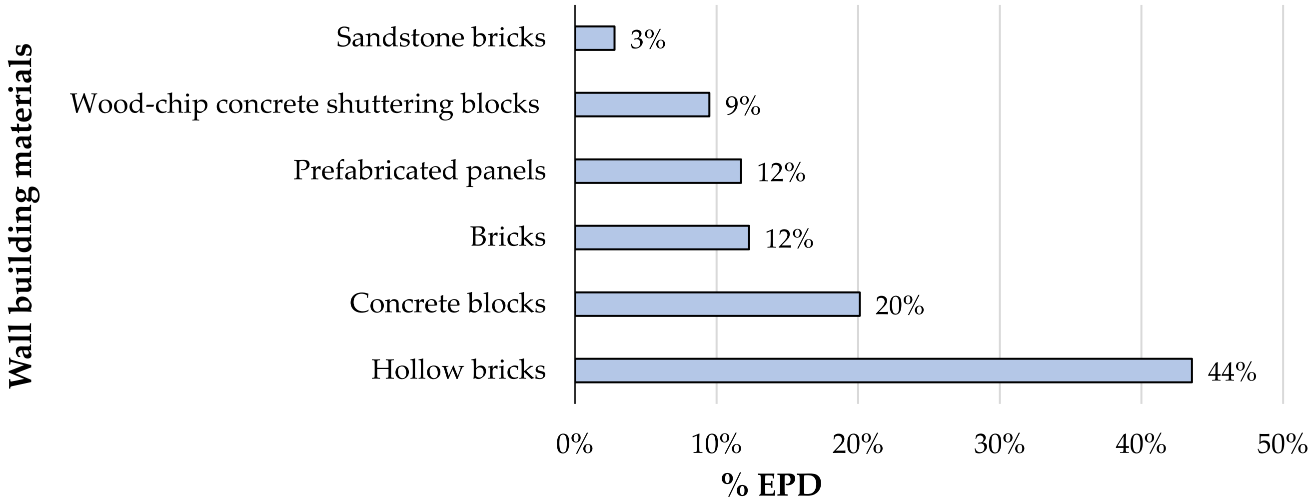


Figure 3. Percentage distribution of the various products of the sample.

In addition, Figure 4 shows the wall building materials considered; for each of them, Table 4 reports the total number of values collected from the different sources and for each impact indicator (PENR, PER, or GWP).

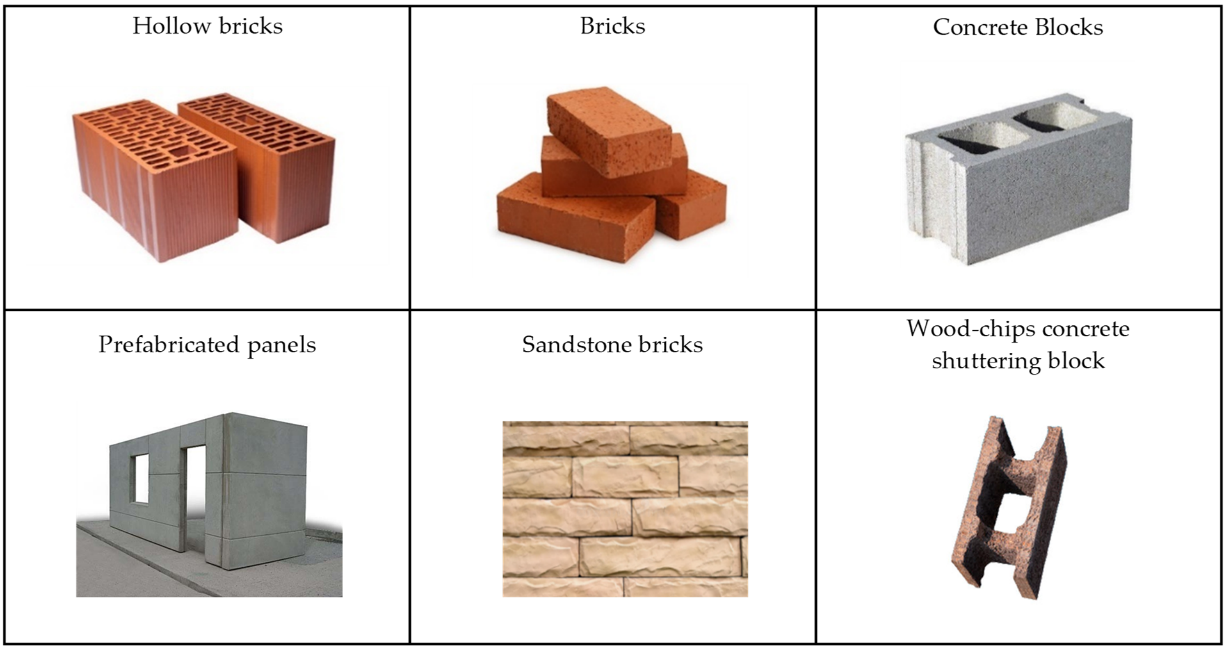


Figure 4. Typologies of construction blocks considered.

Table 4. Wall blocks and total number of values collected for each impact indicator.

Wall Building Materials	Values for each Impact Indicator and Corresponding Source	Total n.
Hollow bricks	51 Bau; 14 Vups; 9 Ita; 4 Ibu	78
Bricks	16 Den; 2 Ocl; 2 Bre; 1 Aen; 1 Ibu	22
Concrete Blocks	15 Ibu; 11 Nor; 4 Bau; 1 Bre; 1 Oek; 3Env; 1Tur	36
Prefabricated panels	13 Env; 4 Ibu; 4 Nor	21
Sandstone bricks	4 Ibu; 1 Oek	5
Wood-chips concrete shuttering blocks	17 Ita	17
All types of wall	All	179

4. Results and Discussion

The range of density, compressive resistance, and service life was identified for each product category, taking the information from the collected data sample. In particular, from Table 5, it is possible to observe the corresponding maximum and minimum values.

Table 5. Maximum and minimum value of the parameters characterizing the different products.

Wall Building Material	Density Range [kg/m^3]	Compression Resistance [MPa]	Service Life [Years]
Bricks	600–2300	4.0–60	150 *
Hollow bricks	400–1604	7.5–60	150 *
Concrete Blocks	115–2245	0.9–48	100 *
Prefabricated panels	550–2377	2.8–45	75 *
Sandstone bricks	1450–2570	10–60	50 *
Wood-chips shuttering blocks	550	-	100 *

* Value of the useful life used to subsequently normalize the values of PENR, PER, and GWP.

The density values range from a minimum of 400 kg/m^3 to a maximum of 2570 kg/m^3, except for concrete blocks, which show a minimum density value of 115 kg/m^3; the compression resistance reaches the maximum value of 60 MPa while the service life varies between 50 and 150 years for each type of product, except for prefabricated panels which display much lower values, with a service life between 50 and 100 years.

Subsequently, the study focused on the analysis and comparison of PENR, PER, and GWP values for 1 kg of the different products focusing on the A1–A3 life cycle stages (A1–A3 and A5 for the shuttering blocks). Table 6 illustrates the minimum and maximum of the respective impact categories.

Table 6. Minimum and maximum values of PENR, PER, and GWP of the different products. Stages A1–A3 were considered for all the products analyzed. In addition, if data were available, stage A5 was considered for the shuttering block.

Wall Building Material	PENR [MJ/kg]		PER [MJ/kg]		GWP [kgCO_2eq/kg]	
	Min.	Max.	Min.	Max.	Min.	Max.
Bricks	0.30	4.03	0.06	5.99	0.01	0.33
Hollow bricks	0.07	3.51	0.06	6.96	0.04	0.35
Concrete blocks	0.37	2.82	0.01	1.72	0.08	0.40
Prefabricated panels	0.48	5.51	0.10	0.78	0.16	0.44
Sandstone bricks	0.77	1.43	0.02	1.18	0.06	0.21
Wood-chips shuttering blocks	1.14 *	5.02 **	1.61 *	6.58 **	0.15 *	0.65 **

* Values calculated without considering phase A5; ** Values calculated considering phase A5.

Figure 5 offers an immediate view of the average values of PENR, PER, and GWP recorded for each material considered. It shows that the maximum average PENR value is recorded for the bricks (2.56 MJ/kg) and the hollow bricks (2.38 MJ/kg), while the lowest values are assumed by sandstone bricks (0.97 MJ/kg). On the other hand, as regards the average values collected for the PER, the maximum one was recorded for the wood-chips concrete shuttering blocks (3.14 MJ/kg), while the lowest values were obtained by sandstone bricks (0.35 MJ/kg) and prefabricated panels (0.38 MJ/kg). Furthermore, from the figure, it can be seen that the average values of PENR exceed those of PER for all the different materials with the exception of the wood-chips concrete shuttering blocks, for which the highest average values of PER are recorded. In fact, the average values of PER and PENR assumed by the wood-chips shuttering blocks are 3.14 MJ/kg (PER) and 2.05 MJ/kg (PENR).

