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Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential

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A B S T R A C T

The building industry uses great quantities of raw materials that also involve high energy consumption. Choosing materials with high content in embodied energy entails an initial high level of energy consumption in the building production stage but also determines future energy consumption in order to fulfil heating, ventilation and air conditioning demands.

This paper presents the results of an LCA study comparing the most commonly used building materials with some eco-materials using three different impact categories. The aim is to deepen the knowledge of energy and environmental specifications of building materials, analysing their possibilities for improvement and providing guidelines for materials selection in the eco-design of new buildings and rehabilitation of existing buildings.

The study proves that the impact of construction products can be significantly reduced by promoting the use of the best techniques available and eco-innovation in production plants, substituting the use of finite natural resources for waste generated in other production processes, preferably available locally. This would stimulate competition between manufacturers to launch more eco-efficient products and encourage the use of the Environmental Product Declarations.

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1. Introduction

At world level, civil works and building construction consumes 60% of the raw materials extracted from the lithosphere. From this volume, building represents 40%, in other words 24% of these global extractions. In Europe, the mineral extractions per capita intended for building amount to 4.8 tonnes per inhabitant per year [1], which is 64 times the average weight of a person, highlighting the need to work towards dematerialisation in building.

In Spain, every habitable square metre[1] of a conventional building requires a total of 2.3 tonnes of more than 100 types of materials. This figure represents only those materials that directly form part of the construction site. Additionally, if we consider the "Material Intensity per Service Unit" concept, which expresses the relationship between the weight of the resources (biotic, abiotic, air, water, erosion, etc.) affected by the manufactured goods process on the weight of the material produced, the previous figure is multiplied by 3, reaching 6 t/m^2 [1].

The manufacture, transport and installation in a building made of materials such as steel, concrete and glass require a large quantity of energy, despite them representing a minimal part of the ultimate cost in the building as a whole. This contradiction is known as the "Rule of the Notary" [2]. In addition, the extraction of minerals causes a significant reduction in the exergy of our planet's natural stock, which is mainly concentrated in iron ore with 63% of the total, aluminium with 24%, and copper with 6% [3,4], all of which are commonly used in construction.

The life cycle focus must help decision-making when selecting the best technology available and minimising the environmental impact of the buildings through their design or refurbishing [5,6]. Often, products that are presented as cheap in the medium term can have high maintenance or waste management costs and highly technological products can have very high production costs that are never recouped. Contrarily, it may be that when we consider the

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[1] The habitable area of a building is the usable area for housing, excluding other areas such as corridors, staircases, gardens, garages, streets, etc.

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Nomenclature

LCA	Life Cycle Assessment
GHG	Greenhouse Gases
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene
CED	Cumulative Energy Demand
GWP	Global Warming Potential
IPPC	Intergovernmental Panel on Climate Change
BREF	Best Available Techniques Reference Document

whole life cycle, materials with significant CO_2 emissions, such as concrete, can see their emissions reduced by giving them a second life as a filler material in infrastructure, with a double effect: the reduction of emissions compared with obtaining filler materials from quarries and the absorption of CO_2 due to the recarbonation processes. Therefore, it is fundamental to apply the life cycle vision and take into account both the economic and environmental costs when identifying the most eco-efficient technology.

The aim of this paper is to evaluate, based on the life cycle assessment method, the high impact in terms of energy and the environment of the construction materials most used at the moment in the building sector in comparison with the reduced impact of different eco-materials, proposing and assessing, whenever possible, specific measures for the reduction of these impacts in all stages of the product: manufacture, transport and final disposal. The improvements proposed in the manufacturing stage are based on the BREF on the best techniques available for energy efficiency, and for the different sectors to analyse (ceramic, cement, polymers, steel, etc.) with a time frame between 2007 and 2009.

2. State of the art: lca studies of building materials

Energy behaviour in several building materials [7] has been investigated outlining the importance of using recycled and natural building materials [8] due to their low level of incorporated energy, whenever quality requirements allow it.

