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Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions

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ABSTRACT

In the European Union, the building sector accounts for more than 40% of the total energy consumption and environmental impacts, representing the area with the greatest potential for intervention. In addition to the existing policies that promote energy efficiency in buildings, the embodied energy and the environmental impacts contained in the building materials should be considered. In the case of the construction of insulation façade systems, the environmental implications are different depending on the type of façade system, the insulation materials used and the location of the building. This article aims to provide all of this information for Spain, including not only the production of the components of the façade system but also the installation phase and the transport to the building site. The results show that the most impactful alternative is the ventilated façade combined with the most impactful insulation materials of stone wool and expanded polystyrene. Meanwhile, the most advisable façade in all of the climate zones is the external thermal insulation system combined with any type of insulation. The environmental impacts of insulation materials are very different. Moreover, it is recommended that further studies complete these results with the economic and social implications of the use and maintenance phases for robust decision-making.

1. Introduction

In the European Union (EU), buildings are one of the leading environmental sectors, accounting for more than 40% of the total energy consumption and environmental impacts (European Comission, 2010). However, the building sector also represents the area with the greatest potential for intervention (Proietti et al., 2013). Therefore, increasing building energy efficiency is crucial for the transformation of the EU energy framework (European Commission, 2011b). Indeed, the sustainability concerns of Horizon 2020 could strongly impact the future of the European construction industry (Pacheco-Torgal, 2014a). More sustainable construction and efficient use of buildings in the EU would decrease the final energy consumption by 42%, greenhouse gas emissions by approximately 35%, all extracted materials by more than 50% and water use by up to 30% (European Comission, 2011a). The existing energy policies promote energy efficiency and renewable energy use in buildings, such as in the European Energy Performance of Buildings Directive 2002/91/EC (EPBD) (European Commission, 2010). This directive introduces the concept of nearly zero-energy buildings (NZEB) and establishes that all new construction must be NZEB by the 31st of December 2020. For public buildings, the deadline is even sooner: the end of 2018.

The implementation of these regulations means less energy consumption during the use phase of the building, called the operating energy, used to maintain the inside environment through heating and cooling, lighting and operating appliances. However, in addition to the operating energy, the total life cycle energy of a building also includes the embodied energy, which is the sequestered energy in building materials throughout all of processes of production, on-site construction, final demolition and disposal. If all efforts focused on reducing operational energy, the relative

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Nomenclature

EPBD	Energy Performance of Buildings Directive
XPS	Extruded polystyrene
EPS	Expanded polystyrene
PU	Polyurethane
SW	Stone wool
GW	Glass wool
ETICS	External Thermal Insulation Composite System
NZEB	Nearly zero-energy building
SME	Small and medium-sized enterprises
LCA	Life cycle assessment
DIN	German Institute for Standardization
DU	Declared unit
EN	European norm
CML	Institute of Environmental Sciences
ADP	Abiotic depletion potential
AP	Acidification potential
EP	Eutrophication potential
GWP	Global warming potential
OLDP	Ozone layer depletion
PCOP	Photochemical oxidation
EE	Embodied energy

importance of the embodied energy of materials will be more relevant with regard to the baseline situation (Thormark, 2002; Pacheco-Torgal et al., 2010). Therefore, according to the European Commission (2011a), reducing embodied energy needs to be further strengthened and complemented with policies for resource efficiency, which look at a wider range of environmental impacts across the life cycle of buildings and infrastructure. In this way, life cycle thinking represents a basic concept of considering the whole product system life cycle from the "cradle to the grave" and aims to prevent individual parts of the life cycle from being addressed in a way that results in the environmental burden being shifted to another part (Finkbeiner et al., 2010). Life cycle assessment (LCA) is the methodology used to quantify and identify the potential environmental impacts throughout a building's life cycle (ISO/EN 14040 2000).

The LCA methods used in sustainable building can be classified into three main groups: process-based LCA (ISO/EN 14040 2000), input–output-based LCA (Carnegie Mellon University Green Design Institute, 2008) and hybrid LCA (Treloar et al., 2000), which is the integration of the two methodologies. In a process-based LCA, one itemizes the inputs and the outputs for a given step in the construction of a single building or several buildings. Input–output LCA is a model that considers not only the direct effects of resources and related emissions to the environment but also all of the indirect effects involved in the supply chain. Hybrid LCA is proposed for complex products, such as construction projects, and integrates the comprehensive input–output model with more reliable LCA data (Onat et al., 2014; Guinée et al., 2011). Moreover, a new dimension of this methodology has been developed with the inclusion of the triple bottom line (TBL)-based LCA model; this model quantifies not only the environmental loads but also the social and economic impacts (Wiedmann and Lenzen, 2006).

Focussing on the environmental implications, LCA has recently increased its international acceptance in the building sector (Zabalza Bribián et al., 2009) and is employed for the selection of environmentally preferable products as well as for the evaluation and optimization of construction processes (Asdrubali et al., 2013). A certain awareness of the embodied energy and the environmental impacts of building materials could encourage the use of not only the production and development of more sustainable materials but also their preference among construction design and industry (Cabeza et al., 2013). Consequently, less use of resources will lead to fewer emissions, therefore reducing the environmental impacts in the construction of the building and identifying improvement opportunities towards more sustainable solutions. In addition, LCA is widely used to compare different alternatives in the design of buildings. Most studies have focused on building solutions: different types of exterior walls (Monteiro and Freire, 2012; Islam et al., 2014; González-García et al., 2012), the structure of the building (Xing et al., 2008) and, more recently, green roofs (Pérez et al., 2012; Cerón-Palma et al., 2013). In these studies, the parameters used to compare different alternatives are the composition of the building system and the materials used in each solution along with considering the location of the building as a comparison between alternatives (Dean et al., 2006; Richman et al., 2009; Ramesh et al., 2012). LCA can also be a support tool in the selection of the materials to include in the solutions. Zabalza et al. (2011a) used the process-based LCA framework to evaluate the environmental impacts of different building materials used in different construction solutions, including floors, roofs, the structure and insulation materials. Moreover, some studies have focused on the evaluation of the embodied energy and the embodied CO_2 inherent in building materials (Dixit et al., 2010, 2012; Cabeza et al., 2013; Moncaster and Symons, 2013).