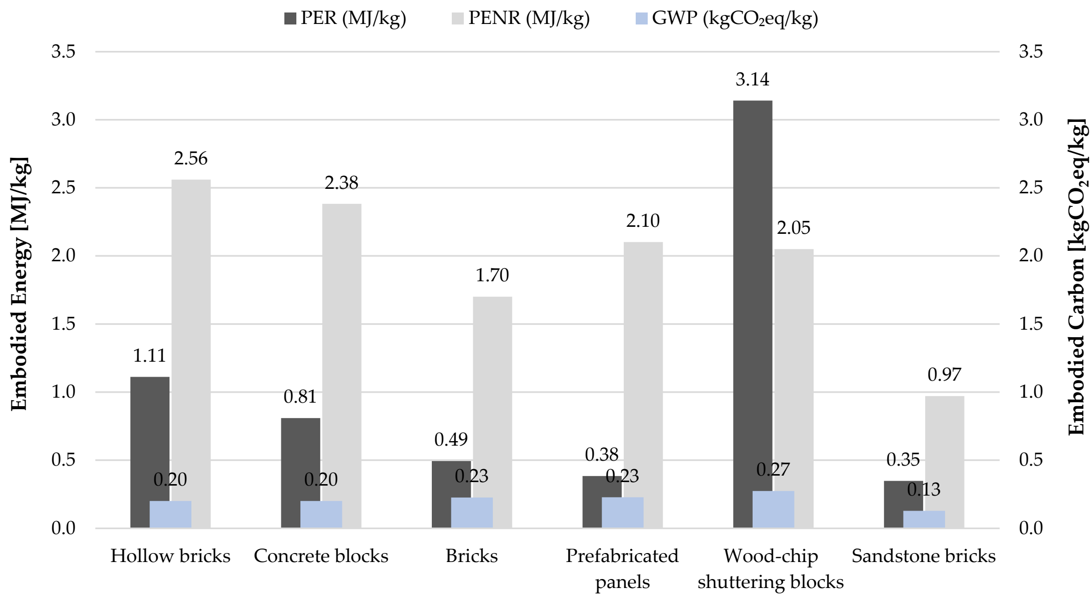
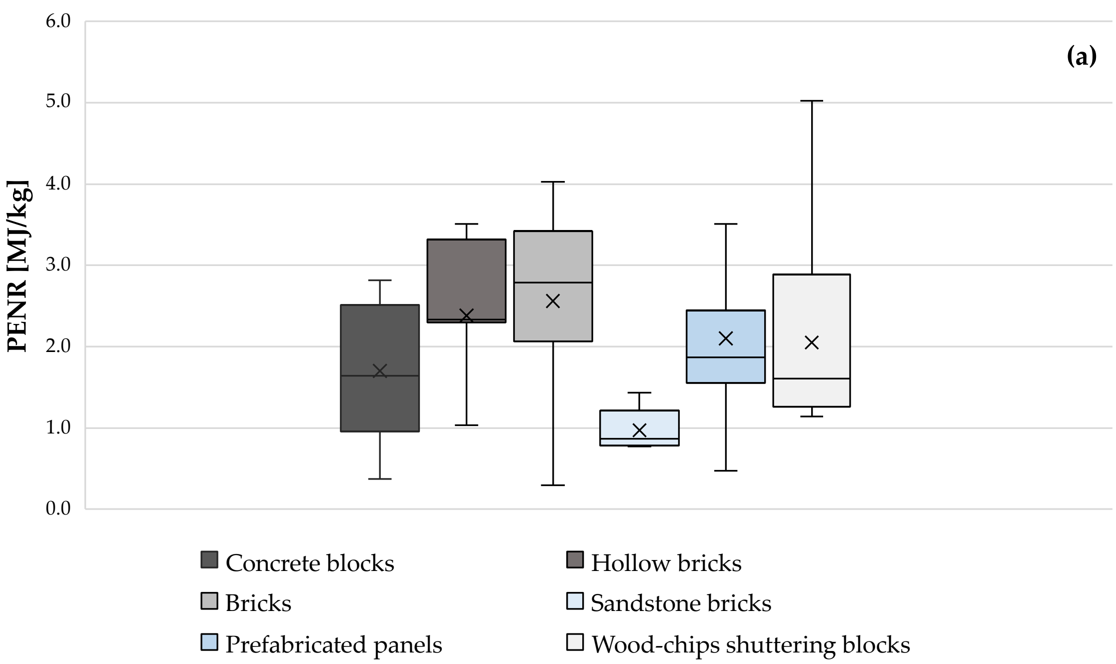


Figure 5. Average values of PENR, PER, and GWP for the different products.

Analyzing the average GWP values obtained for each type of material (Figure 5), it can be observed that the lowest value is assumed by the sandstone bricks (0.13 kgCO_2eq/kg); the highest value is recorded for the wood-chips shuttering blocks (0.27 kgCO_2eq/kg), followed by concrete blocks and prefabricated panels (0.23 kgCO_2eq/kg), while the lowest average values are displayed for bricks and hollow bricks (0.20 kgCO_2eq/kg).

Figure 6 summarizes in graphic form the embodied impacts of the different products: (a) PENR, (b) PER, (c) GWP. From the graphs shown in Figure 6, it emerges that the wood-chips shuttering blocks, characterized by average values of PENR, PER, and GWP respectively equal to 2.05 MJ/kg (PENR), 3.14 MJ/kg (PER), and 0.27 kgCO_2eq/kg (GWP), being less common in the market and with different categorization of blocks, have the highest variability. Their incorporated impacts are in fact included between 1.14 MJ/kg and 5.02 MJ/kg for PENR, between 1.61 MJ/kg and 6.58 MJ/kg for PER, and finally between 0.15 kgCO_2eq/kg and 0.65 kgCO_2eq/kg for GWP.



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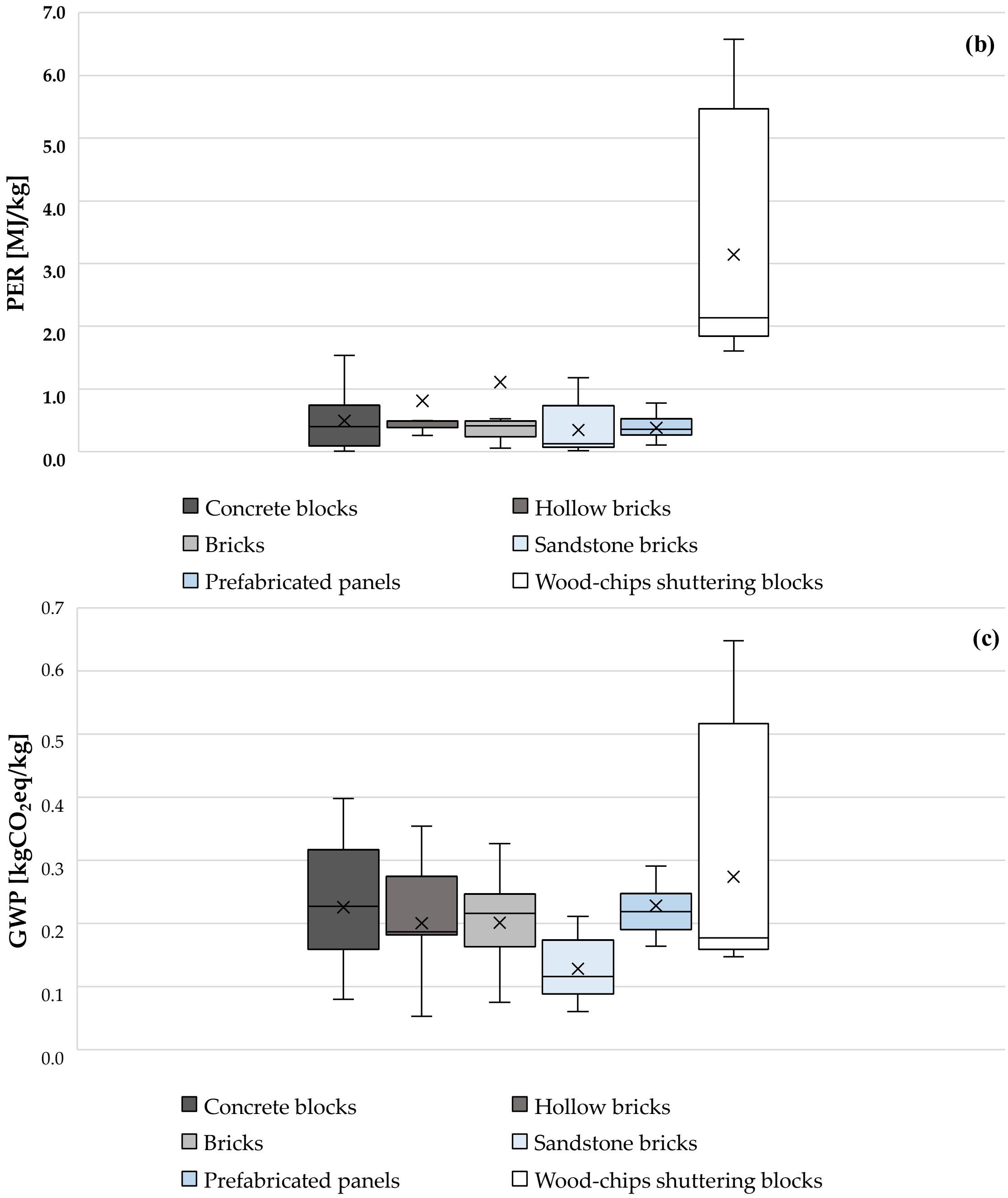

Figure 6. Embodied impacts of different products: (**a**) PENR, (**b**) PER, (**c**) GWP. Whiskers: maximum and minimum value; box: median of 1st, 2nd and 3rd quartile; ×: mean of the sample.

On the other hand, sandstone bricks, which distinguish themselves from other wall materials by their standard manufacturing technique, have limited variations. The PENR in fact oscillates between 0.770 and 1.4303 MJ/kg, the PER between 0.020 MJ/kg and 1.1803 MJ/kg, while the GWP from 0.0600 $kgCO_2eq/kg$ to 0.2100 $kgCO_2eq/kg$.

Instead, with regard to prefabricated panels, it is deduced that the use of different types of concrete can significantly influence the values of the respective incorporated impacts, whose values for the PENR range between 0.48 MJ/kg and 5.5 MJ/kg, for the PER between 0.104 MJ/kg and 0.779 $kgCO_2eq/kg$, and finally for the GWP between 0.1600 $kgCO_2eq/kg$ and 0.4400 $kgCO_2eq/kg$.

Other interesting considerations can be made by relating the environmental impacts and the service life of the products. Indeed, the prefabricated panels have an average impact in terms of GWP of 0.23 $kgCO_2eq/kg$ with an average service life of 75 years, while the bricks have a GWP of 0.20 $kgCO_2eq/kg$ with a service life of 150 years. Tables 7 and 8 show the previous values normalized for the respective average service life of the different products considered.

Table 7. Minimum, maximum, and average values of PENR and PER normalized for the service life. Stages A1–A3 were considered for all the products analyzed. In addition, if data were available, stage A5 was considered for the shuttering block.

Wall Building Material	PENR [MJ/kg y]			PER [MJ/kg y]		
	Min.	Max.	Avg.	Min.	Max.	Avg.
Bricks	0.0020	0.0269	0.0171	0.0004	0.0399	0.0074
Hollow bricks	0.0005	0.0234	0.0159	0.0004	0.0464	0.0054
Concrete blocks	0.0037	0.0282	0.0170	0.0001	0.0172	0.0049
Prefabricated panels	0.0064	0.0735	0.0280	0.0014	0.0104	0.0051
Sandstone bricks	0.0154	0.0286	0.0194	0.0004	0.0236	0.0070
Wood-chips shuttering blocks	0.0114 *	0.0502 **	0.0205 **	0.0161 *	0.0658 **	0.0314 **

* Values calculated without considering phase A5; ** Values calculated considering phase A5.

Table 8. Minimum, maximum, and average values of GWP normalized for the service life. Stages A1–A3 were considered for all the products analyzed. In addition, if data were available, stage A5 was considered for the shuttering block.