Sixty studies of different buildings [9] located in 9 countries (including Sweden, Germany, Australia, Canada and Japan) have been performed and found that the proportion of embodied energy in materials used and life cycle assessed varied between 9% and 46% of the overall energy used over the building's lifetime when dealing with low energy consumption buildings (with good insulation, adequate orientation, passive conditioning, etc.) and between 2% and 38% in conventional buildings. The lifetime usually considered is 50 years. A lifetime of 30 years is considered only in one building and a longer lifetime (between 75 and 100 years) is taken in eight buildings. Other studies assert that in conventional buildings, located mainly in Northern and Central European countries, the embodied energy in materials is around 10–20%, while 80–90% corresponds to energy in the usage stage, and less than 1% to energy for end-of-life treatments [10]. In these studies the lifetime presents significant differences in each country. For instance, in the Netherlands the usual value is 75 years for dwellings and 20 years for offices, where as in the UK, 60 years is used for both commercial and domestic buildings, and in Finland and Switzerland 100 years and 80 years are considered respectively. The wide range in results is due to the variety of buildings, materials, the lifetime considered and the geographic and climatic conditions.

Different approaches and simplifications can be considered in order to perform an LCA for building materials [11]. In Spain, the amount of energy invested in manufacturing some specific materials for one square metre (considering the gross floor area) in

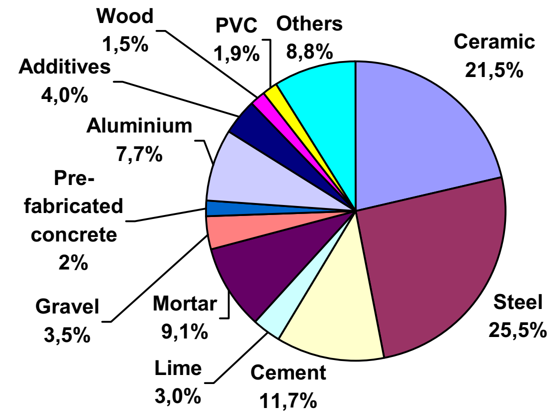

Fig. 1. Contribution of primary energy demand for the manufacture of the materials needed in the construction of 1 m^2 (gross floor area) [12].

a standard building equals the amount of energy produced from the combustion of more than 150 L of petrol [12]. Each squared metre built entails an average emission of 0.5 tonnes of carbon dioxide and an energy consumption of 5754 MJ (which is variable depending on the building design), only including the impact associated with materials. Fig. 1 and Fig. 2 show the relative contribution of the main building materials to the primary energy demand and CO_2 emissions associated with a square metre in a Spanish standard block of flats. The high impact of commonly used materials such as steel, cement and ceramics is notable.

There are numerous studies published in which the LCA is applied to evaluate the impact of different construction materials and solutions [13].

Within the area of thermal insulation, LCA studies have been carried out on kenaf [14] fibre boards, which lead to a significant reduction in environmental impact compared to other insulation based on synthetic materials. Similarly, based on the LCA and including energy, emissions and economic aspects, the advantages have been proven of External Thermal Insulation Composite Systems [15] that can reduce the energy consumption, CO_2 equivalent emissions and total economic cost in the life cycle by up to 20% when compared with conventional insulation.

At the same time, LCA studies have been carried out of different wood coverings for floors [16], whose opportunities for improvement are centred on the processes of laying, surface finish and maintenance, and the type of glues and varnishes used in each of these stages.

The environmental impact of phase change materials in Mediterranean buildings throughout the life cycle has been evaluated experimentally [17], obtaining a reduction in the energy

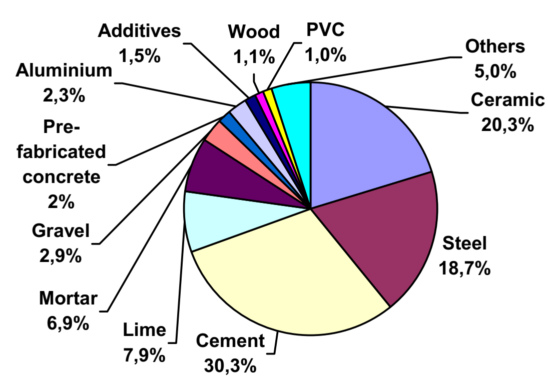

Fig. 2. Contribution of CO_2 emissions associated with the manufacture of the materials needed for the construction of 1 m^2 (gross floor area) [12].

consumption during the functioning of the buildings, but without significantly reducing the global impact throughout the service life of the building, with the energy impact associated with the manufacture of the materials used requiring 25 years to be compensated for by the energy savings obtained in the use of the building.

