Environmental life cycle assessment based on the retrofitting of a twentieth-century heritage building in Spain, with electricity decarbonisation scenarios

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Abstract

The aim of this study is to estimate the environmental impacts associated with modernization measures that improve the energy efficiency of an office building listed as of cultural interest and located in northern Spain, a region with an Atlantic climate. European Climate Action for 2020-2030 sets a long-term goal of achieving neutrality of greenhouse gas emissions and towards the end of 2019 the Spanish Government presented its Integrated National Energy and Climate Plan. It is of interest to the international audience to know how energy policies can affect decisions on building retrofitting to improve sustainability: reduction in energy consumption, climate change and other environmental impacts. A life cycle assessment from cradle to grave was carried out for the retrofitting of the building envelope and different energy supply scenarios: only electricity from the electricity mix (scenario of reference that of 2018, and decarbonisation scenarios proposed for 2020 and 2030), and the installation of heat pump and photovoltaic panels. The impacts will decrease 40% for Global Warming Potential and 15% for Cumulative Energy Demand in 2030 with respect to the reference scenario. These reductions will further increase up to 54% and 61%, respectively, if photovoltaic panels and a heat pump are implemented.

Keywords: life cycle assessment; heritage building retrofit; decarbonisation; climate change mitigation; renewable energy.

Introduction

Buildings in the European Union represent 40% of final energy consumption, 36% of CO_2 emissions, 30% of consumption of raw materials, 12% of consumption of drinking water and are producers of 30% of the waste destined for landfill (European Commission, 2017). EU Directives (Directive 2018/844/EU; Directive 2010/31/EU; Directive 2012/27/EU) encourage Member States to increase the number of high energy performance buildings. Given that around 35% of the buildings in the EU are currently over 50 years old, almost 75% of the building stock is energy inefficient, while only 0.4-1.2 is retrofitted each year, depending on the country. Furthermore, new rules for greener and smarter buildings are foreseen to increase the quality of life for all Europeans (European Commission, 2019). This means that most of the energy reductions will have to be achieved by deep retrofitting existing buildings (Visscher et al., 2016). The majority of the buildings in Spain, more than 93%, were built before 2008, before the application of the Energy Performance of Buildings Directive (Directive 2010/31/EU), which means that the vast majority of these buildings have poor energy performance. According to an estimation in Gangolells et al. (2016), office buildings have an average energy consumption of 317.8 kWh/m^2 year.

With respect to listed (heritage) buildings built before 2001 in the UE-27, the counties with the highest numbers are: France with 28702, Italy with 27269, UK with 25472 and Spain with 20823 (Troi, 2011). Troi makes an analysis with a wider interpretation of listed buildings, which takes into account formally protected and listed buildings constructed before 1945, and states that even if only 30% of these buildings that form a part of Europe's typical city-centres and "cityscape" were retrofitted, it could save 180 million tonnes (Mt) of CO_2 by 2050 (3.6 % of 1990's EU-27-emissions).

Deep renovations of buildings have been undertaken in Spain through the "Long-term strategy for rehabilitation energy in the building sector in Spain" (Spanish Ministry of Development, 2014) and the "Update of the long-term strategy for energy rehabilitation in the building sector in Spain" (Spanish Ministry of Development, 2017). Grants for specific renovation proposals take the country's different climatic zones into account. The application of these measures decreases the operational energy use (also called energy use) of new and retrofitted buildings. Consequently, other energy consumed in other stages of the life cycle such as embodied energy, has gained in importance.

The refurbishment of residential and non-residential buildings was analysed by Vilches et al. (2017) for different cases using Life Cycle Assessment (LCA). The authors reported that embodied energy (initial and recurring) has a higher variance in the total life cycle impact for non-residential buildings compared to residential buildings: the embodied energy varies from 2-10% up to 55% of the total energy and up to 57% of the GWP. Asdrubali et al. (2019) studied a school in Northern Italy under different scenarios of retrofitting of the envelope insulation and of installing active systems. They estimated a range of variation in energy demand savings of between 55 and 74%. They also examined the variation in savings in total primary energy and total CO_2 emissions with respect to an optimal cost scenario (defined by the authors as one that meets the minimum requirements imposed by the standards in Italy). The savings in the two impacts were found to vary between 30 and 44% with respect to this scenario. Ming Hu (2019) determined the life-cycle environmental impacts associated with energy-retrofit strategies on an urban scale. The results indicate that energy retrofits overall have a positive effect in terms of reducing life-cycle environmental impacts in all environmental categories except ozone-depletion potential.

Recently, Ghose et al. (2020) estimated potential environmental impacts associated with adopting energy efficiency refurbishments on the existing office building stock in New Zealand and identified the potential contribution to New Zealand's 2050 climate change mitigation target. They proposed adopting efficient resources such as the installation of PV panels and waste management measures and found that these actions can contribute to reductions in greenhouse gas emissions in the range of 40 to 98%. However, they did not relate their results to variations in the country's electricity mix.