Wall Building Material	GWP [$kgCO_2eq/kg$ y]		
	Min.	Max.	Avg.
Bricks	0.0001	0.0022	0.0013
Hollow bricks	0.0003	0.0023	0.0013
Concrete Blocks	0.0008	0.0040	0.0023
Prefabricated panels	0.0021	0.0059	0.0030
Sandstone bricks	0.0012	0.0042	0.0026
Wood-chips shuttering blocks	0.0015 *	0.0065 **	0.0027 *

* Values calculated without considering phase A5; ** Values calculated considering phase A5.

From Tables 7 and 8, it emerges that sandstone bricks, characterized by a low average service life (50 years) compared with that of other wall materials, now have more impacting average values of PENR, PER, and GWP, respectively equal to 0.0194 MJ/kg y (PENR), 0.0070 MJ/kg y (PER), and 0.0026 $kgCO_2eq/kg$ y (GWP).

On the other hand, for bricks and hollow bricks, described by a higher average service life of 150 years, there is a significant reduction in the impacts compared with other materials. In fact, hollow bricks and bricks have the lowest average PENR and GWP values. In particular, in terms of PENR, hollow bricks assume values equal to 0.0159 MJ/kg y, followed by bricks with 0.0171 MJ/kg y. Instead, the values assumed for the GWP are equal to 0.0013 $kgCO_2eq/kg$ y for both bricks and hollow bricks. In terms of PER, the values are reduced to 0.0054 MJ/kg y for hollow bricks and to 0.0074 MJ/kg y for bricks.

Among all the materials studied, the wood-chips shuttering blocks, characterized by an average useful life of 100 years, assume the highest average value in terms of PER, equal to 0.0314 MJ/kg y, while their average values of PENR and GWP are the second highest, respectively equal to 0.0205 MJ/kg y (PENR) and 0.0027 $kgCO_2eq/kg$ y (GWP), preceded by prefabricated panels with an average value of PENR equal to 0.0280 MJ/kg y and of GWP equal to 0.0030 $kgCO_2eq/kg$ y.

The average results obtained and displayed in Figure 5 were compared with generic literature data about the environmental performances of similar masonry products (see Figure 7). Only the construction products that are popular in the construction practice and of which we got an adequate number of data (i.e., bricks and concrete panels) were considered in the comparison; the results obtained for the other products (e.g., sandstone bricks) for which we collected a reduced number of EPDs are too strongly dependent on the manufacturer, product typology, and production site. Moreover, for wood chips shuttering blocks, the wide variety of product typologies found reduced the amount of data available to characterize a specific type, thereby limiting the possibility of finding an adequate sample for comparability purposes.

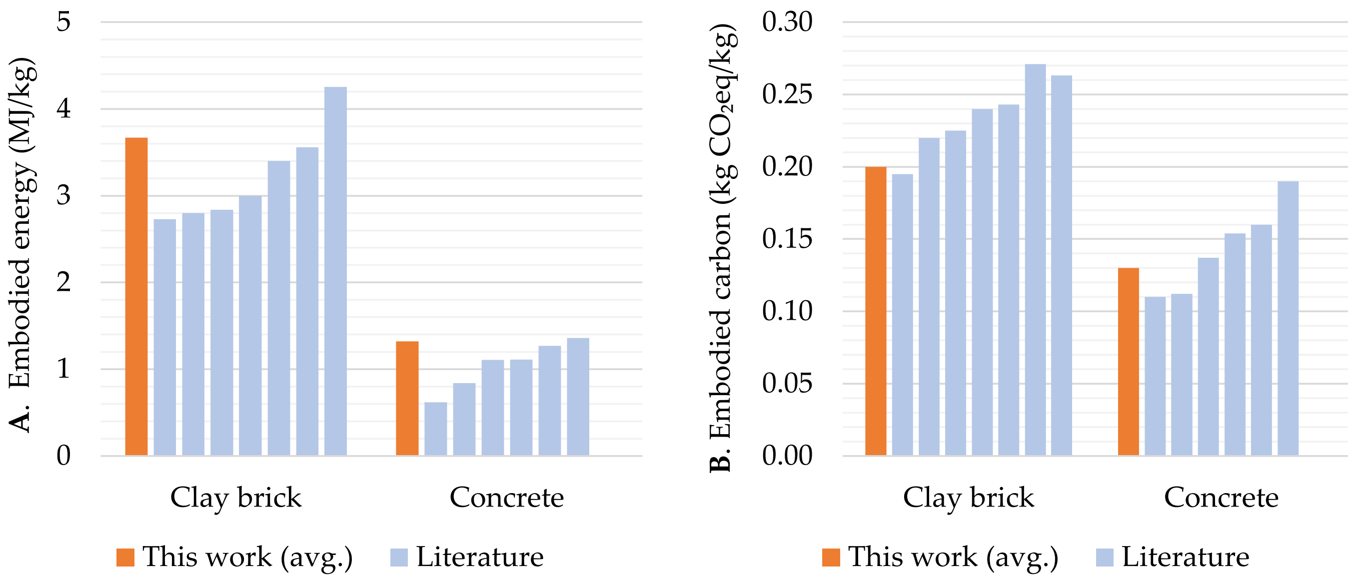

Figure 7. Comparison with literature data of the average embodied energy (**A**) and carbon (**B**) of bricks and concrete.

The comparison suffers from a high uncertainty since different methodologies and boundary conditions are applied in the literature or in life cycle databases. Nonetheless, results in line with the literature values were achieved in this study (see Table 9): the embodied energy of bricks ranges between 2 and 4.25 MJ/kg, while, in this study, the average value found is equal to 3.67 MJ/kg; the range for embodied carbon is 0.195–0.271 kgCO_2eq/kg, while we found an average value of 0.20 kgCO_2eq/kg. Similarly, for concrete panels, we got average values equal to 1.32 MJ/kg and 0.137 kgCO_2eq/kg, while the literature values were respectively in the range of 0.62–1.36 MJ/kg and 0.11–0.19 kgCO_2eq/kg.

Table 9. Literature values for the embodied energy and carbon of brick and concrete products.

Ref.	Material	Embodied Energy [MJ/kg]	Embodied Carbon [kgCO_2eq/kg]
This study	Ordinary bricks (avg.)	3.67	0.20
[77]	Clay brick	2.73	0.243
[39]	Ordinary bricks	3.56	0.271
[78]	Ordinary bricks	3.00	0.225
[79]	Bricks	2.8	0.240
[80]	Ceramic bricks	2.84	0.220
[81]	Bricks	2.00–3.40	-
[82]	Bricks	4.25	-
[83]	Ordinary bricks	-	0.195–0.263
	Bricks with olive pomace	-	0.310–0.424
[44]	Adobe bricks	0.033–0.17	0.0017–0.0129

Table 9. *Cont.*

Ref.	Material	Embodied Energy [MJ/kg]	Embodied Carbon [kgCO_2eq/kg]
This study	Concrete (avg.)	1.32	0.130
[77]	Concrete	1.27	0.154
[39]	Concrete	1.105	0.137
[78]	Concrete	0.84–1.36	0.11–0.16
[79]	Concrete	1.11	0.190
[80]	Concrete	0.62	0.112
This study	Concrete block (avg.)	2.19	0.230
[77]	Autoclaved concrete blocks	2.33	0.355
[84]	Autoclaved concrete blocks	4.00	0.9
	Hollow concrete blocks	1.10	-
[77]	Concrete block	1.14	0.132

This good agreement makes the average values found a good reference for LCA practitioners when specific products have not been selected yet (e.g., in preliminary buildings design) or in cases where regional-specific data do not exist.

5. Case Study: A Comparison of Different Wall Options

The results developed in the previous sections highlight the main environmental impacts of the wall building materials that are on the market with an EPD certification in relation with their physical and mechanical characteristics. The results of the analysis give useful information to the scholars on the development of buildings components or materials with optimized environmental characteristics.

Furthermore, the analysis provides the producers of building materials a critical insight on the landscape of certified products on the market, thanks to a comparison between different categories of envelope products that underlines which of them should develop a better environmental approach to guarantee their competitiveness.

However, the results expressed per kg or m^3 in the EPDs do not often suffice for designers who intend to compare different wall solutions. It is therefore necessary to evaluate the environmental impacts related to the entire wall system. For this purpose, this paper proposes a further investigation on some simple wall options. The case study was conceived to give an example of the choice of a wall technology based on environmental, architectural, and physical criteria. It was developed in the following three steps:

1. Different wall typologies based on the building materials analyzed in this study were considered;
2. Comparable performances were assessed, i.e., same thermal resistance of the wall and similar superficial masses;
3. An environmental impact assessment of the different wall typologies was performed: PENR [MJ/m^2], PER [MJ/m^2], and GWP [kgCO_2eq/m^2] were calculated considering that the wall options have the same type of insulation on the outside but different thicknesses of insulation and of the wall elements. The FU considered in the case study is equal to 1 m^2 of wall.

5.1. Case Study Assumptions

A case study that highlights how the analyzed EPDs can be used to support the selection of wall materials and components was performed. The comparative analysis is oriented to the early design stage with the scope of finding the most effective solution: "What types of walls have the lowest environmental impact with the same physical performance? What are the best optimizations for the wall element in terms of environmental, technological and physical performance?". The case study consists of six types of walls, each one representing one of the six categories of products that are considered in this study: concrete blocks, prefabricated panels, bricks, hollow bricks, sandstone bricks, and shuttering wood chips blocks (Figure 8).

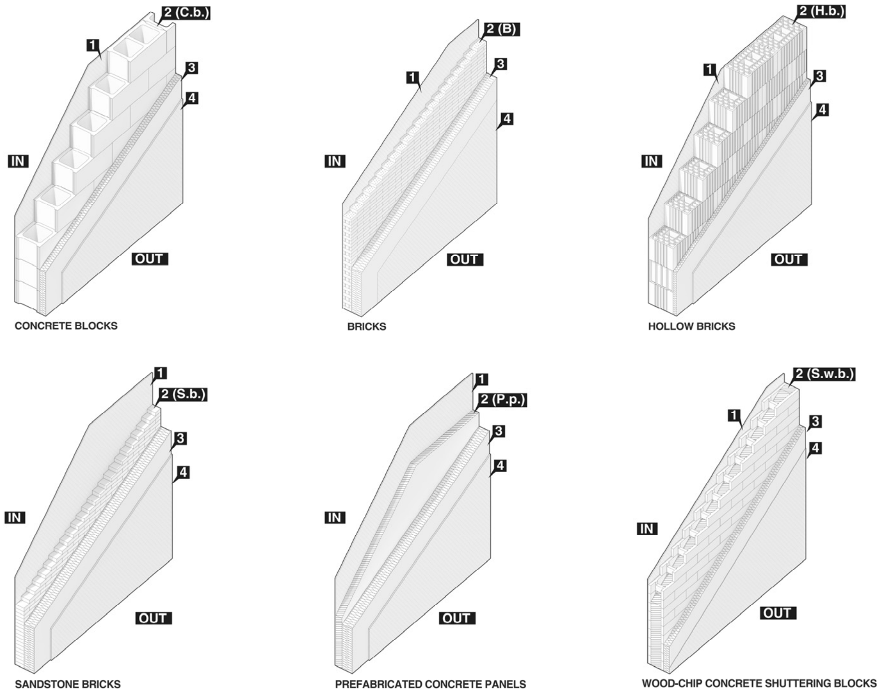

Figure 8. Wall types represented by stratigraphy that includes: 1 = Internal plaster; 2 = Wall building material (C.b. = Concrete block; B. = Bricks; H.b. = Hollow bricks; S.b. = Sandstone bricks; S.w.b. = Shuttering wood chips blocks; P.p. = Prefabricate concrete panels); 3 = Thermal insulation (EPS); 4 = External plaster.