The environmental benefits, based on the LCA method, provided by green roofs have been widely studied [18–20].

Similarly there are several LCA studies on ceramic products [21–24] that note the high energy intensity of the production processes, especially the firing stage and the different improvement possibilities that exist.

The use of products such as adobe, despite increasing the embodied energy related to the maintenance of the building, reduces the embodied energy in the life cycle of the building [25] between 1.5 and 2 times compared with conventional materials.

Generally, the materials used for the structure of buildings represent more than 50% of the embodied energy in the building [26]. In this sense, the use of alternative materials, such as hollow concrete blocks, stabilised soil blocks or fly-ashes, instead of materials with a high embodied energy such as reinforced concrete could save 20% of the cumulative energy over a 50-year life cycle [27]. In addition, recycling building materials [28,29] is essential to reduce the embodied energy in the building. For instance, the use of recycled steel and aluminium confers savings of more than 50% in embodied energy [30].

The type of structure of the buildings strongly conditions the environmental assessment of the building. Within this subject, we have carried out comparative LCA studies of two different construction structures -steel and concrete- in office buildings [31]. Despite the energy per square metre for the manufacture of the steel structure being 25% lower than that needed to manufacture the concrete structure due to the poorer thermal transfer coefficient, considering the complete life cycle, the building with the steel structure has a greater impact in terms of primary power and emissions.

Studies of various countries have shown that buildings with wooden structures require less energy and emit less CO_2 during their life cycle than buildings with other types of structures [32–34]. For example, in a Canadian office building, the embodied energy in a steel structure is 1.61 times greater than that in a concrete structure, which in turn is 1.27 times greater than that of a wooden structure [35]. In northern European countries various life cycle studies have been carried out that indicate the advantages of wooden structures. Thus, the quantity of greenhouse gases avoided by replacing steel with wood in buildings in Norway and Sweden is 0.06–0.88 kg CO_2-Eq per kg input of timber; while replacing concrete with wood reaches 0.16–1.77 kg CO_2-Eq/kg [36], despite the fact that, depending on the treatments applied to the wood, there may be certain toxicological effects on human health and ecosystems. It is important to note that, under certain determining factors, blocks of flats with wooden structures and a biomass cogeneration system will manage to produce a net absorption of CO_2 in its life cycle [37].

3. Methodology

In this study the methodological standard in the regulations ISO 14040:2006 and ISO 14044:2006 with the hypotheses and simplifications listed below have been adopted.

The aim of this LCA study is to evaluate certain energy and environmental specifications of different building materials, analysing their possibilities for improvement and providing guidelines for materials selection.

The impact categories to analyse in this study were selected considering the current energy and environmental problem in the European area, and the need to reach the 20-20-20 targets. Therefore the impact categories considered in this study are primary energy demand (in MJ-Eq) according to the CED method, GWP (in kg CO_2-Eq) according to the IPPC 2007 methodology and water demand (in litres).

The CED method has been used since the seventies [38,39] as an indicator for energy systems. It states the entire demand is assessed as the primary energy which arises in connection with the production, use and disposal of an economic good (product or service) or which may be respectively attributed to it through cause. The CED distinguishes between non-renewable (fossil and nuclear) and renewable primary energy use (hydraulic, biomass, wind, solar and geothermal).

The anthropogenic greenhouse effect caused by the emissions from human activities can be expressed in terms of their GWP in CO_2-equivalents [40]. For this study, a GWP indicator has been evaluated based on 2007 IPCC characterisation factors [41] considering a time horizon of 100 years.