Ramesh et al. (2010) carried out a study of the life cycle energy, embodied energy and energy use of a large number of offices for developing and/or non-cold countries. The size of the net floor area ranged from 60000 to 1253 m^2 and the useful life from 40 to 50 years. A wide variation was found in energy use during the life cycle: the primary energy requirement during the life cycle was in the range of 250-550 kWh / m^2 per year and the embodied energy was in the range of 33- 139 kWh / m^2 per year. The differences found were mainly due to the differences in the climatic conditions of the places where these buildings are located. The authors remark that the building's life cycle energy demand can be reduced by significantly reducing its operational energy through the use of passive and active technologies, even if this leads to a slight increase in embodied energy. However, they point out that overuse of passive and active technologies in a building could be counterproductive. Furthermore, as operating energy is expressed in terms of primary energy, energy conversion factors from end-use to primary (particularly in the case of electricity) also influence this variation. Countries that have clean energy sources (hydro, wind, solar) have lower primary energy figures than other countries with fossil fuel energy sources. Another reason for this variation, which may make a slight contribution, is the energy content of the materials used in the construction of buildings, which again depends on the energy carriers and the efficiency of a country's processes in the manufacture of construction products.

Cabeza et al. (2014) performed a review for different countries, usable area and construction material. It was found that the materials used in offices, with high percentages of concrete and steel, increase the embodied primary energy with respect to residential buildings and that energy use impact is conditioned both by the relative high energy consumption and by the electricity mix used in the different countries under study. Another LCA was performed in Ghose et al. (2019) for several retrofitting scenarios in office buildings under representative climatic conditions of New Zealand. Better construction practice and increasing renewable energy supply from the national electricity grid proved to be determining factors. Malabi et al (2019) apply a LCA allocation method to a Danish office building where the concrete structure is designed for disassembly for subsequent reuse. The savings are significantly influenced by the building's material composition, particularly the number of component-use cycles as well as the service life of the building and its components.

The improvement of the performance of the building envelope in listed buildings should be done by using interior lining because of the need to preserve their appearance. Identifying the environmental impacts of different lining materials is of importance when a retrofit is planned, which is independent of the use to which the building is put. The majority of studies in the literature into this question have been performed for residential buildings. The analysis of the impact of different lining systems was addressed in Thormark (2006) for the retrofitting of a terraced house in Sweden; Radhi (2010) analysed CO_2 equivalent (CO_2 eq) emissions due to the choice of stucco, vinyl and aluminium coating materials, among others, and Piccardo et al. (2020) studied different insulating materials (glass wool, mineral fibre and extruded polystyrene) and final linings (aluminium, wood, brick and glass) applying the passive house standard.

The calculation of primary energy and CO_2 eq emissions for the electricity consumed in buildings depends greatly on the country's electricity mix. Decarbonisation policies regarding electricity production are being increasingly studied in various countries, such as Hungary, in Kiss et al. (2020) and Spain, in García-Gusano et al. (2017). Regulation (EU) 2018/1999 on the governance of the Energy Union and Climate Action for 2021-2030 (European Parliament, 2018) sets a long-term goal of achieving neutrality of greenhouse gas (GHG) emissions by 2050, which means achieving a 100% renewable electricity system by that date. To achieve this objective in Spain, the authorities presented the Integrated National Energy and Climate Plan (Spanish Ministry of

Ecological Transition, 2019). This plan includes a series of measures that will enable the following results to be achieved in 2030: 23% reduction in GHG emissions compared to 1990; 42% share of renewables in the final use of energy; 39.5% improvement in energy efficiency; and 74% share of renewable energy in electricity generation. This plan proposes an appreciable decrease in nuclear power and a moderate decrease in mineral oils. In addition, coal energy is intended to reach zero by 2030 (coal currently represents 14%), whereas a very significant parallel increase in wind and solar energy is contemplated. The contribution of renewable resources represented 39% (2018) and is foreseen to represent 44% of gross electricity generation in 2020 and 78% in 2030. These plans designate scenarios that are working objectives to strive for, and although they are set to be achieved by specific dates, this is not easy to do, since variations occur in the conditions of each country. This does not detract from the validity of the study of the repercussions of each milestone, even if it takes longer to achieve than expected. For example, in Spain the electricity mix that was planned for 2020 has not currently been achieved. Although there has been a reduction in coal powered generation, this has been produced by a decrease in electricity consumption since January 2020 due to a global pandemic. Gonzalez-Prieto et al. (2020) analysed the environmental implications of this change and its repercussion due to thermal-electricity consumption in the heating and cooling of single-family houses in different Spanish climates.