For each type, a 1 m^2 model of an external infill wall without a load-bearing function was conceived. All the wall models that were compared have the same thermal resistance (5 ± 0.25 m^2K/W) and the same superficial mass (260 ± 30 kg/m^2). The control of these two parameters permitted to define wall models that are characterized by the same thermal performance on a steady state hypothesis and also by very similar performances when it comes to dynamic, thermal, and acoustical sound insulation behavior. The superficial mass, in fact, influences the calculation of the thermal mass of the walls since it can be determined as the product between the superficial mass and the specific heat capacity of the material composing the wall [63]. Since the specific heat capacities of the wall materials considered vary in a restricted range (850–1000 J/Kg K), the superficial mass significantly affects the thermal mass and thus the dynamic thermal performance of the walls; namely, superficial mass properly describes the capacity in dampening and delaying the thermal wave of the selected walls [64]. At the same time, the "mass law" [65] identifies a quite linear relationship between the logarithm of the squared surface mass of a wall element and its air-borne sound insulation, which means that the higher the mass, the higher the sound insulation at a certain frequency.

Each wall option was represented by a wall stratigraphy that, in addition to the non-load-bearing blocks, included: fixing dowels, an external insulation coating in expanded synthetized polystyrene (EPS), a reinforced smoothing with a fiberglass mesh, an exterior finishing (2 cm), and internal cement plaster (1.5 cm of thickness). Since the blocks considered have different thermal conductivity values, variable thicknesses of insulation were employed to guarantee the same overall thermal resistance. Similarly, if possible (e.g., avoiding non-homogeneous blocks splitting), a variable thickness was also considered for the construction blocks to obtain the same superficial mass. All the wall options were reported in the Supplementary Materials.

5.2. Environmental Impacts Assessment of the Wall Options

For each wall typology, three EPDs were considered and selected among the ones analyzed in the previous sections. The selection was based solely on representative EPDs, namely the ones of the products being characterized by environmental impacts that were close to the average values found.

The wall models were reconstructed calculating their thermal resistance and superficial mass based on the thermal conductivity values, dimensions, and densities derived from the EPDs, together with the values related to the insulation layer and to the other materials.

After that, taking into account the data contained in the EPDs and in life cycle databases [77], the environmental impacts related to stages A1–A3 were calculated. Actually, stage A5 was also considered for the shuttering blocks to take into account the infilled concrete: these blocks, in fact, as previously mentioned, require to be assembled on the construction site with a casting of concrete and with reinforcing steel bars.

Moreover, to account for the lifespan of the wall systems, a service life of 150 and 50 years was given; 150 years corresponds to the maximum value of service life of the construction blocks considered (see Table 10), and on the other hand, 50 years is the minimum service life of the construction blocks selected but also the life span that is usually recommended by the PCR for buildings [41]. The two life span scenarios, therefore, are the maximum and the minimum than can occur and are representative of the widest variation range. In a LCA study, the selection of the service life span of a building and of its components is quite important since it is one of the most significant assumptions that can alter the replacement frequencies and maintenance cycles significantly affecting the results of the analysis [85,86]. Actually, there is not a clear agreement about which life span should be considered in the LCA studies of buildings and, sometimes, the assumptions made by different authors vary from the standard recommendation (50 years) [87]. Goulouti et al. [88], for example, showed that the uncertainty in the service life of six building elements (the external insulation, windows, roofing, flooring, wall, and ceiling coverings) is the most important factor that affects the building LCA uncertainty; a probabilistic approach was therefore suggested to tackle this issue. In this study, the consideration of a maximum and minimum value for the life span of the wall models evaluated permitted to take into account the effect of a higher longevity of the materials in the LCA.

Table 10. Parameters characterizing the masonry layer of the walls considered in this study.

Wall Building Materials	Wall Element	Density (kg/m^3)	λ (W/mK)	Service Life (Years)	$PENR_{A1–A3}$ (MJ/m^2)	$GWP_{A1–A3}$ ($kgCO_2/m^2$)
Concrete blocks	C.b. EPD 1	800	0.190	150	516	67
	C.b. EPD 2	500	0.130	50	300	43
	C.b. EPD 3	750	0.180	100	414	60
Bricks	B. EPD 1	1825	0.650	150	784	75
	B. EPD 2	1550	0.500	150	697	39
	B. EPD 3	1600	0.500	150	782	52
Hollow bricks	H.b. EPD 1	575	0.120	150	520	55
	H.b. EPD 2	575	0.120	150	712	71
	H.b. EPD 3	807	0.179	150	293	40
Sandstone bricks	S.b. EPD 1	1800	1.030	50	192	28
	S.b. EPD 2	1890	1.000	50	173	27
	S.b. EPD 3	1800	1.000	50	242	33
Wood-chips concrete shuttering blocks	S.w.b. EPD 1	1152	0.122	100	452	64
	S.w.b. EPD 2	801	0.079	100	419	47
	S.w.b. EPD 3	1455	0.282	100	363	46
Prefabricated concrete panels	P.p EPD 1	2400	1.660	100	403	52
	P.p EPD 2	2400	1.660	100	242	41
	P.p EPD 3	2400	1.660	100	464	55

For example, the value of PENR was determined for each product at the end of its service life ($PENR_{A1–A3\,|\,LC}$). It was calculated by multiplying the $PENR_{A1–A3}$ derived from the EPD for the ratio between the maximum useful life considered and the service life of the product as detailed in the following equation:

$$PENR_{A1-A3|LC} = PENR_{A1-A3}\ (\text{maximum Useful life [150 years] / Service life of the product}) \quad (1)$$

Thus, the products with a lower service life were supposed to be entirely substituted within the life cycle of the wall. Non-integer numbers are considered in the calculations to model partial substitutions.

Whether the FU adopted by the EPD is the unit of mass or volume, the value of $PENR_{A1–A3}$ was reconducted to the m^2 using the following operations:

$$PENR_{A1-A3} = PENR_{EPD} \times \text{ mass of } 1\ m^2\ (\text{if the FU is the mass}) \quad (2)$$

$$PENR_{A1-A3} = PENR_{EPD} \times \text{ volume of } 1\ m^2\ (\text{if the FU is the volume}) \quad (3)$$

For the calculation of the $PENR_{A1–A3\,|\,50y}$, instead, the sum of the values of $PENR_{A1–A3}$ for each wall component was considered without accounting for any substitution. Similar calculations were performed for the determination of the PER and the GWP.

The parameters of the wall masonry elements adopted in the calculation arise from the EPD or instead from the technical sheets of the companies. Table 10 reports the values used for the masonry layer in the environmental impact assessment of the walls. If the thermal conductivity was not declared in the EPD, the values recommended by the UNI 10351:2015 standard were used [89].

The values concerning the finishing and insulating materials that are employed in the definition of the wall stratigraphies in the case study are reported in Table 11. The data regarding their environmental impacts arise from the Ecoinvent database [77] or EPD, while thermal conductivity and density from the UNI 10351 (2015) standard [89].

Table 11. Parameters characterizing finishing and insulation materials.

Wall Layers	Thickness (m)	Density (kg/m^3)	λ (W/mK)	Service Life (Years)	$PENR_{A1–A3}$ (MJ/m^2)	$GWP_{A1–A3}$ ($kgCO_2/m^2$)
Internal plaster	0.015	920	0.410	40	27.5	2.1
Insulation (EPS)	Variable	30	0.035	50	Variable	Variable
External finishing	0.030	1800	0.900	40	83	11.2

Insulation thicknesses are variable in relation to the wall typology adopted, as reported in Table 11.

The characteristics of the different wall configurations are underlined in Table 12, based on wall thermal resistance, wall superficial mass, $PENR_{A1–A3}$, and $GWP_{A1–A3}$, considering a life span of 50 years. As can be noted, the values of thermal resistance and superficial mass deviate from the target value by ±5% and ±11.5%, respectively, due to the impossibility of finding the exact thickness required for some of the wall elements. These variability ranges are considered acceptable for the aims of this study.

Table 12. Characteristics of the wall options considered.

Wall Building Materials	Wall Case Study	Thickness Insulation Layer (m)	Block Thickness (m)	Superficial Mass of the Wall (kg/m^2)	Wall Thermal Resistance (m^2 K/W)	PENR A1–A3 50 Years (MJ/m^2)	GWP A1–A3 50 Years ($kgCO_2/m^2$)
Concrete blocks	C.b. EPD 1	0.10	0.400	240	5.05	964	94
	C.b. EPD 2	0.11	0.240	240	5.08	784	71
	C.b. EPD 3	0.10	0.400	240	5.17	862	87
Bricks	B. EPD 1	0.17	0.135	246	5.15	1363	108
	B. EPD 2	0.16	0.160	248	4.98	1261	72
	B. EPD 3	0.16	0.150	240	4.96	1346	85
Hollow bricks	H.b. EPD 1	0.06	0.400	240	5.14	924	80
	H.b. EPD 2	0.06	0.400	240	5.15	1117	96
	H.b. EPD 3	0.12	0.280	252	5.20	793	70
Sandstone bricks	S.b. EPD 1	0.17	0.135	243	5.08	771	62
	S.b. EPD 2	0.17	0.135	243	5.08	752	61
	S.b. EPD 3	0.17	0.135	243	5.08	822	66
Shuttering wood chips blocks	S.w.b EPD 1	0.10	0.25	288	5.07	900	91
	S.w.b EPD 2	0.14	0.25	272	5.09	856	74
	S.w.b EPD 3	0.15	0.20	290	5.16	911	78
Prefabricated concrete panels	P.p EPD 1	0.17	0.100	240	5.01	983	85
	P.p EPD 2	0.17	0.100	240	5.01	822	75
	P.p EPD 3	0.17	0.105	238	5.01	1044	88

Figures 9 and 10 show the percentage contribution attributable to the wall construction elements considered in this study in relation to the total PENR and GWP calculated at 150 (LC, life cycle) and 50 years (50y). In the first case, the effect of the insulation coating on the whole environmental impact turns out to be remarkable because of its high embodied non-renewable energy (see Figure 9b) and since it undergoes a triple substitution in the presumed whole life cycle of the system (the EPD used to model the coating declared a service life of 50 years). In terms of percentage to the total $PENR_{A1–A3|LC}$, the insulation coating overcomes 60% for all the wall models considered, reaching a maximum of 84%; similar results were obtained for the $GWP_{A1–A3|LC}$, with a maximum of 71% and a minimum of 46%. On the other hand, when the life span is equal to 50 years, the impacts of the blocks acquire a more significant share in the totals. That is to say that the choice of the life span in the calculations, the definition of the service life of buildings materials, and the increment of their durability had a very important effect on the LCA results.