No method has been yet developed for incorporating desiccation into the LCA as desiccation potential. In the building sector, water consumption is nevertheless an important matter [42,43]. In the absence of a characterisation factor for desiccation, the indicator selected for this study aggregates all freshwater extractions (from rivers, lakes, ocean, soil and wells) including water used for cooling processes but excluding water used in turbines in hydraulic power production.

One kg of material is the selected functional unit and the stages considered are the material manufacture, the transport from production plant to building site, the construction and demolition of the building, and the final disposal of the product. The European averages of the Ecoinvent v2.0 database (2007) inventories were selected for all analysed stages [44–46]. As we are dealing with average data, its applicability to each European country depends on the level to which its specific characteristics (energy mix, manufacture technology, origin of the starting materials, etc.) are adapted to these averages. The study was carried out according to a static focus, so the life cycle inventories include intermediate values of the current processes within the system analysed, without analysing their variation over time. The software tool used in the study is SimaPro v7.1.8.

In the manufacture stage the supply of starting materials, the associated transport needs and the factory manufacturing processes of the different construction materials analysed are considered.

Regarding transport from the production plant to the building site, a 20–28 t lorry covering an average distance of 100 km has been considered. A sensitivity assessment for other means of transport has also been developed.

Table 1 shows the values to be applied in order to evaluate the impact of transporting 1 tonne by several means of transport from a linear correlation (Eq.(1)), where d_i is the distance travelled by each form of transport (in km) and m_i represents the coefficients applied to each form of transport.

Table 1
Impact calculation coefficients for transport stage from production plant to building site of 1 tonne.

Impact category	Lorry, road m_1	Freight rail m_2	Transoceanic freight ship m_3
Primary energy demand (MJ–Eq/km)	3.266	0.751	0.170
Global Warming Potential (kg CO_2–Eq/km)	0.193	0.039	0.011
Water demand (l/km)	1.466	1.115	0.097

Table 2
LCA results for several types of bricks and tiles.

Building product	Density (kg/m^3)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
Ordinary brick	1800	0.95	3.562	0.271	1.890
Light clay brick	1020	0.29	6.265	−0.004	1.415
Sand-lime brick	1530	0.7	2.182	0.120	3.009
Ceramic tile	2000	1	15.649	0.857	14.453
Quarry tile	2100	1.5	2.200	0.290	3.009
Ceramic roof tile	2000	1	4.590	0.406	2.456
Concrete roof tile	2380	1.65	2.659	0.270	4.104
Fibre cement roof slate	1800	0.5	11.543	1.392	20.368

$$\text{Transport impact} = m1 \times d1 + m2 \times d2 + m3 \times d3 \qquad (1)$$

Regarding the final disposal stage, the impact related to building demolition and the most common final disposal methods for materials [47] such as land-filling or incineration has been taken into account. Direct recycling at the building site was only considered for copper and aluminium. In accordance with the Ecoinvent method, the impact reduction due to recycling is fully allocated to the new secondary material created by recycling the primary material, but not the primary material itself.

4. Results and discussion

Tables 2–6 show results for grouped LCA studies according to different typologies of assessed building materials. It is worth mentioning that outcome impacts refer to 1 kg of material. The impacts could be different (depending on the density of the materials) if 1 cubic metre of material was considered as the functional unit.

4.1. Bricks and tiles

Within this group of products, ceramic floor tiles are those that have the greatest primary energy demand, mainly due to the high consumption of natural gas in their manufacture stage. In fact, the firing stage in the kiln can account for up to 80% of the total consumption in the production plant. In addition, the demand for water in the ceramic floor tiles -mainly evaporated in cooling processes- is 7.5 times greater than that of ceramic roof tiles and bricks.

At the same time, in countries such as Spain with red-pigmented clay, manufacturing ceramic floor tiles from white-pigmented clay requires this to be imported from distant countries, which multiplies the primary energy demand and emissions by a factor of 1.6, which would make it worthwhile to provide incentives for manufacturers to use local clays.