Among the building materials, the thermal insulation materials have recently drawn increased interest in the environmental field (Papadopoulos, 2005; Anastaselos et al., 2009; Jelle, 2011; Pargana et al., 2014). These types of materials have an important role because, in addition to influencing the environmental impacts of construction, they also influence the use phase of the building. For example, the introduction of insulation in the building envelope can decrease the energy demand in buildings by 64% in summer and up to 37% in winter and can also decrease the CO_2 emissions (Cabeza et al., 2010). Therefore, a first move towards efficient use of operating energy is to reduce the energy required to maintain a good interior temperature. According to the NZEB, the use of passive solutions for the envelope will result in increased insulation thicknesses in buildings. Thus, the contribution of these materials to the life cycle environmental impact of buildings is critical (Pargana et al., 2014), and the environmental assessment of different insulation solutions is a strategic issue in building sustainability. Almost all existing LCAs of insulation materials focused on the comparison between the environmental impacts generated by a given amount of material with the same thermal insulation requirements (Schmidt et al., 2004; Ardente et al., 2008; Kymäläinen and Sjöberg, 2008; Proietti et al., 2013; Pargana et al., 2014; Batouli et al., 2014). However, very few international studies have included how the insulation solution will be installed, which is an important factor to consider when comparing different building materials (Tettey et al., 2014; Densley Tingley et al., 2015). These installation parameters are defined by the construction system itself as well as the type and amount of material to install (CSIC, 2008; Ministerio de Vivienda, 2013; ISOVER, 2013). The amount of material to be installed will also be determined by the climatic conditions at the building location. Therefore, any factor that influences the amount of insulating material should be included in the environmental assessments.

Unlike other European countries where only one (Germany and United Kingdom) or two (France) climate zones exist, Spain has five areas with four sub-divisions with very different climatic conditions (Rodríguez-Soria et al., 2014; Ministerio de Vivienda, 2013). The insulation requirements for the same building in each climate zone are very different, resulting in a huge quantity of data to analyse and a complicated and unknown optimization of the insulation thickness required from a balanced combination of the energy demand and the environmental impacts. To our knowledge, no information has been published related to the environmental effect of the climatic conditions on the optimum combination of building façade systems and thermal insulation materials. This paper will help to fill this gap by providing a detailed environmental impact assessment comparing different construction systems in Spain, which includes different climate zones with diverse climatic conditions. Therefore, the desirability of the insulation materials will be very different. The novelty of the paper also consists of the inclusion of the installation phase in the environmental assessment of thermal insulation materials, which are applied in different building façade systems.

The article aims to determine the best environmental alternative for the thermal insulation of a building façade located in Spain and to evaluate the environmental impact of the most common types of façade systems. The specific objectives are:

- To develop an inventory of the materials, machinery and energy consumption in the production, transport and installation phases of the life cycle of the façade systems analysed.
- To assess the environmental impact of the different façade systems considering different insulation materials to determine the least impactful construction alternatives under different climate conditions.
- To compare the environmental impact of different insulation materials in each façade system according to the different climate zones in Spain.

2. Materials and methods

2.1. Insulation materials under study

The European market of insulation materials is still dominated by two groups of products. Inorganic fibrous materials account for 60% of the market, primarily consisting of stone wool (SW) and glass wool (GW). Organic foamy materials account for approximately 30% of the market, the most common of which is expanded polystyrene (EPS), followed by extruded polystyrene (XPS) and the less widespread polyurethane (PU) (Papadopoulos, 2005; Ardente et al., 2008). All of the other materials accounted for less than 13% together, including insulation cork board (ICB), wood wool, and Aerogel. These materials have been encouraged as efficient insulation and sustainable solutions (Korjenic et al., 2011). However, few studies have been published about these alternative materials (Dias et al., 2014; Pargana et al., 2014; Proietti et al., 2013; Rives et al., 2013, 2012a, 2012b; Baetens et al., 2011). This study considers the environmental assessment of the most common materials, representing 90% of the worldwide market: SW, GW, EPS, XPS and PU.

2.2. Description of the façade systems under study

This section illustrates in detail the structural features, construction and installation of the various façade systems included in the study and those most commonly used in Spain for both new construction and retrofitting (Fig. 1) (ISOVER, 2013; IDAE, 2012).

2.2.1. External Thermal Insulation Composite Systems (ETICS)

External Thermal Insulation Composite Systems (ETICS) are a constructive system for façades composed of multiple layers: the wall, the insulation material, the fixing on the substrate, the reinforcing intermediate coating, reinforcement mesh and a decorative finish coating. The objective of ETICS is to minimize the heat bridges and losses and to remain reliable and durable to protect the building against environmental and climatic factors. The system must have high resistance to mechanical stress, impermeability to water and permeability to CO_2 and water vapour. Insulation boards are fixed on the wall with adhesive mortar and/or dish-shaped dowels depending on the quantity and type of insulation and the type of substrate.

2.2.2. Ventilated façade

The ventilated façade is a system consisting of a multi-layered building envelope with an outer layer made of different materials (metal, stone, wood facade boards (bars), composite, ceramic granite, etc.) that is mechanically connected by a galvanized steel, stainless steel or aluminium frame to the inner layer. This inner layer is insulated from the outside with board or foam insulation and is attached with adhesive mortar and/or dish-shaped dowels, depending on the thickness and type of insulation. The ventilated façade allows free air circulation through the intermediate cavity, removing moisture and improving the energy performance of these façade systems under the effect of the solar radiation relative to conventional façades. Furthermore, the installation of the insulation material outside the main wall eliminates thermal bridges, which are localized areas of the building envelope where the heat flow is different (usually increased) compared to the adjacent areas.

2.2.3. Internal insulation façade

The internal insulation façade is a construction solution of an enclosure composed of an outer main wall, insulation and inner cladding. The insulation layer is fixed with metallic profiles that are mechanically connected to the floor and ceiling. This system is the most common for the construction of new building facades and the rehabilitation of existing buildings. The inner insulation separates the thermal mass of the walls of the living space and reduces both the response time and the energy required to achieve thermal comfort. Internal insulation is one of the cheaper options but must take into account the interruption of insulation in the ceilings and walls, which can produce thermal bridges.

2.3. Climate considerations in the selection of façade systems

Considering the climate zone where the facade is located should take into account several factors that can influence the performance of the solutions. The most important factors are:

1) Solar radiation that supports the façade.
2) The thermal inertia of the whole façade.
3) The evacuation of the possible condensation produced.

For the first parameter, the facades located in warm zones will have more impact from sunlight and high outside temperatures. For these areas, the ventilated facades prevent heat from entering into the building, maintaining comfortable temperatures in summer. The white colour of the external coating of ETICS will reflect the sunlight. Thermal inertia will influence climates that have marked temperature changes between day and night. Therefore, the ceramic block used in ETICS as the internal wall allows a