5.3. Results

Figures 11 and 12 display the results about the $PENR_{A1–A3|LC}$, $PER_{A1–A3|LC}$, and $GWP_{A1–A3|LC}$, showing that the wall models, composed of different construction blocks, are characterized by different environmental impacts.

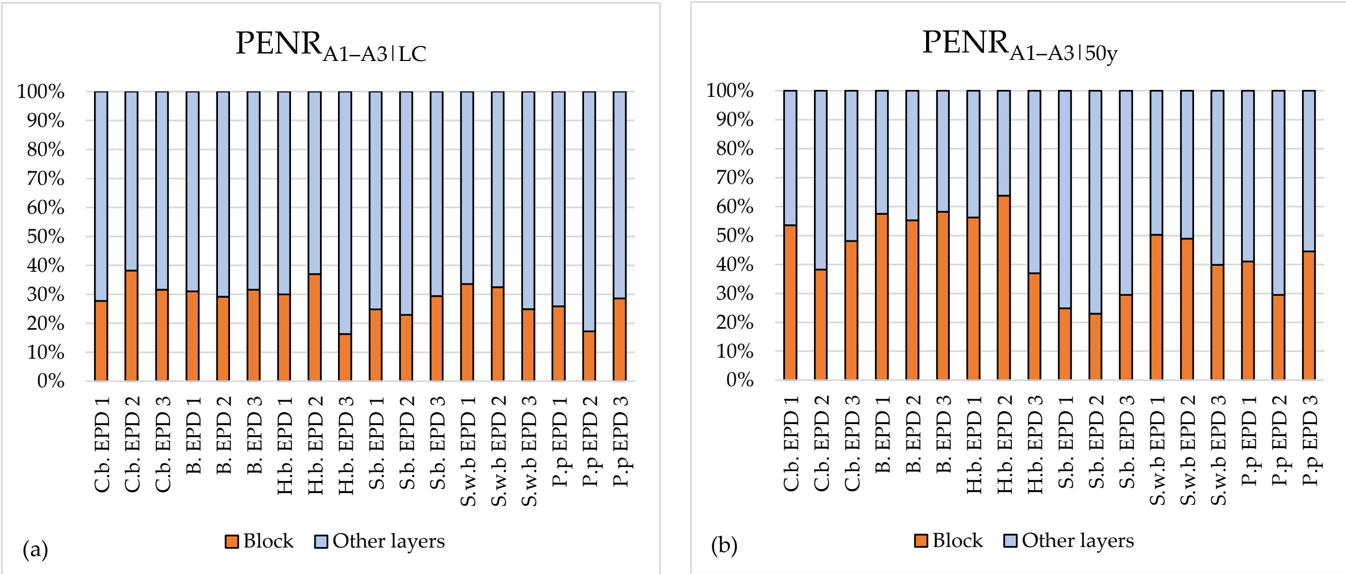

Figure 9. (**a**) $PENR_{A1-A3|LC}$ and (**b**) $PENR_{A1-A3|50y}$: contribution of construction blocks and other layers to the total. (C.b. = Concrete block; B. = Bricks; H.b. = Hollow bricks; S.b. = Sandstone bricks; S.w.b = Shuttering wood chips blocks; P.p. = Prefabricate concrete panels).

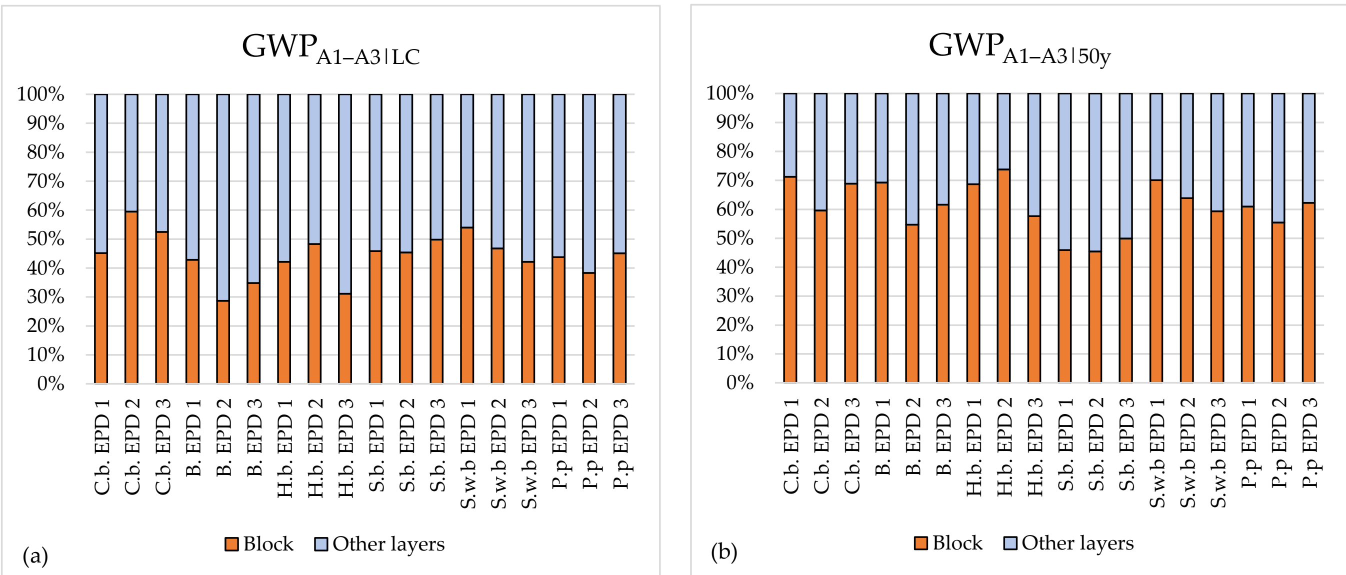

Figure 10. (**a**) GWP $_{A1-A3|LC}$ and (**b**) $GWP_{A1-A3|50y}$: contribution of construction blocks and other layers to the total. (C.b. = Concrete block; B. = Bricks; H.b. = Hollow bricks; S.b. = Sandstone bricks; S.w.b. = Shuttering wood chips blocks; P.p = Prefabricate concrete panels.

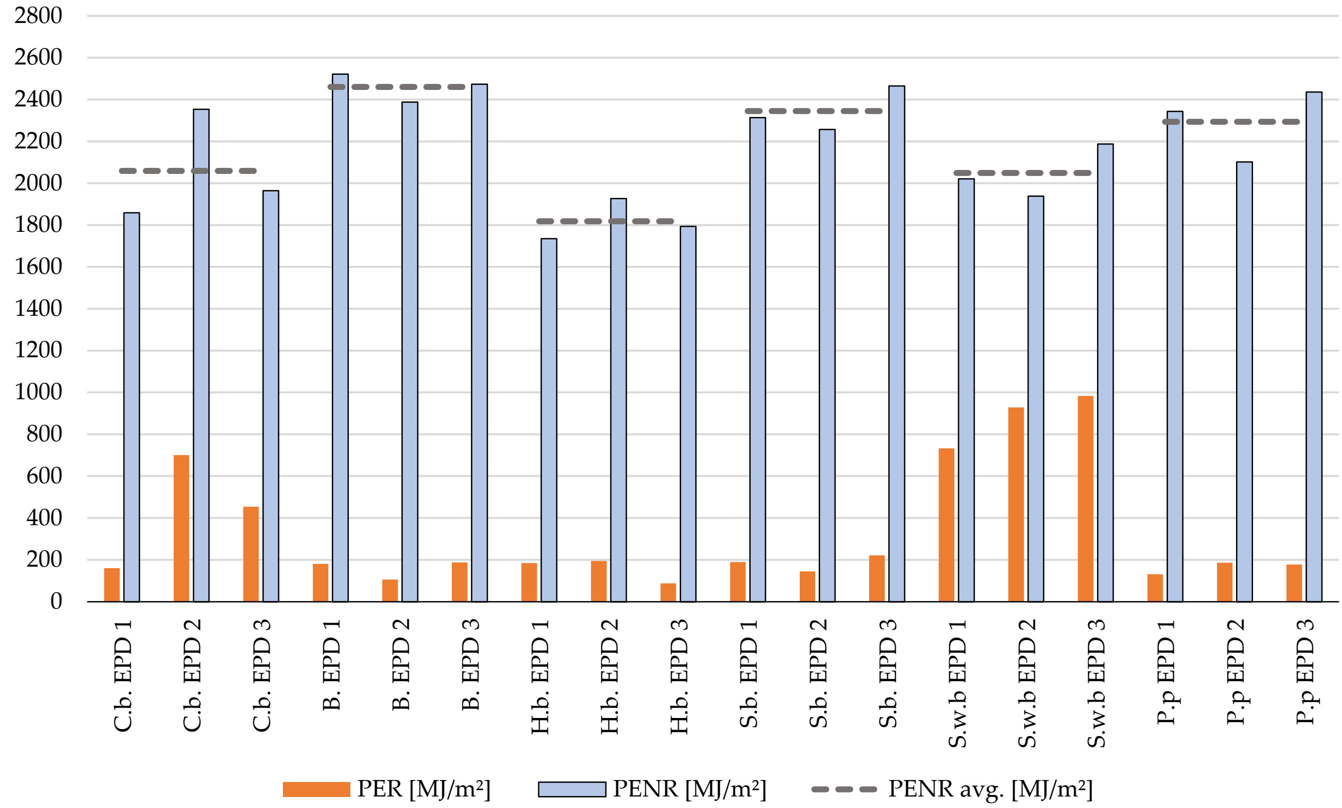

Figure 11. PENR $_{A1–A3|LC}$ and PER $_{A1–A3|LC}$ for each wall model considered. (C.b. = Concrete block; B. = Bricks; H.b. = Hollow bricks; S.b. = Sandstone bricks; S.w.b. = Shuttering wood chips blocks; P.p =Prefabricate concrete panels).