For exterior paving, the use of quarry tiles as opposed to ceramic tiles is recommended, and would lead to a saving in primary energy of 13.45 MJ-Eq/kg (86%) and a reduction in emissions of 0.57 kg CO_2-Eq/kg (66%).

At the same time, the high impact associated with fibre cement make it the worst option for use in roofs, where, in general, concrete tiles are preferable to ceramic tiles. Thus, ceramic tiles produce a saving of 6.95 MJ-Eq/kg (60%) compared to fibre cement roofs, and at the same time, concrete tiles lead to a saving of up to 1.93 MJ-Eq/kg (42%) compared to ceramic tiles.

Regarding bricks, the use of light clay bricks (85% clay and 15% straw) or silico-calcareous (90% lime and 10% sand) bricks clearly reduces the impact. Although in light clay bricks the primary energy demand is relatively high, it is important to note that 45% of this energy originates from biomass, due to the straw content. In addition, light clay bricks have a practically neutral CO_2 balance, so their use instead of conventional bricks prevents the emission of 0.27 kg of CO_2 per kg.

It is important to note the potential for reducing existing impacts in ceramic products associated with technological improvements in their manufacture, like for example, the replacement of old intermittent kilns with tunnel kilns with an increased energy efficiency of 20%, the use of high speed burners and the recovery of the heat from the kiln smoke to preheat/dry the product to be fired, thus achieving a reduction in the consumption of the kiln of 5% and 8% respectively, and the installation of cogeneration systems with a reduction of 10% in the primary power.

4.2. Insulation materials

It is important to underline that the impact of conventional insulation with a high level of industrial processing -such as EPS- is clearly higher than the impact of natural materials such as cork, wood fibre and sheep's wool, or recycled ones such as cellulose fibre. Thus, while insulation such as EPS or polyurethane emits on average 7 kg CO_2-Eq/kg with high consumptions of gas and petroleum, insulation of natural origin, such as sheep's wool, emits 98% less if its final disposal method is incineration. It could even become a carbon dioxide drain if it is recycled at the end of its service life. Therefore it is fundamental to promote a radical change in the architectonic-structural design of buildings that facilitates their disassembly.

Due to the ever more widespread use of the synthetic fabrics, for today's society sheep's wool has seen its market shrink and is already seen in many cases as a "waste product" that is difficult to use. The creation of production companies of wool for thermal insulation in buildings will convert this "waste" of our time into a cheap and abundant raw material, which in addition will contribute to sustainable and balanced development in rural areas.

At the same time, obtaining cork in the forests and farms in the south of Europe is one of the most ecological production types there is, as the cork is extracted from the tree during the summer every 10 years. This does not damage the tree and it contributes to

Table 3
LCA results of several insulation materials.

Building product	Density (kg/m^3)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
EPS foam slab	30	0.0375	105.486	7.336	192.729
Rock wool	60	0.04	26.393	1.511	32.384
Polyurethane rigid foam	30	0.032	103.782	6.788	350.982
Cork slab	150	0.049	51.517	0.807	30.337
Cellulose fibre	50	0.04	10.487	1.831	20.789
Wood wool	180	0.07	20.267	0.124	2.763

Table 4
LCA results for cement and concrete.

Building product	Density (kg/m^3)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
Cement	3150	1.4	4.235	0.819	3.937
Cement mortar	1525	0.7	2.171	0.241	3.329
Reinforced concrete	2546	2.3	1.802	0.179	2.768
Concrete	2380	1.65	1.105	0.137	2.045

Table 5
LCA results for wood products.

Building product	Density (kg/m^3)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
Sawn timber, softwood, planed, kiln dried	600	0.13	20.996	0.3	5.119
Sawn timber, softwood, planed, air dried	600	0.13	18.395	0.267	4.192
Glued laminated timber, indoor use	600	0.13	27.309	0.541	8.366
Particle board, indoor use	600	0.13	34.646	0.035	8.788
Oriented strand board	600	0.13	36.333	0.62	24.761

the maintenance of an ecosystem of high ecological value that would probably disappear if it were not of economic use. Despite the primary energy demand in cork tiles being slightly high, it is important to underline that more than 50% is of biomass origin so, in reality, this impact is very low.