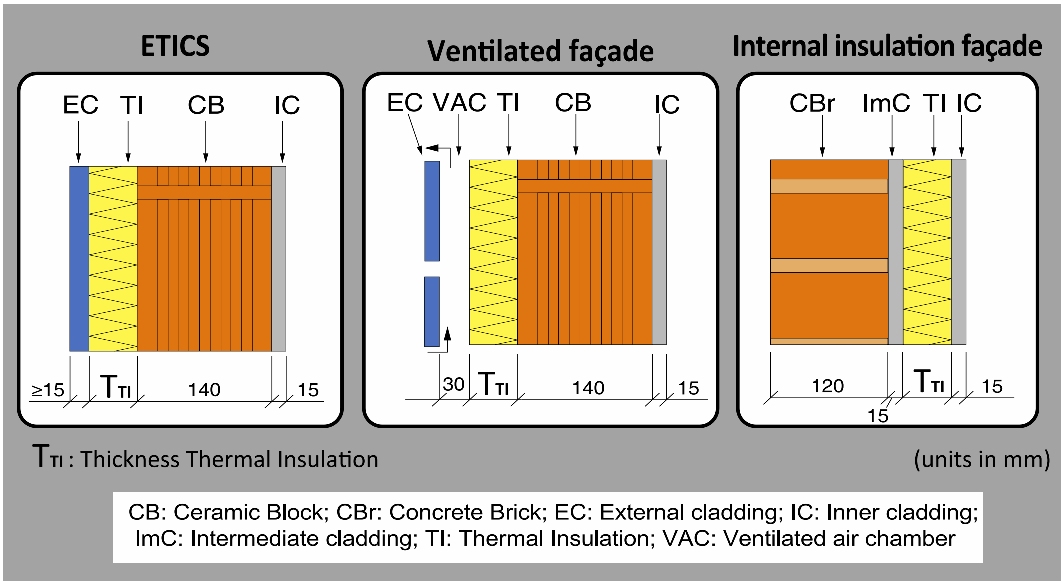

Fig. 1. Constructive details of the studied façade systems (CSIC, 2008).

constant temperature within the building even though the outer conditions change throughout the day. Finally, rain or temperature changes can cause condensation of water vapour. ETICS is the least used in the wetlands, either by rain or coastal areas, because the outer coating is more easily degraded and requires maintenance actions. To facilitate the evacuation of condensation, different solutions included in the internal insulation façade and ventilated façade systems are recommended.

2.4. Declared unit

The declared unit (DU) is used instead of the functional unit when the precise function of the product or building-level scenarios are not stated or known. In this case, to insulate a given surface of a building façade, the amount of insulation material required will vary depending on the type of construction solution and the geographic location of the building, among other factors. A DU has been established according to the environmental product declaration (EDP) for construction products EN 15804:2014 (European Committee for Standardization, 2014) to compare the environmental impacts of the construction solutions based on the different insulation materials.

The DU is the production, transport and installation of the necessary quantity of materials to construct 1 m^2 of the three façades systems selected. The use and maintenance phase and end-of-use phase were excluded from the study. The use phase includes large variations in energy consumption when the building is inhabited due to the influence of factors such as climatic conditions, building orientation, building occupation, and buildings that are attached to it. The end-of-life phase includes different processes by both type of material and type of final treatment (recycling, reusing, disposal in the landfill, incineration, etc.). Each possibility supposes great variations in the environmental impacts and energy consumption. Therefore, it is necessary to assess the building by focussing on the construction phase to clearly visualize the variations in the environmental impacts from the construction of different solutions in different climate zones.

As noted above, commonly used building insulation materials have been selected for the study: EPS, XPS, PU, SW and GW. To establish an adequate quantity of each insulation material, the DU must be related to the heat transferred through it (Papadopoulos and Giama, 2007; Ingrao et al., 2014; Pargana et al., 2014), using the following equation to calculate the amount of insulation required:

$$DU = R\lambda\rho A \tag{1}$$

where R represents the thermal resistance (m^2 K/W), which is a heat property and a measurement of the temperature difference by which a material resists heat flow. The greater the R value is, the more insulation material there is. The inverse of R is also used, which is called the thermal transmittance (U). The factor λ is the thermal conductivity (W/m K), which is the most important property of any thermal insulation material, i.e., the low capacity of a substance to transport thermal energy (Pfundstein et al., 2012). ρ corresponds to the density of the material (kg/m^3), which is shown in Table 1. A is the surface of the façade (m^2), which is 1 m^2. Consequently, to determine the adequate quantity of the insulation material, a thermal transmittance value of U = 0.27 (W/m^2 K) or R = 3.7 (m^2 K/W) has been established to insulate the façades (Table 1). These values are according to the parameters required by the Spanish Technical Building Code for a building located in Spain in the climate zone “D” in any of its sub-divisions (Ministerio de Vivienda, 2013). This climate zone is the largest in Spain and is the climate zone with the second highest winter and summer severity (Rodríguez-Soria et al., 2014). If we take Zaragoza as a reference city, from the Spanish State Meteorological Agency (AEMET), the monthly/annual average maximum daily temperature is 21 °C and the monthly/annual average minimum daily temperature is 10 °C.

Additionally, a sensitivity analysis focused at the location of the building has been performed. Several climate zones have been defined in Spain. The climate zones are determined from the calculation of winter and summer severities as recorded in each locality through the combination of the degree days and solar radiation. Therefore, the requirements of insulation are different for each climate zone, i.e., the data for thermal transmittance (U) is different for each climate zone, which changes the insulation thickness. Table 2 shows the insulation required in each climate zone for each type of façade system, with “α” being the warmest climate zone and “E” being the coldest.

2.5. Methodology

The LCA methodology is used in this paper, conducting a process-based LCA framework to evaluate the environmental impact of building façade systems and the thermal insulation materials for different climate conditions. This study has a cradle-to-site approach, meaning that the environmental impact analysis includes the production (extraction and processing of raw materials, transport to manufacturer and manufacturing), transportation to the building site and the installation in the building (Fig. 2).

The limitations of this research include the selection of a unique building façade system in isolation and not as part of an entire building. Thus, for example, the use of scaffolding, the need for cranes or the displacement of workers to the building are excluded from the study.

2.5.1. Inventory data

The inventory data for the production of materials used in construction and installation of the façades under study and for their transport to the building location were collected from different sources of information. The Supplementary data section contains the specific data for each process and the reference of the source where the data were collected. Table 3 presents the assumptions made in the LCA.

The software Simapro 7.3 was used (PRé Consultants, 2010), and the ecoinvent 3.1 database was used to obtain the environmental information related to the processes involved with the materials, energy and transport (ecoinvent 2009). The results of the LCA do not represent “exact” or “precise” data but are affected by several uncertainty sources. However, the trend of the results can be meaningful. The information of the inventory of the construction process and the environmental information are obtained from the same database. Therefore, the asymmetries will be reduced, allowing for the comparability of the different façade systems and insulation materials. Moreover, the building sector has not experienced important technological changes in the last year, so the frequency of the database updates is not critical in this study.

2.5.2. Impact categories

According to the European standard that provides the core product category rules for all construction products and services, EN 15804:2014 (European Committee for Standardization, 2014), the following six midpoint impact categories from the CML 2 baseline 2002 (Guinée et al., 2002) were included in the assessment: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (OLDP) and photochemical oxidation potential (PCOP). Additionally, as noted above, the embodied energy (EE) has been included due to its increasing importance in the building energy demand.