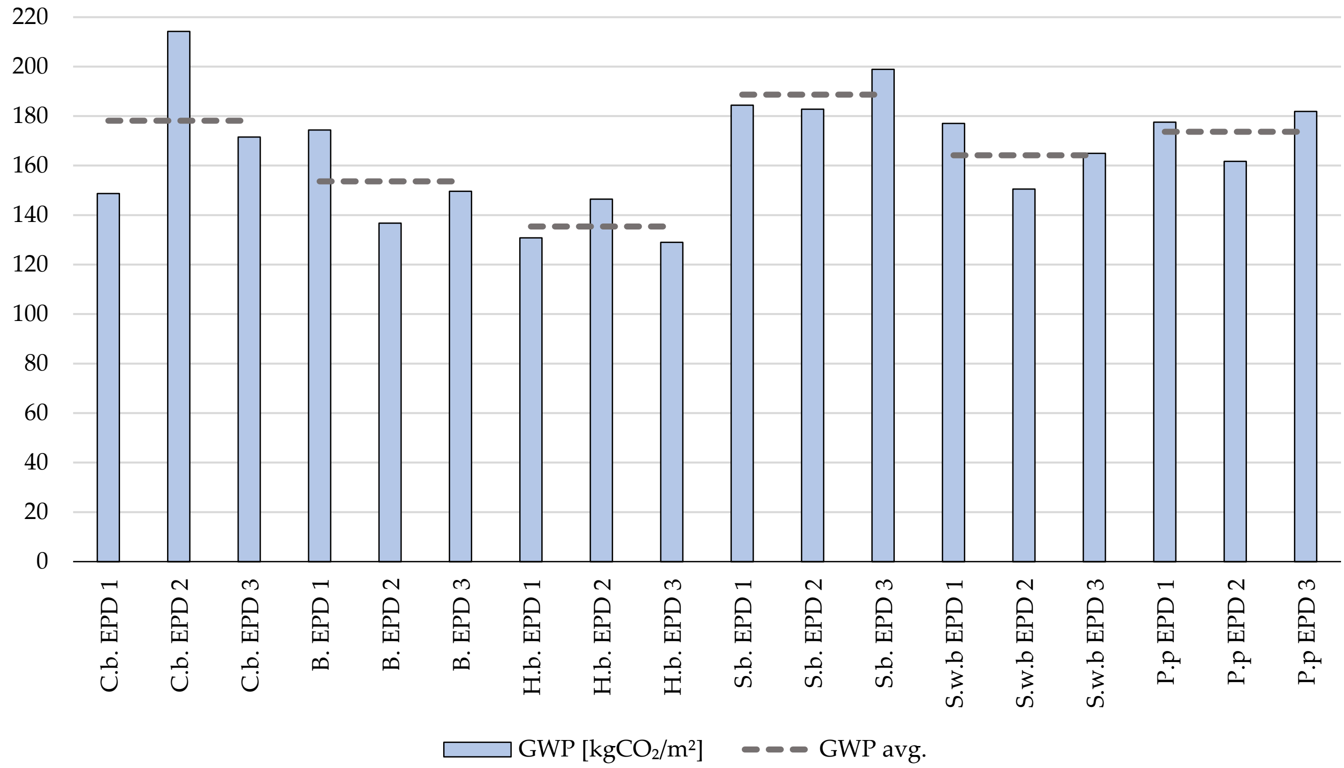

Figure 12. GWP$_{A1–A3|LC}$ for each wall model considered. (C.b. = Concrete block; B. = Bricks; H.b = Hollow bricks; S.b. = Sandstone bricks; S.w.b. = Shuttering wood chips blocks; P.p = Prefabricate concrete panels).

Looking at these results, brick walls are characterized by the highest average value of $PENR_{A1–A3|LC}$ (2461 MJ/m^2), which underlines how the production process is very energy intensive and still strongly dependent on fossil fuels.

Hollow brick walls have good performance both in terms of $PENR_{A1–A3|LC}$ and $GWP_{A1–A3|LC}$, showing the lowest average impacts in both cases; the obtained results are 1818 MJ/m^2 and 135 kgCO_2eq/m^2, respectively.

Sandstone brick walls deteriorate their low embodied impacts because of their short durability, as shown in Table 12; in fact, these systems are characterized by very low values of $PENR_{A1\text{-}A3}$ and $GWP_{A1–A3}$ but have a low service life (50 years) that implies a hypothetical triple substitution during the wall life cycle.

Walls made of concrete blocks and prefabricated concrete panels are characterized by high average values of global warming potential (respectively 178 and 174 kgCO_2eq/m^2). The model C.b. EPD 2 deserves a specific mention due to its composition of a lightweight concrete block with expanded clay inside. As shown in Table 12, it displays lower environmental impacts in comparison with the other concrete blocks. However, its lower durability (50 years) plays a critical role when the whole life cycle is considered, making the total $PENR_{A1–A3|LC}$ and $GWP_{A1–A3|LC}$ of the wall model C.b. EPD 2 quite higher than the ones belonging to the same category.

Walls made of wood-chips concrete shuttering blocks showed a very high embodied energy content that has, however, a remarkable renewable composition (the average $PER_{A1–A3|LC}$ is the highest among the models considered) and good $GWP_{A1–A3|LC}$; furthermore, the biogenic carbon that is stored in the wooden material is not included in the results and this can further improve the environmental performance of the material. However, several limitations in the comparability hypothesis and a high uncertainty in the data provided by the EPDs must be underlined:

- When it comes to shuttering wood-chips concrete blocks with an integrated insulation layer which is placed inside the formwork, single service life is provided by the EPD for the entire product. However, the insulating layer may have a lower service life than the one declared for the whole system; thus, some correction factors should be used to model the decay in the insulating performances during its end-of-life.
- The impacts connected to the A5 stage are not always provided by the EPDs even if they need to be included to compare those blocks to other wall elements ready to be installed.
- The superficial masses of the wall models made of shuttering wood-chips concrete blocks are sensibly higher than the others.

The case study analyzed in Chapter 5 shows that the environmental comparison between products is affected by the design of the building element. Comparing the results reported in Chapter 4, in which the individual products were evaluated per unit of mass, with the results of Chapter 5 where wall systems were simulated and calculated per square meter, the following points can be highlighted:

- Hollow bricks and bricks in the wall system have lower impacts compared with the product assessment (PENR).
- Sandstone bricks become more impactful compared with the single-element assessment due to the hypothetical multiple substitutions required in the life cycle (PENR and GWP).
- Concrete blocks and prefabricated panels in the wall system have a similar trend compared with the product assessment (GWP).

6. Conclusions

This paper analyzes nearly 180 EPDs related to the construction blocks used to infill non-load-bearing walls. The scope of the analysis is to collect a significant amount of data about their embodied environmental impacts (e.g., GWP, PER, PENR) and to present a case study about the application of environmental labeling in the design process for the selection of wall typologies.

The results underline how different wall elements are characterized by different environmental impacts during the whole life cycle of the construction system. A high embodied non-renewable energy was found for clay bricks (2.56 MJ/kg on average) and a high embodied global warming potential for concrete blocks and concrete prefabricated panels (0.23 kg CO_2eq/kg on average in both cases). Similar results were obtained for the wall models considered as a case study in which, on the life cycle, the brick walls showed the highest average non-renewable energy (2461 MJ/m^2), while the wall made of concrete blocks showed the second highest average global warming potential (178 kg CO_2eq/m^2), followed by concrete prefabricated panels (174 kg CO_2eq/m^2). The response of the brick industry should be focused on a higher innovation regarding energy and environmental aspects (e.g., increase in the thermal resistance of the products or in the use of secondary/recycled materials) or on the technological ones (e.g., dry systems with low mortar necessity, hybrid, and light systems).

Durability also plays a crucial role in the reduction of the life cycle environmental impacts of the wall models analyzed. The results obtained, in fact, clearly highlight how the lower service life of some components, and the consequent necessity of multiple substitutions of them in the wall life span, can have a detrimental role in the life cycle environmental performances of the model. The sandstone brick walls, for example, showed the lowest impacts if the analysis is performed within a 50-year window frame (782 MJ/m^2 and 63 kg CO_2eq/m^2); however, if a 150-year life cycle is considered, the reduced service life of the material raised their average value of PENR and GWP to the maximum (respectively 2345 MJ/m^2 and 189 kg CO_2eq/m^2). On the contrary, hollow brick models showed slightly higher impacts for the upstream phase of the life cycle (945 MJ/m^2 and 82 kg CO_2eq/m^2) but their long service life permitted them to be the most competitive solutions for both PENR and GWP (the average values obtained are 1818 MJ/m^2 and 135 kg CO_2eq/m^2). Design for durability is therefore the just pathway to implement for a reduction of the embodied environmental impacts of walls.

A strong limitation of the adopted approach is linked to the impossibility of an end-of-life disassembly of the components with the lowest service life. The declared durability in the EPD for single products turns out to not be representative of the whole wall system. This issue is also valid for single blocks that are composed by heterogeneous materials. Considering shuttering wood-chips concrete blocks, for example, the insulation layer that is placed inside the formwork has a lower service life than the one declared for the whole system. Since its substitution is not possible, some correction factors should at least be employed to consider the decay of the performances of the insulation layer during its end-of-life phase.

Finally, the real comparability potential of the environmental impacts of products having a similar function is determined by the accuracy and the integration of all the data reported by the EPD. Most of them, in fact, do not contain the required parameters for the functional unit conversion that is necessary to perform a comparison. In other cases, the parameters reported are not specific and a wide variation range is declared. A higher standardization is required to establish the complete parameters that must be contained in the EPDs.

However, the European guidelines relating to Green Public Procurements (EU directives 2014/23/EU, 2014/24/EU, and 2014/25/EU) are strengthening the dissemination of the Environmental Product Declarations in the construction sector. As a result, the market (productors, retailers, end users) is being encouraged to use these EPD-labeled materials since their environmental impact is proved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16041846/s1. Table S1. Hypotheses and calculations made in the case study.

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Glossary

The abbreviations used in the paper are reported in this section.