The greatest impact in the insulation analysed was seen in expanded polystyrene tiles and rigid polyurethane foam. Both share the highest water footprint –mainly water evaporated in cooling processes– and the highest primary energy demand, due to the demand for substances such as natural gas and oil for different manufacturing processes. These processes, in conjunction with the final disposal of the products in municipal incinerators, also bring a greater impact in terms of global warming potential. In comparison with this insulation, the impact of rock wool includes a primary energy demand that is 4 times lower, a carbon footprint 4.7 times lower, and a water footprint 8.4 times lower. Nevertheless rock wool requires a certain consumption of coal to fuse the basaltic rock and the use of phenolic resins with a high specific impact.

Currently, there is a certain inertia in the use of conventional insulation, as there is a widespread commercial network that, therefore, generally leads to a lower price, linked to ignorance and, sometimes, scepticism among designers towards other more environmentally respectful solutions. To change this situation the various administrations must encourage the use of natural and/or recycled insulation materials, which provide a similar of higher level of insulation and thermal comfort in buildings, promoting the creation of a powerful commercial network for ecological insulation capable of competing in the same conditions with traditional insulation.

4.3. Cement and concrete

As shown in Table 4, the impact of cement (clinker, gypsum and limestone), mainly conditioned for the manufacture of clinker, is greater than that of cement mortar (cement and sand) and that of concrete (cement, gravel and water), as mixing cement with lower-impact materials such as gravel, sand or water helps reduce the impact.

It is important to point out that, even if the impact expressed per kilogramme is not excessively high, when the functional unit is changed to express the impact per cubic metre of material, due to the high density of all these products, the impact is high. In addition we must consider that these products typically make up 40–60% of the total weight of a conventional building, which greatly affects their environmental impact.

Table 6
LCA results for several common building products.

Building product	Density (kg/m^3)	Thermal conductivity (W/mK)	Primary energy demand (MJ–Eq/kg)	Global Warming Potential (kg CO_2–Eq/kg)	Water demand (l/kg)
Reinforcing steel	7900	50	24.336	1.526	26.149
Aluminium	2700	239	136.803	8.571	214.341
Polyvinylchloride	1400	0.17	73.207	4.267	511.999
Flat glass	2500	0.95	15.511	1.136	16.537
Copper	8920	380	35.586	1.999	77.794

The impact of reinforced concrete is much higher than that of mass concrete, as the inclusion of corrugated steel increases the impact notably. Thus, the increase in the primary energy demand is 700 MJ–Eq/t (+63%), and the emissions also increase by 42 kg/t (+31%).

At the same time, it would be interesting to use lime mortars instead of cement mortars, as they facilitate the transpiration of the buildings and absorb a noticeable quantity of CO_2 during the setting process, which can be up to 62% of the decarbonation and combustion process emissions, as opposed to cement or concrete mortars, where this absorption is less than 2%.

As has been mentioned, the influence of the clinker manufacturing process on the life cycle of all the products that use cement is highly significant, so in trying to reduce the impact of these products it is essential to achieve a more eco-efficient production of clinker, which acts as a starting material for all of them. Therefore, the cement industry must opt decisively for the replacement of conventional materials and fossil fuels with alternative materials and fuels for the clinker manufacturing process.

Even though in the majority of European countries the percentage of use of alternative fuels for manufacturing clinker is above 35% (even up to 80% in the case of Holland) in countries such as Spain this percentage is below 5%.

The use of alternative fuels in the cement industry entails an energy assessment of different types of waste, which would otherwise end up in a dump or incinerator, causing a higher environmental impact. This assessment means waste can be converted into resources, helping to close the cycle of the materials, a key concept for reaching a true industrial ecology.

To achieve this objective the use of alternative fuels in cement production plants must be favoured by all the public institutions, creating a suitable legislative framework. With this, in countries such as Spain, the equivalent emissions of CO_2 of the sector could be reduced by up to 30%, with an investment of between €1 M and €5 M per cement plant.