2.5.3. Environmental impact assessment of the construction solutions

The assessment of the façade systems requires data about the insulation materials, quantity, and installation. According to the established DU and the building technical considerations, the Supplementary data indicates the materials and energy content for 1 m^2 of the various façade systems.

For the installation phase, the materials and energy for the assembly of all of the components were considered. Different solutions exist for fixing the insulation that depend on the façade system, the type of insulation materials, and the insulation thickness. In the case of ETICS and ventilated façades, the insulation board is attached on the outside for all of the climate zones and must be fixed with adhesive mortar for XPS and EPS and for thickness less than 40 mm. The dish-shaped dowels are used for PU, SW and GW and for XPS and EPS boards with thicknesses greater than 40 mm. In the case of the “D” climate zone, all of the insulation materials are greater than 40 mm thick, so all of the insulations are fixed with the same elements: adhesive mortar and dish-shaped dowels. For ventilated façades, the fixation of insulation is made with the metals profiles that hold the external cladding. In the case of the internal insulated façade, the same fixation solution is used for all of the materials, thicknesses and climate zones: a structure made of metallic profiles attached to the ceiling and the floor and where the insulation boards are fitted.

3. Results and discussion

3.1. Comparison of the environmental impact of the different façade systems

The life cycle impacts of 1 m^2 of the various façade systems are presented in absolute values in Fig. 3 and are disaggregated in the following sections.

A comparison of the construction solutions for façades reveals differences between the environmental impacts derived from each system due to the insulation material used. Related to the construction systems, the ventilated façade has the greatest impacts in most categories, except for in AP and PCOP, for which the internal insulation façade has 6% and 13% greater impacts, respectively. ETICS has the lowest value in most of the categories, except for EP, GWP and OLDP, for which it has similar values as the internal insulation façade. There are important differences between façade systems in the EE category, especially the ventilated facade with respect to the other facade systems. The results for the ventilated façade are 30–70% greater than the ETICS results and 15–40% greater than the internal insulation façade results. The desirability of designing buildings with a particular type of façade will be analysed in future studies that include the efficiency of each façade system in the use phase of the building.

Table 1
Declared unit (kg) required of insulation per façade system to provide a thermal resistance in “D” climate zone in Spain.

		XPS	EPS	PU	SW	GW
Thermal conductivity (λ) (W/m K)		0.032	0.035	0.023	0.039	0.036
Density (kg/m^3)		20	35	31	130	21.8
ETICS	Thickness (m)	0.10	0.11	0.07	0.13	0.12
	Weight (Kg)	2.06	3.95	2.30	16.35	2.53
Ventilated façade	Thickness (m)	0.10	0.11	0.07	0.12	0.11
	Weight (Kg)	2.0	3.8	2.2	15.8	2.5
Internal insulation façade	Thickness (m)	0.11	0.12	0.08	0.13	0.12
	Weight (Kg)	2.2	4.2	2.5	17.5	2.7

Table 2
Declared unit (m) required of insulation per façade system to provide a thermal resistance in the climate zones established in Spain.

			XPS	EPS	PU	SW	GW
Thermal conductivity (λ) (W/m K)			0.032	0.035	0.023	0.039	0.036
Density (kg/m^3)			20	35	31	130	21.8
		U-value	Thickness (m)				
ETICS	Climate α	0.94	0.02	0.02	0.01	0.02	0.02
	Climate A	0.5	0.05	0.05	0.03	0.06	0.05
	Climate B	0.38	0.07	0.07	0.05	0.08	0.08
	Climate C	0.29	0.09	0.1	0.07	0.11	0.11
	Climate E	0.25	0.11	0.12	0.08	0.13	0.12
Ventilated façade	Climate α	0.94	0.01	0.02	0.01	0.02	0.02
	Climate A	0.5	0.04	0.05	0.03	0.05	0.05
	Climate B	0.38	0.06	0.07	0.05	0.08	0.07
	Climate C	0.29	0.09	0.1	0.07	0.11	0.1
	Climate E	0.25	0.11	0.12	0.08	0.13	0.12
Internal insulation façade	Climate α	0.94	0.02	0.02	0.01	0.02	0.02
	Climate A	0.5	0.05	0.06	0.04	0.06	0.06
	Climate B	0.38	0.07	0.08	0.05	0.09	0.08
	Climate C	0.29	0.1	0.11	0.07	0.12	0.11
	Climate E	0.25	0.12	0.13	0.09	0.14	0.13

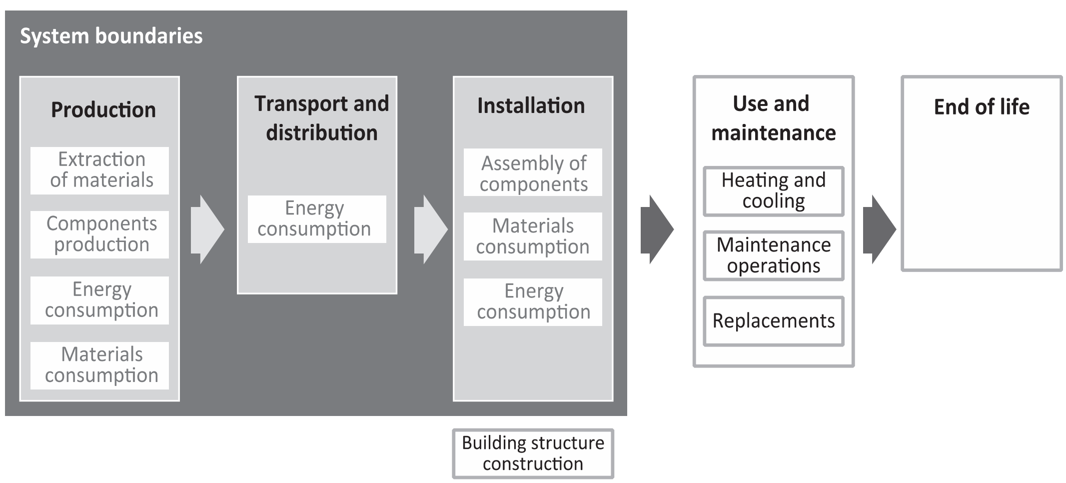

Fig. 2. Diagram of the façade life cycle and system boundaries.

Table 3
Main assumptions for the Life Cycle Analysis.