Impact assessment	
EPDs	Environmental products declarations
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential (100 years)
LCA	Life cycle assessment
PCR	Product category rules
PER	Primary energy, renewable
$PER_{A1–A3 \mid LC}$	Life cycle primary renewable energy (stages A1–A3, 150 years)
$PER_{A1–A3 \mid 50y}$	Primary renewable energy (stages A1–A3, 50 years)
PENR	Primary energy, non-renewable
$PENR_{A1–A3 \mid LC}$	Life cycle primary non-renewable energy (stages A1–A3, 150 years)
$PENR_{A1–A3 \mid 50y}$	Primary non-renewable energy (stages A1–A3, 50 years)
Program operators	
Bau	Baubook
Den	EPD Danmark
Env	EPD international AB
Ita	EPD Italy
Nor	EPD Norge
IBU	Institut Bauen & Umwelt e.V.
Vups	Výzkumný ústav pozemních staveb-Certifikační společnost, s.r.o.
Bre	BRE GLOBAL
Ocl	One Click LCA
Oek	OEKOBAUDAT
Aen	AENOR
Tur	EPD TURKEY
Constructions blocks	
B.	Brick
C.b.	Concrete block
H.b.	Hollow brick
P.p.	Prefabricated panel
S.b.	Sandstone brick
S.w.b.	Shuttering wood-chips block

References

1. Karimpour, M.; Belusko, M.; Xing, K.; Bruno, F. Minimising the Life Cycle Energy of Buildings: Review and Analysis. *Build. Environ.* **2014**, *73*, 106–114. [CrossRef]
2. Koezjakov, A.; Urge-Vorsatz, D.; Crijns-Graus, W.; van den Broek, M. The Relationship between Operational Energy Demand and Embodied Energy in Dutch Residential Buildings. *Energy Build.* **2018**, *165*, 233–245. [CrossRef]
3. Röck, M.; Saade, M.R.M.; Balouktsi, M.; Rasmussen, F.N.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T.; Passer, A. Embodied GHG Emissions of Buildings—The Hidden Challenge for Effective Climate Change Mitigation. *Appl. Energy* **2020**, *258*, 114107. [CrossRef]
4. IEA; EBC. *Evaluation of Embodied Energy and CO_2eq for Building Construction (Annex 57)*; IEA: Cambridge, UK, 2016.

5. Birgisdottir, H.; Moncaster, A.; Wiberg, A.H.; Chae, C.; Yokoyama, K.; Balouktsi, M.; Seo, S.; Oka, T.; Lützkendorf, T.; Malmqvist, T. IEA EBC Annex 57 'Evaluation of Embodied Energy and CO_2eq for Building Construction. *Energy Build.* **2017**, *154*, 72–80. [CrossRef]
6. Ramesh, T.; Prakash, R.; Shukla, K.K. Life Cycle Energy Analysis of Buildings: An Overview. *Energy Build.* **2010**, *42*, 1592–1600. [CrossRef]
7. Shadram, F.; Johansson, T.D.; Lu, W.; Schade, J.; Olofsson, T. An Integrated BIM-Based Framework for Minimizing Embodied Energy during Building Design. *Energy Build.* **2016**, *128*, 592–604. [CrossRef]
8. Ferreira, A.; Pinheiro, M.D.; de Brito, J.; Mateus, R. Embodied vs. Operational Energy and Carbon in Retail Building Shells: A Case Study in Portugal. *Energies* **2022**, *16*, 378. [CrossRef]
9. Monteiro, H.; Freire, F.; Fernández, J.E. Life-Cycle Assessment of Alternative Envelope Construction for a New House in South-Western Europe: Embodied and Operational Magnitude. *Energies* **2020**, *13*, 4145. [CrossRef]
10. Koroneos, C.; Dompros, A. Environmental Assessment of Brick Production in Greece. *Build. Environ.* **2007**, *42*, 2114–2123. [CrossRef]
11. Kumbhar, S.; Kulkarni, N.; Rao, A.B.; Rao, B. Environmental Life Cycle Assessment of Traditional Bricks in Western Maharashtra, India. *Energy Procedia* **2014**, *54*, 260–269. [CrossRef]
12. European Commission. A European Green Deal. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed on 7 September 2022).
13. Röck, M.; Baldereschi, E.; Verellen, E.; Passer, A.; Sala, S.; Allacker, K. Environmental Modelling of Building Stocks—An Integrated Review of Life Cycle-Based Assessment Models to Support EU Policy Making. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111550. [CrossRef]
14. European Commission COM/2020/98 Final—A New Circular Economy Action Plan for a Cleaner and More Competitive Europe. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0098 (accessed on 12 September 2022).
15. Murmu, A.L.; Patel, A. Towards Sustainable Bricks Production: An Overview. *Constr. Build. Mater.* **2018**, *165*, 112–125. [CrossRef]
16. Cabeza, L.F.; Boquera, L.; Chàfer, M.; Vérez, D. Embodied Energy and Embodied Carbon of Structural Building Materials: Worldwide Progress and Barriers through Literature Map Analysis. *Energy Build* **2021**, *231*, 110612. [CrossRef]
17. Sáez-de-Guinoa, A.; Zambrana-Vasquez, D.; Fernández, V.; Bartolomé, C. Circular Economy in the European Construction Sector: A Review of Strategies for Implementation in Building Renovation. *Energies* **2022**, *15*, 4747. [CrossRef]
18. European Commission Level(s). Available online: https://environment.ec.europa.eu/topics/circular-economy/levels_en (accessed on 31 October 2022).
19. LETI Embodied Carbon Primer. Available online: https://www.leti.london/ecp (accessed on 12 June 2022).
20. Dixit, M.K.; Fernández-Solís, J.L.; Lavy, S.; Culp, C.H. Identification of Parameters for Embodied Energy Measurement: A Literature Review. *Energy Build.* **2010**, *42*, 1238–1247. [CrossRef]
21. Azari, R.; Abbasabadi, N. Embodied Energy of Buildings: A Review of Data, Methods, Challenges, and Research Trends. *Energy Build.* **2018**, *168*, 225–235. [CrossRef]
22. Dixit, M.K. Life Cycle Embodied Energy Analysis of Residential Buildings: A Review of Literature to Investigate Embodied Energy Parameters. *Renew. Sustain. Energy Rev.* **2017**, *79*, 390–413. [CrossRef]
23. Zhang, Y.; Yan, D.; Hu, S.; Guo, S. Modelling of Energy Consumption and Carbon Emission from the Building Construction Sector in China, a Process-Based LCA Approach. *Energy Policy* **2019**, *134*, 110949. [CrossRef]
24. Saade, M.R.M.; Guest, G.; Amor, B. Comparative Whole Building LCAs: How Far Are Our Expectations from the Documented Evidence? *Build. Environ.* **2020**, *167*, 106449. [CrossRef]
25. Akbarnezhad, A.; Xiao, J. Estimation and Minimization of Embodied Carbon of Buildings: A Review. *Buildings* **2017**, *7*, 5. [CrossRef]
26. El Khouli, S.; John, V.; Zeumer, M. *Sustainable Construction Techniques*; Detail Green Books: Munich, Germany, 2015; ISBN 978-3955532383.
27. Thiel, C.; Campion, N.; Landis, A.; Jones, A.; Schaefer, L.; Bilec, M. A Materials Life Cycle Assessment of a Net-Zero Energy Building. *Energies* **2013**, *6*, 1125–1141. [CrossRef]
28. Pal, S.K.; Takano, A.; Alanne, K.; Siren, K. A Life Cycle Approach to Optimizing Carbon Footprint and Costs of a Residential Building. *Build. Environ.* **2017**, *123*, 146–162. [CrossRef]
29. Reilly, A.; Kinnane, O.; O'Hegarty, R. Energy Embodied in, and Transmitted through, Walls of Different Types when Accounting for the Dynamic Effects of Thermal Mass. *J. Green Build.* **2020**, *15*, 43–66. [CrossRef]
30. Ching, F.D.K. *Building Construction Illustrated*, 6th ed.; Wiley: Hoboken, NJ, USA, 2020; ISBN 978-1-119-58316-5.
31. European Parliament and Council. Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. *Off. J. Eur. Union* **2011**, *88*, 5–43.
32. ECO Platform EPD Facts & Figures. Available online: https://www.eco-platform.org/epd-facts-figures.html (accessed on 10 September 2022).
33. Grazieschi, G.; Asdrubali, F.; Thomas, G. Embodied Energy and Carbon of Building Insulating Materials: A Critical Review. *Clean. Environ. Syst.* **2021**, *2*, 100032. [CrossRef]