Comparing the current energy consumption of the clinker furnaces of 2900–3200 MJ/t with the theoretical energy consumption of 1700–1800 MJ/t, by means of continued technological improvement, by 2050 the CO_2 emissions of cement could be halved with respect to levels in 1990 [48]. Therefore it is recommended to apply diverse measures of technological improvement in clinker manufacturing plants, for example making better use of the residual heat from the furnace, reducing the sintering temperature and implementing fluidised bed technology in the medium term.

4.4. Wood products

In general, all construction materials based on wood have a lower-impact, especially specific products that require less industrial processing. The primary energy demand in all these products is basically from biomass, representing 69–83% of the total primary energy demand. The balance in equivalent carbon dioxide emissions is almost neutral, due to the low level of industrial processing and would be negative (net absorption of emissions) if product is recycled or reused instead of incinerated at the end of its life. We must consider that every m^3 of laminated wood (not incinerated at the end of its useful life) absorbs 582 kg of CO_2, while reinforced concrete emits 458 kg CO_2/m^3 and steel 12.087 kg CO_2/m^3.

All of this makes it advisable to modify the current legal framework for building in order to promote the design of buildings with wooden structures rather than conventional structures based on reinforced concrete, as in addition of the clear environmental advantages, wooden structures offer better resistance against fires. In the current climate of promoting and investing large amounts of money into the capture and confinement of CO_2 in thermoelectric plants, it must be considered that, provided the logging processes are sustainable, the use of structural wood in buildings entails a prior capture of CO_2 in the forests and a storage of this CO_2 for the whole useful life of the building (50 years at least), that in addition may be longer if the wood is reused at the end of its service life. This makes the buildings with wooden structures real "CO_2 warehouses" that should be encouraged by the Administrations.

Despite the low impact of these products, there is room for improvement, in particular related to the replacement of conventional urea-formaldehyde and melamine-formaldehyde resins with natural resins with the same specifications in the final product. With this, and depending on the quantity of resin used in each product, the equivalent emissions of CO_2 would be further reduced. On average, this reduction is estimated at 16% for laminated wood and 46% for fibreboard. In addition, obtaining natural resins is a traditional profession that in many areas is dying out. The use of new resin-farming techniques for use with different wood products would create jobs and wealth in the rural areas.

At the same time, in the right climates and periods, drying cut wood in the open air -humidity levels of up to 20-25%- rather than drying in a furnace would reduce the equivalent CO_2 emissions by 11%, simply by increasing the stock of wood to guarantee supply.

4.5. Other common products

A good number of materials currently used in the construction of buildings, such as steel, aluminium, copper, PVC and glass entail significant environmental loads, due to their high consumption of energy and raw materials in the numerous production processes that make up their life cycle. In addition, they are all products made in fully globalised industries, which multiplies the impact related to the transport. Thus in the case of aluminium, the need for transport amounts to 32,000 kg*km and 13,800 kg*km for copper, 6800 kg*km for steel and 2500 kg*km for glass.

Of all of these, aluminium is notable as its productive process has a high energy demand, especially electricity, which considerably raises its impact on primary energy demand and potential for global warming. Similarly, it is important to note the significant water footprint associated with the evaporation of water in the different cooling processes necessary for the production of PVC.

The reduction in the impact of the metals analysed occurs due to the increase in production of the secondary industry of steel, aluminium and copper to the detriment of the primary industry. This industry contributes to the depletion of reserves of iron, bauxite and copper and to the gradual increase in the energy costs of extraction, including high impact processes such as electrolysis and pyrometallurgy.

Therefore agreements must be established at international level to limit mineral extractions and establish incentives for the development of the secondary industry of these products, which would help increase their recycling, favouring the transformation of waste into resources that help preserve the planet's mineral reserves. Thus, every kilogramme of secondary steel produced prevents the emission of 1.2 kg CO_2–Eq (74%) with respect to the same quantity of primary steel produced. In the case of the secondary copper, the reduction is 1.7 kg CO_2–Eq/kg (64%), and 11.3 kg CO_2–Eq/kg (92%) in the case of secondary aluminium.