Assumption	Inventory data	Reference
The lifespan of the façade	50 years	(Monteiro and Freire, 2012; Sharma et al., 2011; Sartori and Hestnes, 2007)
The distance for transport from factory to the building location	100 km	(Sanjuan-Delmás et al., 2014; Zabalza Bribián et al., 2011a; Oliver-Solà et al., 2009)

3.1.1. Environmental impacts of the production phase

With regard to the data disaggregated by phase of the life cycle, for the ETICS and ventilated façade, the greatest impacts are concentrated in the production phase, accounting for 60–90% of the global impact (Fig. 4). As noted above, the ventilated façade system is more complex than the ETICS and internal insulation façade system. In environmental terms, the ventilated façade has the largest impacts in the production phase. Regarding the contribution from materials to the environmental impact of the production phase, the external cladding with the metallic frame contributes the most to the total embodied energy (See Supplementary data). However, its performance during the use phase is better than the other systems. The ETICS construction system is not as complex, but the other life cycle phases do not represent significant impacts. In this case, the concrete brick has the highest impact on the composition of the façade (See Supplementary data). For the internal insulation façade, the production phase accounts for 20–70% of the total impact. Its construction solution is very simple, containing few processes and materials associated with this phase. This is the façade system where the insulation represents the most influential material in the production phase (See Supplementary data).

3.1.2. Environmental impacts of the transport phase

For the transport phase, the differences between the alternatives by type of construction solution are related to the amount of material to construct 1 m^2 of the façade for each system. Depending on the insulation material used, different quantities will be required for each alternative. Therefore, the rest of the material required is the same for each facade system, and the differences in the impact are derived from the production phase.

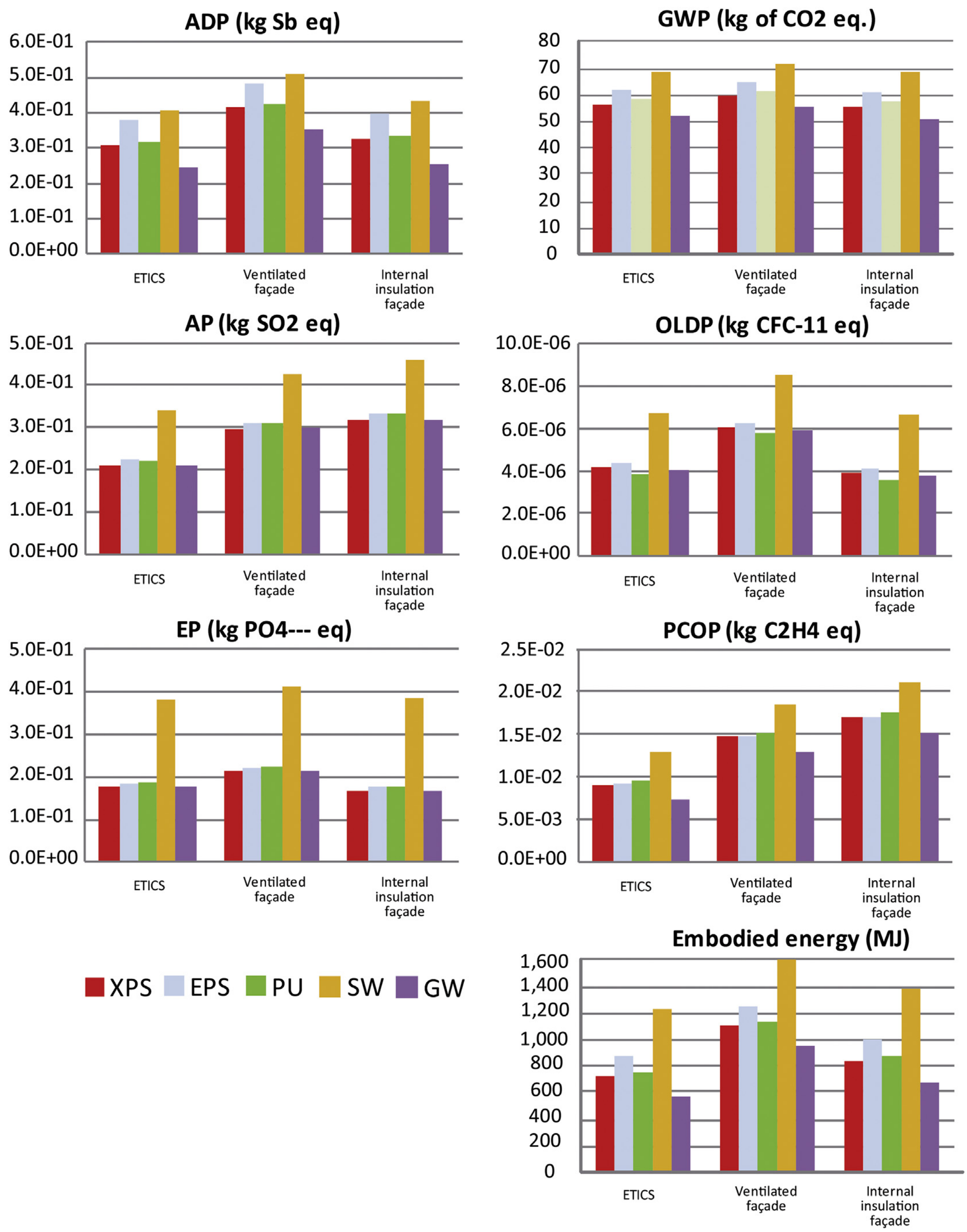

Fig. 3. Environmental comparative between combinations of façade systems with different insulation materials.

3.1.3. Environmental impacts of the installation phase

The quantity of insulation material used in the installation for each facade systems is the same in all of the insulation alternatives because they are within the same climate zone. The insulating panels required in ETICS and the ventilated façade exceed 40 mm of thickness. Therefore, these systems must be fixed with dish-shaped dowels using building machineries with significant energy consumption that represent higher impacts during the installation of the façade (See Supplementary data). For the internal insulation façade, the installation phase produces a great portion of the environmental impact in most of the alternative insulation materials, reaching more than 70% of the global impact in several alternatives (Fig. 4). This phase exceeds the values of the production phase in all the GW impact categories and for the rest of the insulation materials in AP, EP, OLDP and PCOP. The metallic profiles required in this type of façade greatly influence the environmental impacts in the installation phase (See Supplementary data).

The high environmental impacts of the metal profiles may be due to two reasons: 1) the construction solution is very simple itself, so the production phase contains fewer processes and materials and hence is less relevant; and 2) the system used to fix the insulation boards are made from metallic materials (aluminium profiles), which have a significant environmental impact. Therefore, an opportunity for environmental improvement is observed here,