34. Hill, C.; Norton, A.; Dibdiakova, J. A Comparison of the Environmental Impacts of Different Categories of Insulation Materials. *Energy Build.* **2018**, *162*, 12–20. [CrossRef]
35. Asdrubali, F.; Roncone, M.; Grazieschi, G. Embodied Energy and Embodied GWP of Windows: A Critical Review. *Energies* **2021**, *14*, 3788. [CrossRef]
36. Rasmussen, F.; Andersen, C.; Wittchen, A.; Hansen, R.; Birgisdóttir, H. Environmental Product Declarations of Structural Wood: A Review of Impacts and Potential Pitfalls for Practice. *Buildings* **2021**, *11*, 362. [CrossRef]
37. Carbonaro, C.; Tedesco, S.; Fantucci, S. Block_Plaster: High Energy/Environmental Performance Brick Building Envelope. *Techne—J. Technol. Archit. Environ.* **2018**, *16*, 177–186. [CrossRef]
38. Kua, H.W.; Kamath, S. An Attributional and Consequential Life Cycle Assessment of Substituting Concrete with Bricks. *J. Clean. Prod.* **2014**, *81*, 190–200. [CrossRef]
39. Zabalza Bribián, I.; Valero Capilla, A.; Aranda Usón, A. Life Cycle Assessment of Building Materials: Comparative Analysis of Energy and Environmental Impacts and Evaluation of the Eco-Efficiency Improvement Potential. *Build. Environ.* **2011**, *46*, 1133–1140. [CrossRef]
40. Almeida, M.I.; Dias, A.C.; Demertzi, M.; Arroja, L. Contribution to the Development of Product Category Rules for Ceramic Bricks. *J. Clean. Prod.* **2015**, *92*, 206–215. [CrossRef]
41. Wiklund, U. PCR 2014:02 Buildings (Version 2.0). Available online: https://www.environdec.com/PCR/Detail/?Pcr=5950 (accessed on 20 July 2022).
42. Goedkoop, M.; Spriensma, R. *The Eco-Indicator 95*; PRé Consultants: Amersfoortthe, The Netherlands, 1995.
43. European Commission Ceramic Manufacturing Industry–Best Available Techniques. Available online: https://eippcb.jrc.ec.europa.eu/reference/ceramic-manufacturing-industry (accessed on 12 September 2022).
44. Christoforou, E.; Kylili, A.; Fokaides, P.A.; Ioannou, I. Cradle to Site Life Cycle Assessment (LCA) of Adobe Bricks. *J. Clean. Prod.* **2016**, *112*, 443–452. [CrossRef]
45. Ramos Huarachi, D.A.; Gonçalves, G.; de Francisco, A.C.; Canteri, M.H.G.; Piekarski, C.M. Life Cycle Assessment of Traditional and Alternative Bricks: A Review. *Environ. Impact Assess. Rev.* **2020**, *80*, 106335. [CrossRef]
46. Sutcu, M.; Akkurt, S. The Use of Recycled Paper Processing Residues in Making Porous Brick with Reduced Thermal Conductivity. *Ceram. Int.* **2009**, *35*, 2625–2631. [CrossRef]
47. Muñoz, P.; Juárez, M.C.; Morales, M.P.; Mendívil, M.A. Improving the Thermal Transmittance of Single-Brick Walls Built of Clay Bricks Lightened with Paper Pulp. *Energy Build.* **2013**, *59*, 171–180. [CrossRef]
48. Bories, C.; Borredon, M.-E.; Vedrenne, E.; Vilarem, G. Development of Eco-Friendly Porous Fired Clay Bricks Using Pore-Forming Agents: A Review. *J. Environ. Manag.* **2014**, *143*, 186–196. [CrossRef]
49. Bories, C.; Vedrenne, E.; Paulhe-Massol, A.; Vilarem, G.; Sablayrolles, C. Development of Porous Fired Clay Bricks with Bio-Based Additives: Study of the Environmental Impacts by Life Cycle Assessment (LCA). *Constr. Build. Mater.* **2016**, *125*, 1142–1151. [CrossRef]
50. Lozano-Miralles, J.; Hermoso-Orzáez, M.; Martínez-García, C.; Rojas-Sola, J. Comparative Study on the Environmental Impact of Traditional Clay Bricks Mixed with Organic Waste Using Life Cycle Analysis. *Sustainability* **2018**, *10*, 2917. [CrossRef]
51. Beal, B.; Selby, A.; Atwater, C.; James, C.; Viens, C.; Almquist, C. A Comparison of Thermal and Mechanical Properties of Clay Bricks Prepared with Three Different Pore-Forming Additives: Vermiculite, Wood Ash, and Sawdust. *Environ. Prog. Sustain. Energy* **2019**, *38*, 13150. [CrossRef]
52. Zhang, Y.; Luo, W.; Wang, J.; Wang, Y.; Xu, Y.; Xiao, J. A Review of Life Cycle Assessment of Recycled Aggregate Concrete. *Constr. Build. Mater.* **2019**, *209*, 115–125. [CrossRef]
53. Colangelo, F.; de Luca, G.; Ferone, C.; Mauro, A. Experimental and Numerical Analysis of Thermal and Hygrometric Characteristics of Building Structures Employing Recycled Plastic Aggregates and Geopolymer Concrete. *Energies* **2013**, *6*, 6077–6101. [CrossRef]
54. Anderson, J.; Moncaster, A. Embodied Carbon of Concrete in Buildings, Part 1: Analysis of Published EPD. *Build. Cities* **2020**, *1*, 198–217. [CrossRef]
55. Mohamad, N.; Muthusamy, K.; Embong, R.; Kusbiantoro, A.; Hashim, M.H. Environmental Impact of Cement Production and Solutions: A Review. *Mater. Today Proc.* **2022**, *48*, 741–746. [CrossRef]
56. Orsini, F.; Marrone, P. Approaches for a Low-Carbon Production of Building Materials: A Review. *J. Clean. Prod.* **2019**, *241*, 118380. [CrossRef]
57. Manjunatha, M.; Seth, D.; Balaji, K.V.G.D.; Bharath, A. B. Engineering Properties and Environmental Impact Assessment of Green Concrete Prepared with PVC Waste Powder: A Step towards Sustainable Approach. *Case Stud. Constr. Mater.* **2022**, *17*, e01404. [CrossRef]
58. *CEN EN 15804–2012*; Sustainability of Construction Works, Environmental Product Declarations, Core Rules for the Product Category of Construction Products. European Standards: Bruxelles, Belgium, 2012.
59. *CEN EN 15804:2012+A2:2019*; Sustainability of Construction Works—Environmental Product Declarations–Core Rules for the Product Category of Construction Products. European Standards: Bruxelles, Belgium, 2019.
60. Božiček, D.; Kunič, R.; Košir, M. Interpreting Environmental Impacts in Building Design: Application of a Comparative Assertion Method in the Context of the EPD Scheme for Building Products. *J. Clean. Prod.* **2021**, *279*, 123399. [CrossRef]

61. Palumbo, E.; Soust-Verdaguer, B.; Llatas, C.; Traverso, M. How to Obtain Accurate Environmental Impacts at Early Design Stages in BIM When Using Environmental Product Declaration. A Method to Support Decision-Making. *Sustainability* **2020**, *12*, 6927. [CrossRef]
62. Anderson, J.; Rønning, A.; Moncaster, A. The Reporting of End of Life and Module D Data and Scenarios in EPD for Building Level Life Cycle Assessment. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*, 012051. [CrossRef]
63. Hischier, R.; Weidema, B.; Althaus, H.-J.; Bauer, C.; Doka, G.; Dones, R.; Frischknecht, R.; Hellweg, S.; Humbert, S.; Jungbluth, N.; et al. *Implementation of Life Cycle Impact Assessment Methods Data v2.2*; Ecoinvent Report No. 3 v2.2.; Swiss Centre for Life Cycle Inventori: Dübendorf, Switzerland, 2010.
64. Asan, H.; Sancaktar, Y.S. Effects of Wall's Thermophysical Properties on Time Lag and Decrement Factor. *Energy Build.* **1998**, *28*, 159–166. [CrossRef]
65. Baubook GmbH Baubook Database. Available online: https://www.baubook.info/ (accessed on 15 July 2022).
66. EPD Danmark EPD Danmark Database. Available online: https://epddanmark.dk/ (accessed on 15 July 2022).
67. EPD International AB International EPD®System Database. Available online: http://environdec.com/ (accessed on 10 July 2022).
68. EPDItaly EPD Database. Available online: https://www.epditaly.it/ (accessed on 15 July 2022).
69. The Norwegian EPD Foundation Epd-Norge. Available online: https://www.epd-norge.no/ (accessed on 10 July 2022).
70. Institut Bauen und Umwelt IBU. Data. Available online: https://ibu-epd.com/en/ibu-data-start/ (accessed on 10 July 2022).
71. Building Research Institute–Certification Company Ltd. Verification of Environmental Product Declaration. Available online: https://www.vups.cz/en/ (accessed on 10 July 2022).
72. Building Research Establishment Ltd. Environmental Product Declarations (EPD) EN 15804. Available online: https://www.greenbooklive.com/search/scheme.jsp?id=260 (accessed on 10 July 2022).
73. Bionova, Ltd. One Click LCA Database. Available online: https://www.oneclicklca.com/ (accessed on 10 July 2022).
74. German Federal Ministry of the Interior Building and Community ÖKOBAUDAT Database. Available online: https://www.oekobaudat.de/en/database/database-oekobaudat.html (accessed on 15 July 2022).
75. AENOR Global EPD Declarations in Effect. Available online: https://www.en.aenor.com/certificacion/certificacion-de-producto/declaraciones-ambientales-de-producto/declaraciones-globalepd-en-vigor (accessed on 15 July 2022).
76. The Turkish Centre for Sustainable Production Research and Design EPDs by Sector—Construction Materials. Available online: https://epdturkey.org/en/ (accessed on 16 July 2022).
77. 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**, *21*, 1218–1230. [CrossRef]
78. Hammond, G.P.; Jones, C.I. Embodied Energy and Carbon in Construction Materials. *Proc. Inst. Civ. Eng. Energy* **2008**, *161*, 87–98. [CrossRef]
79. Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L. Investigating the Embodied Energy and Carbon of Buildings: A Systematic Literature Review and Meta-Analysis of Life Cycle Assessments. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110935. [CrossRef]
80. Martínez-Rocamora, A.; Solís-Guzmán, J.; Marrero, M. LCA Databases Focused on Construction Materials: A Review. *Renew. Sustain. Energy Rev.* **2016**, *58*, 565–573. [CrossRef]
81. Cabeza, L.F.; Barreneche, C.; Miró, L.; Morera, J.M.; Bartolí, E.; Inés Fernández, A. Low Carbon and Low Embodied Energy Materials in Buildings: A Review. *Renew. Sustain. Energy Rev.* **2013**, *23*, 536–542. [CrossRef]
82. Venkatarama Reddy, B.V.; Jagadish, K.S. Embodied Energy of Common and Alternative Building Materials and Technologies. *Energy Build.* **2003**, *35*, 129–137. [CrossRef]
83. López-García, A.B.; Cotes-Palomino, T.; Uceda-Rodríguez, M.; Moreno-Maroto, J.M.; Cobo-Ceacero, C.J.; Andreola, N.M.F.; Martínez-García, C. Application of Life Cycle Assessment in the Environmental Study of Sustainable Ceramic Bricks Made with 'Alperujo' (Olive Pomace). *Appl. Sci.* **2021**, *11*, 2278. [CrossRef]
84. Florentin, Y.; Pearlmutter, D.; Givoni, B.; Gal, E. A Life-Cycle Energy and Carbon Analysis of Hemp-Lime Bio-Composite Building Materials. *Energy Build.* **2017**, *156*, 293–305. [CrossRef]
85. Nwodo, M.N.; Anumba, C.J. A Review of Life Cycle Assessment of Buildings Using a Systematic Approach. *Build. Environ.* **2019**, *162*, 106290. [CrossRef]
86. Grant, A.; Ries, R. Impact of Building Service Life Models on Life Cycle Assessment. *Build. Res. Inf.* **2013**, *41*, 168–186. [CrossRef]
87. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) of Buildings and the Building Sector: A Review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416. [CrossRef]
88. Goulouti, K.; Padey, P.; Galimshina, A.; Habert, G.; Lasvaux, S. Uncertainty of Building Elements' Service Lives in Building LCA & LCC: What Matters? *Build. Environ.* **2020**, *183*, 106904. [CrossRef]
89. *UNI 10351:2015*; Materiali e Prodotti per Edilizia–Proprietà Termoigrometriche—Procedura per La Scelta Dei Valori Di Progetto. UNI—Ente Nazionale Italiano di Unificazione: Milan, Italy, 2015.