4.6. Discussion of methodology used

The aim of the analysis was to provide multiple criteria for decision-making [49], according to the values of three different impact categories for several building materials. It is evident that in countries with a water deficit the water demand will have a greater importance than in those that have abundant water resources. For these reasons, the use of single scores calculated from a weighted sum of different values, such as the total score of Eco-indicator 99 [50], has been avoided as they can be subjective.

The functional unit selected was 1 kg of material. This can be useful to initiate accounting of the building LCA, but it is useless to compare the relative merit of two materials if these materials have different physical properties. The main reason is that the materials to be compared are needed to perform a function or meet a need. If their physical properties are different, the mass of each material needed to perform the desired function could be different. For instance, the embodied energy of columns made of reinforced concrete, steel or compressed soil block are similar in magnitude for an equal net supported load: while the steel is very strong and highly energy intensive, the block is neither. However, these properties compensate each other when the column has the same function and there is no significant difference between the three materials.

5. Conclusions

To avoid the production of materials affecting the natural resources it is necessary to promote the use of the best techniques available and innovation in production plants and to replace, as far as possible, the use of finite natural resources with the waste generated in different production processes, closing the cycles of the products. This involves committing decisively to reuse and recycling, and always minimising the transport of the starting materials and products, promoting the use of resources available in local areas.

The results of this paper should be considered as an approximation to real environmental impacts of assessed building materials. For the majority of the materials analysed in this paper, the impact was observed to be, in the medium term, between 20 and 30% greater than the impact obtained in other studies. These differences are justified by the broader limits of the system considered in this study and other hypotheses related to the life cycle assessment method (data quality requirements, useful life, energy mix, end-of-life scenarios, etc.). For instance, the GWP obtained in this study for an ordinary brick was 23% higher than in other studies that neglect some stages and processes (such as disposal and infrastructures) and consider other less pollutant firing fuels. Nevertheless the results show clear tendencies in the impact related to the use of such materials.

With this we can conclude that it is important to extend, adjust and harmonise the existing inventory databases of construction materials to the characteristics and peculiarities of the construction industries in each country. To facilitate this task, the public institutions must urge the manufacturers of materials to use EPDs (or type III ecolabels defined according to the ISO nomenclature), verified by independent entities that provide standardised information based on the LCA of the real impact of every product. This would then stimulate competition between materials manufacturers to launch more eco-efficient products onto the market, which would be more highly regarded by the construction sector as opposed to other products without EPDs, as they would be able to offer a new range of buildings that really do have a low environmental impact, not only due to their low final energy consumption, but also due to the reduced impact of the materials that comprise them. In this sense, there would be accurate information on the impact of each product, which would facilitate a correct assessment of the impact of a building from an LCA perspective. Without this information, this impact can only be estimated approximately using existing inventories that, on occasions, are difficult to adapt to the reality of a specific geographical area.

Currently, the demolition of buildings at the end of their service life makes it very difficult to separate the different materials, and most end up in landfills and/or incinerators. Therefore, for the recycling of construction materials to be possible, it is necessary to promote a radical change in the design of buildings, to favour the disassembly of the construction materials at the end of their service life. For this purpose, the joints between the different materials must be reversible, such as bolted joints, avoiding adhesion as far as possible. This significant conceptual change is already a reality in the automobile sector for example, where the current regulations lead the manufacturers to design their vehicles to facilitate the recycling of the different components by selecting the materials, more and more from recycled sources, and assembly techniques well.

Finally, any sustainable building strategy should be implemented within the framework of a more general strategy of sustainable decline, in such a way that possible rebound effects are avoided, ensuring a per capita decrease in the consumption and exploitation of natural resources. For this purpose, among other aspects, moratoria must be established for the construction of new buildings and large infrastructures, and a population decrease must be promoted. Nevertheless, the modelling of the effects of this decrease in the social, economic, energy and environmental areas is beyond the scope of this paper and should be approached in future work.

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