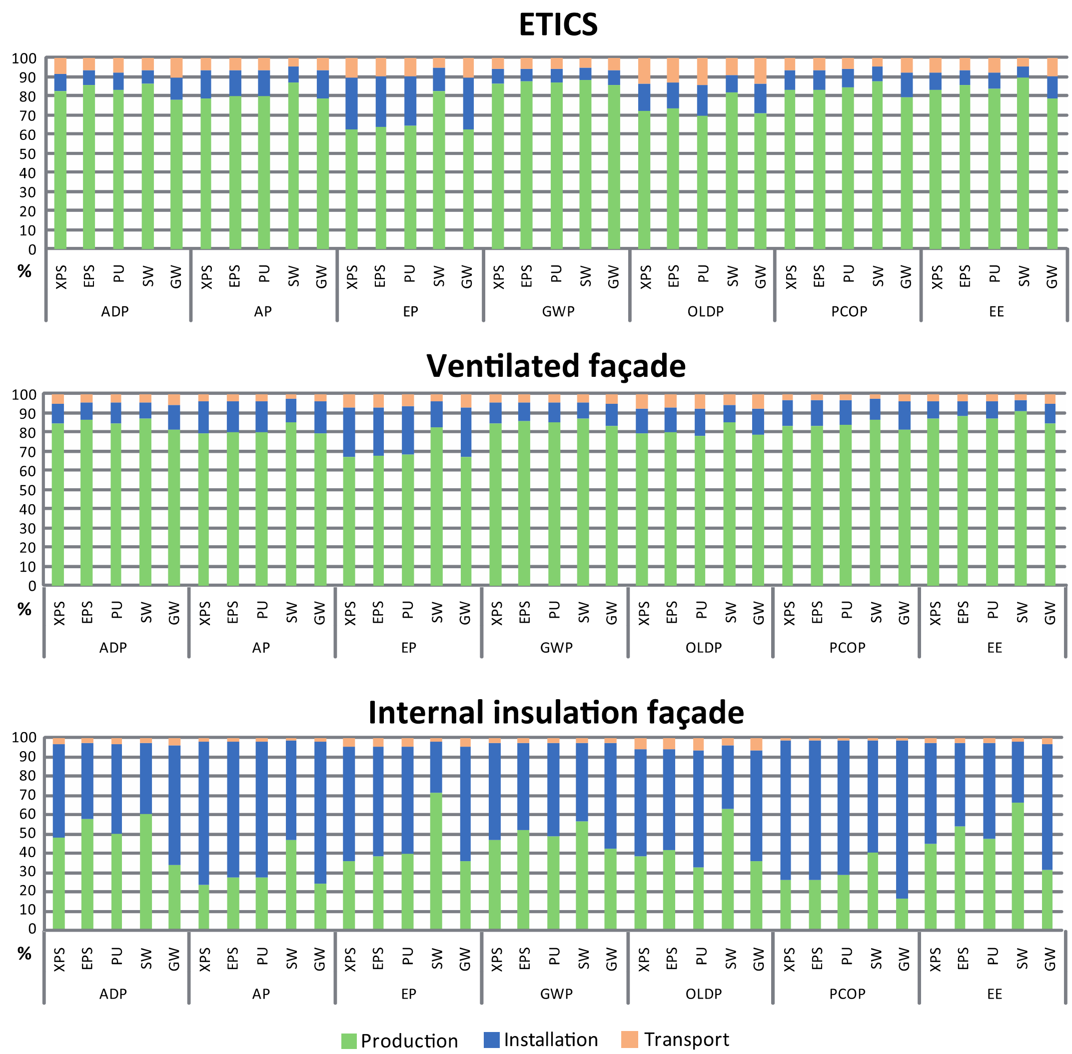

Fig. 4. Contribution of each life cycle phase to the global environmental impact.

either by replacing the material profiles of fixation with a less impactful material or by developing a fixation system that requires less material.

The environmental impacts of the transport and installation phases represent 10–30% of the environmental impact in all of the categories (Fig. 4). These impacts, according to the insulation material used, are greater with better environmental performance of the insulation material due to the production phase being less relevant in environmental terms and so increasing the importance of the other phases. Thus, reducing these environmental impacts involves the optimization of the installation process, using simpler and less impactful material systems. Moreover, the quantity of insulation material used should be optimized without compromising the thermal requirements of the building.

3.2. *Environmental impact of the different insulation materials*

The importance of the production phase for all of the construction systems has been previously noted. The influence of the insulation materials on the environmental behaviour of the façade systems has also been observed. Table 4 shows the relation between the different insulation material impacts and the global impacts of the façade systems. The insulation material that contributes the most to the environmental impact is SW, with more than 30% in most of the categories for all of the façade systems and even exceeding 50% of the global impact for some categories (EP, PCOP and EE). The least impactful insulation material is GW, which contributes between 4 and 14% of the global impact for all categories and façade systems. Moreover, Table 4 shows the differences between the environmental performances of each insulation material in each construction solution. These differences are due to the differences in the structure of the façade systems and varying the amount and type of materials that form. The insulation materials will have more importance on the environmental performance in the simplest construction systems, e.g., ETICS and internal insulation façade.

SW presents the highest environmental impacts in all of the categories and an impact up to 2 times greater than all of the insulation material for almost all of the categories (except for ADP and GWP). The second most impactful material is EPS, but its environmental impacts are far from the SW results, with a 15–90% lower impact than SW. XPS and PU have similar results in almost all of the categories, with a 10–50% lower impact than SW. The reason for the high environmental impact of SW is its high density and its low thermal conductivity, so that a high quantity of this material is required to fulfil the DU (Table 1). Because the determination of the environmental load is made by the weight allocation method, the most impactful materials are those with the highest amounts

Table 4
Relation between the environmental impacts of the insulation materials and the global impacts of the façade systems.

	ETICS					Ventilated façade					Internal insulation façade				
	XPS	EPS	PU	SW	GW	XPS	EPS	PU	SW	GW	XPS	EPS	PU	SW	GW
ADP (kg Sb eq)	8.8E-02	1.6E-01	9.9E-02	1.9E-01	2.4E-02	2.1E-01	1.5E-01	9.6E-02	1.8E-01	2.3E-02	9.4E-02	1.7E-01	1.1E-01	2.0E-01	2.6E-02
AP (kg SO2 eq)	2.8E-02	2.8E-02	1.9E-01	1.6E-01	3.0E-02	2.8E-02	4.2E-02	4.1E-02	1.5E-01	2.9E-02	3.0E-02	4.6E-02	4.6E-02	1.7E-01	3.2E-02
EP (kg PO4--- eq)	1.6E-02	2.3E-02	2.6E-02	2.2E-01	1.6E-02	1.5E-02	2.2E-02	2.5E-02	2.1E-01	1.6E-02	1.7E-02	2.5E-02	2.7E-02	2.3E-01	2.3E-01
GWP (kg CO2 eq)	8.0E+00	1.3E+01	1.0E+01	2.0E+01	3.7E+00	7.7E+00	1.3E+01	9.7E+00	1.9E+01	3.6E+00	8.5E+00	1.4E+01	1.1E+01	2.1E+01	3.9E+00
OLDP (kg CFC-11 eq)	4.3E-07	6.4E-07	1.0E-07	2.9E-06	2.8E-07	4.2E-07	6.2E-07	1.0E-07	2.9E-06	2.7E-07	4.6E-07	6.8E-07	1.1E-07	3.2E-06	3.0E-07
PCOP (kg C2H4 eq)	2.6E-03	2.7E-03	3.2E-03	6.5E-03	8.7E-04	2.6E-03	2.6E-03	3.1E-03	6.3E-03	8.5E-04	2.8E-03	2.9E-03	3.4E-03	6.9E-03	9.3E-04
EE (MJ)	2.0E+02	3.5E+02	2.3E+02	7.1E+02	4.9E+01	2.0E+02	3.4E+02	2.3E+02	6.9E+02	4.8E+01	2.2E+02	3.8E+02	2.5E+02	7.6E+02	5.3E+01

>50% of the global impact

30-50% of the global impact

10-30% of the global impact

<10% of the global impact

needed for the building façade. The good environmental performance of GW during manufacturing makes GW the insulation material with the least environmental impact despite using similar amounts of material to the other facades.

3.3. Environmental impacts according to the climate zone

A sensitivity analysis focused on the location of the building was performed in terms of GWP and EE. Fig. 5 shows the differences between the impacts generated by each type of building façade depending on the area where the building was constructed. Looking at the data for the warmer *α zone*, the ventilated facades generate more impacts, both for GWP and EE. The ETICS and internal insulation façade are less impactful, with similar values in terms of GWP. However, if we look at the EE data, ETICS is the system with the lowest energy contained. As the climate zones become colder, the environmental behaviour patterns are not uniform within a construction solution. The trend is that the critical parameter is the type of insulating material used, and this issue will be discussed in the next section.

If we focus on the type of facade system by climate zone, the system most recommended for warmer zones from an environmental approach is ETICS. However, as noted above, in coastal areas the outside coating of ETICS will require maintenance due to the adverse conditions. From a technical point of view, the ventilated facade would be the most recommended in warmer climate zones

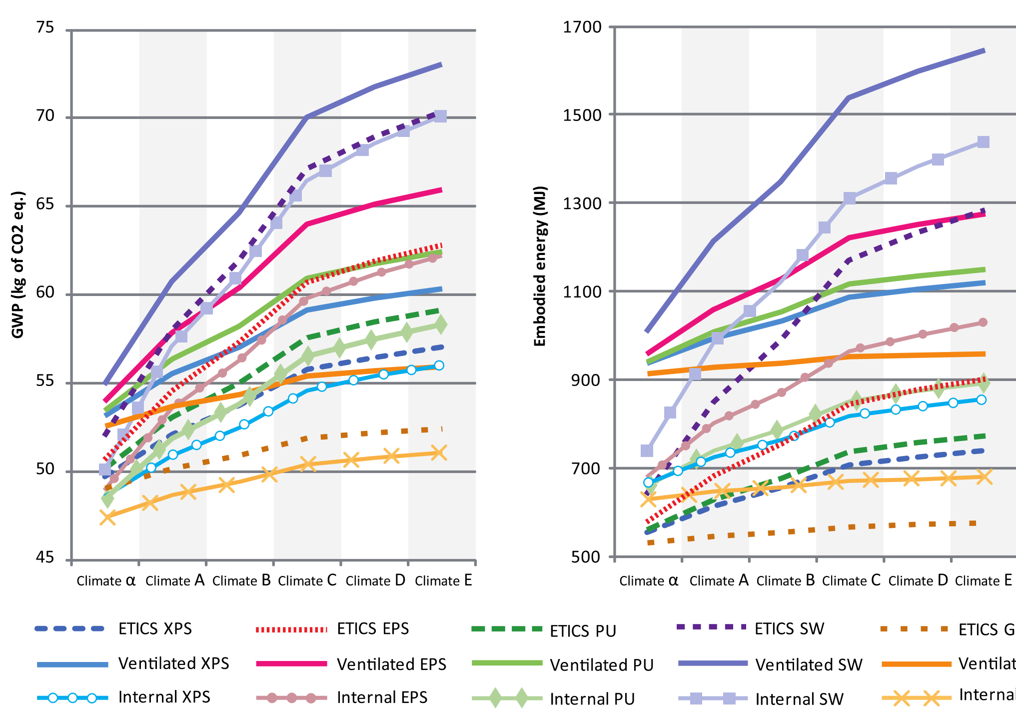

Fig. 5. Comparison of the environmental impacts of different façade systems with different insulation materials in different climate areas.

because of its ability to balance the outside temperature with the inside temperature due to the airflow through the air chamber. Moreover, the possibility of choosing different types of external cladding allows adaptation to the climatic conditions, extending its lifespan. For colder climates, the most advisable facade system would be ETICS in terms of EE, depending on the selected insulation material. However, the humidity should be analysed considering the maintenance required for this façade type in the future. The construction of this type of façade, including the use phase, should be analysed more extensively in future studies.

Regarding the insulation materials, if we consider the geographical location of the building, the weather must be taken into account. Therefore, the thermal insulation needs will vary the quantity of insulation materials required in each climate zone. As the location of the building becomes colder, a larger amount of insulation will be necessary and therefore will have a greater environmental impact. Therefore, a colder climate will increase the influence of the insulation on the overall impact in all of the façade systems. The influence of this parameter is shown in Table 5 in terms of GWP and EE for the climate zones in Spain.

In terms of GWP, a marked increase is seen in the importance of thermal insulation for the cooler areas under study. The most advisable material is the GW, which has impact values lower than 10% for all of the facade systems in all of the climate zones (Table 5). XPS and PU also have values lower than 10% in the α and A zones. In terms of EE, the insulation has great importance in the building facade systems. Some of the materials under study exceed most climate zones by more than 20% of the total embodied energy of the façade system. In the coldest zones (zones C, D and E), the combination of ETICS and the internal façade insulation with EPS, PU and SW materials account for over 30% of the global impact. Meanwhile, in the case of the ventilated façade, all of the insulation materials have the lowest percentages of total impacts in each climate zone.

Fig. 5 compares the different combinations of façade systems and insulation materials according to the climate zone. In the warmest zones, the choice of the insulation material has a lower influence on the environmental performance of the whole façade because of the lower insulation requirements; therefore, the type of façade has the greatest influence. The importance of the insulation material selection increases as the temperature zone becomes cooler. The combination of ventilated facade with SW is the most impactful to all climate zones in terms of GWP and EE. Moreover, the combination of an internal insulation façade with GW is the least impactful in terms of GWP, and the combination of ETICS with GW is the least impactful in terms of EE. All of the combinations with GW have the least environmental impact with increasing need

Table 5
Comparison of the environmental impacts of insulation materials in different façade systems located in the various climate zones defined in Spain.

		GWP (kg CO_2 eq.)					EE (MJ)				
		XPS	EPS	PU	SW	GW	XPS	EPS	PU	SW	GW
Clima α	ETICS	1.3E+00	2.3E+00	1.7E+00	3.4E+00	6.2E-01	3.4E+01	6.0E+01	4.0E+01	1.2E+02	8.3E+00
	Ventilated	1.1E+00	1.9E+00	1.4E+00	2.8E+00	5.2E-01	2.9E+01	5.0E+01	3.3E+01	1.0E+02	6.9E+00
	Internal	1.8E+00	2.2E+00	1.6E+00	3.3E+00	6.0E-01	4.5E+01	5.8E+01	3.8E+01	1.2E+02	8.0E+00
Clima A	ETICS	3.7E+00	6.2E+00	4.6E+00	9.3E+00	1.7E+00	9.4E+01	1.6E+02	1.1E+02	**3.3E+02**	2.3E+01
	Ventilated	3.4E+00	5.8E+00	4.3E+00	8.6E+00	1.6E+00	8.7E+01	1.5E+02	1.0E+02	3.1E+02	2.1E+01
	Internal	4.1E+00	6.8E+00	5.1E+00	1.0E+01	1.9E+00	1.0E+02	1.8E+02	1.2E+02	**3.6E+02**	2.5E+01
Clima B	ETICS	5.3E+00	8.8E+00	6.6E+00	1.3E+01	2.4E+00	1.3E+02	**2.3E+02**	1.5E+02	**4.7E+02**	3.2E+01
	Ventilated	5.0E+00	8.3E+00	6.2E+00	1.2E+01	2.3E+00	1.3E+02	2.2E+02	1.5E+02	**4.4E+02**	3.0E+01
	Internal	5.6E+00	9.4E+00	7.0E+00	1.4E+01	2.6E+00	1.4E+02	2.5E+02	1.7E+02	**5.0E+02**	3.5E+01
Clima C	ETICS	7.3E+00	1.2E+01	9.1E+00	1.8E+01	3.4E+00	1.9E+02	**3.2E+02**	2.1E+02	**6.5E+02**	4.5E+01
	Ventilated	7.1E+00	1.2E+01	8.8E+00	1.8E+01	3.3E+00	1.8E+02	3.1E+02	2.1E+02	**6.3E+02**	4.4E+01
	Internal	7.7E+00	1.3E+01	9.7E+00	1.9E+01	3.6E+00	2.0E+02	**3.4E+02**	2.3E+02	**6.9E+02**	4.8E+01
Clima D	ETICS	8.0E+00	1.3E+01	1.0E+01	2.0E+01	3.7E+00	2.0E+02	**3.5E+02**	**2.3E+02**	**7.1E+02**	4.9E+01
	Ventilated	7.7E+00	1.3E+01	9.7E+00	1.9E+01	3.6E+00	2.0E+02	3.4E+02	2.3E+02	**6.9E+02**	4.8E+01
	Internal	8.5E+00	1.4E+01	1.1E+01	**2.1E+01**	3.9E+00	2.2E+02	**3.8E+02**	2.5E+02	**7.6E+02**	5.3E+01
Clima E	ETICS	8.5E+00	1.4E+01	1.1E+01	**2.1E+01**	3.9E+00	2.2E+02	**3.8E+02**	**2.5E+02**	**7.6E+02**	5.3E+01
	Ventilated	8.3E+00	1.4E+01	1.0E+01	2.1E+01	3.8E+00	2.1E+02	3.7E+02	2.4E+02	**7.3E+02**	5.1E+01
	Internal	9.2E+00	1.5E+01	1.1E+01	**2.3E+01**	4.2E+00	2.3E+02	**4.1E+02**	**2.7E+02**	**8.1E+02**	5.6E+01

>30% of the global impact	**20-30% of the global impact**	10-20% of the global impact	**<10% of the global impact**

for thermal insulation. Conversely, SW presents the greatest increases for all of the façade systems. In EE terms, the most impactful combination triples the least. Therefore, the importance of the façade system and insulation material selections depends on the climate zone where the building is located.

3.4. Implication of the research findings in Spain

The Spanish building sector has changed drastically after the country's economic crisis. Currently, the construction of new buildings has suffered a strong reduction, and the sector is focused on retrofitting due to both the current energy efficiency policies and the need for the energy upgrades of the aged Spanish building stock. These retrofits decrease the building energy consumption and also offer economic savings and reduced environmental impacts. The insulation façade systems most common in retrofitting are ETICS and the ventilated façade (ANDIMA, 2008), which have different performances over their lifespan. From the results presented above, the environmental implications in their construction are different, with the construction of a ventilated façade being more influential. The convenience of each façade system will have to be analysed, according the specific climate requirements and the quantity of energy savings in each case.

The rigid boards are the most common insulation materials in ETICS in Spain, mainly made from EPS, XPS and PU. SW and GW are also used in this façade system taking into account special requirements for the permeability of the mortars and coatings to ensure the maximum water vapour transpiration to reduce the risk of condensation. For ventilated façades, the most used insulation materials are SW and GW due to their lightness, and they are protected from direct contact with water because the external cladding and the primer coat cover them (FENERCOM, 2012). SW and GW have increased in use due to the need to simultaneously meet requirements of thermal and acoustic insulation and fire protection. According to the results, the implications of using one insulation or the other are very different. Insulation decisions should include environmental recommendations to obtain the most efficient life cycle energy possible.

Moreover, in Spain 8–9% of households suffer energy poverty due to the inability to meet suitable energy expenditure by the household (Economics for energy 2014). The most common measures taken to alleviate this problem are granting social bonds, reducing the price of electricity or providing public grants to improve the heating and the thermal insulation of buildings. In addition to improving the efficiency of the building and decreasing the environmental impacts during use, the social and economic compounds of the insulation systems are greatly relevant. The scope of the building and insulation systems LCA should be extended to include all three dimensions of sustainability. Perhaps a complete study could determine that, despite of the low profitability from an economic and energy view, improving building insulation could have great implications in terms of promoting economic activity, recovery of important sectors, and the construction or rehabilitation of cities in social terms.

4. Conclusions

The proposed methodology is intended to calculate the environmental impacts derived from the building construction by property developers, architects and urban planners, which is useful during the decision-making in the design of buildings. The results show that the construction of ventilated façades with stone wool insulation are the most influential and that ETICS with glass wool insulation is the least impactful for all of the climate zones. The ventilated façade system is a more complex construction solution than ETICS and the internal insulation façade. The insulation materials play an important part in the environmental impacts of the production phase, which in turn represents the most impactful phase for ETICS and ventilated façades. The installation phase of the internal insulation façade is especially relevant because of the auxiliary materials required to place the insulation material.

In addition, if the climate conditions where the building is located within Spain are taken into account, the thermal and construction requirements change, and therefore the need for insulation and the suitability of a particular facade system changes. In warm zones, the most recommended façade system is ETICS, especially in terms of embodied energy. For colder climates, the most advisable facade would be ETICS in terms of EE, depending on the selected insulation material. From a technical point of view and taking into account the use and maintenance phase, each façade system performs differently. However, the budgetary reasons and the access to all façade systems by the inhabitants of the buildings should be considered. Therefore, it is recommended to complete these results in further studies with the economic and social implications of the use and maintenance phases for robust decision-making.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.11.090.

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