Previous studies show that the impact produced by buildings largely depends on the climate, typologies of buildings, construction system, time horizon, active energy supply systems of the building and energy policy of each country. However, there is still a lack of studies on non-operational and operational energy when using different materials for retrofitting in combination with the partial substitution of electricity consumption in the country mix by renewable systems that operate according to the energy demand requirements of buildings. This lack is even more noticeable in the case of office buildings subject to cultural protection.

This research analyses the complete life cycle of a listed office building subject to cultural protection and discusses the environmental implications of using different building materials to retrofit the envelope and of adopting renewable active energy systems in the building. The aim is to demonstrate that significant reductions in cumulative energy demand (CED), global warming potential (GWP) and other environmental impacts can be achieved. As regards the energy supply, the changes considered in this study are the installation of photovoltaic (PV) panels on the roof, the use of a heat pump, and both systems in combination.

The reference electricity mix scenario was that for 2018, which represents the situation a year before the COVID-19 pandemic (the review of 2019 data for Spain revealed insignificant differences with respect to 2018). Two further medium-term environmental policy scenarios, 2020 and 2030, which take into account the decarbonisation plan proposed by the Spanish Government, are also included in the research.

Method

The research is based on the LCA methodology following the criteria of ISO 14040 and ISO 14044 standards (ISO 14040, 2006; ISO 14044, 2006). A scheme with the sequence of the steps followed in this study, which are subsequently described, is shown in Figure 1.

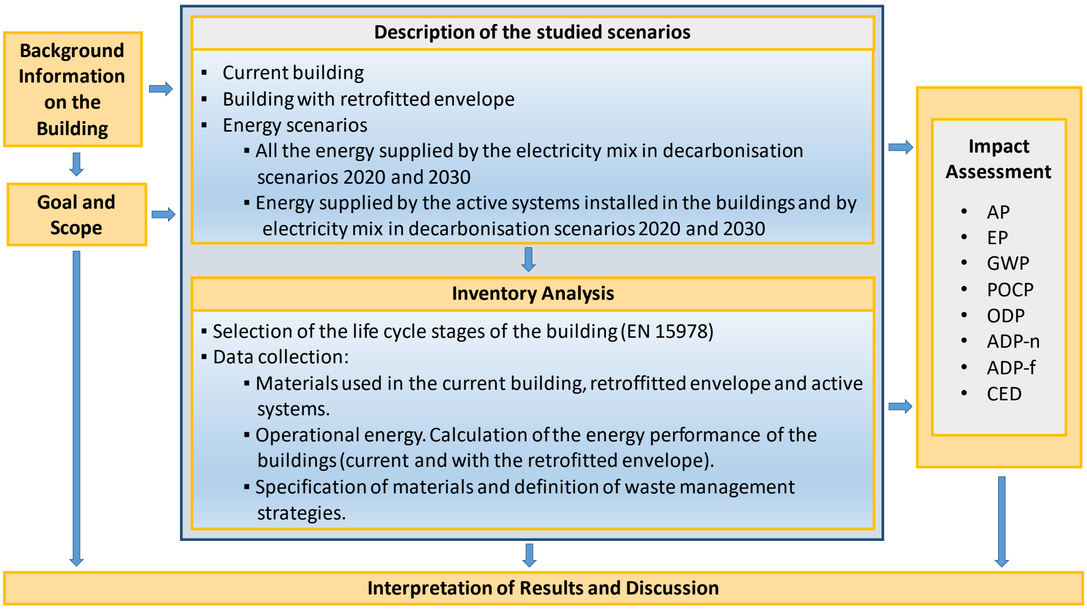

Figure 1. Framework scheme of the applied LCA methodology

Background information on the selected building

The building is regionalist/modernist in style with Neomudejar influences, and belongs to a period in which facing brick was widely used. The use of exposed brick and this architectural style was widespread from the end of the 19th century to the mid-20th century and encompassed official buildings, the finest civil architecture and also factory buildings. The building was a former hollow glass factory built before 1910, located in Gijón (Asturias), on northern Spain's central coast. The building was subject to integral protection measures and was first renovated for use as offices in 1990-1992 (Tielve García, 2010). Its renovation currently requires taking into account EU directives (Directive 2018/844/EU; Directive 2010/31/EU; Directive 2012/27/EU), which have been transposed in Spain into the country's Technical Building Code (Spanish Ministry of Housing, 2006; Spanish Ministry of Development, 2013).

Scope of the study

The scope of the study, established via a cradle-to-grave approach, includes the following stages (Figure 2): material supply, transport and manufacturing of components (modules A1 to A3) in the product stage; transport of materials to the building (module A4) in the construction stage; operational energy use (B6); and demolition, transport to the treatment plant, waste processing and recycling/disposal (modules C1 to C4) in the end-of-life stage. The installation process in the construction stage of the building (stage A5) fall outside the scope of this study because no structural changes are proposed.

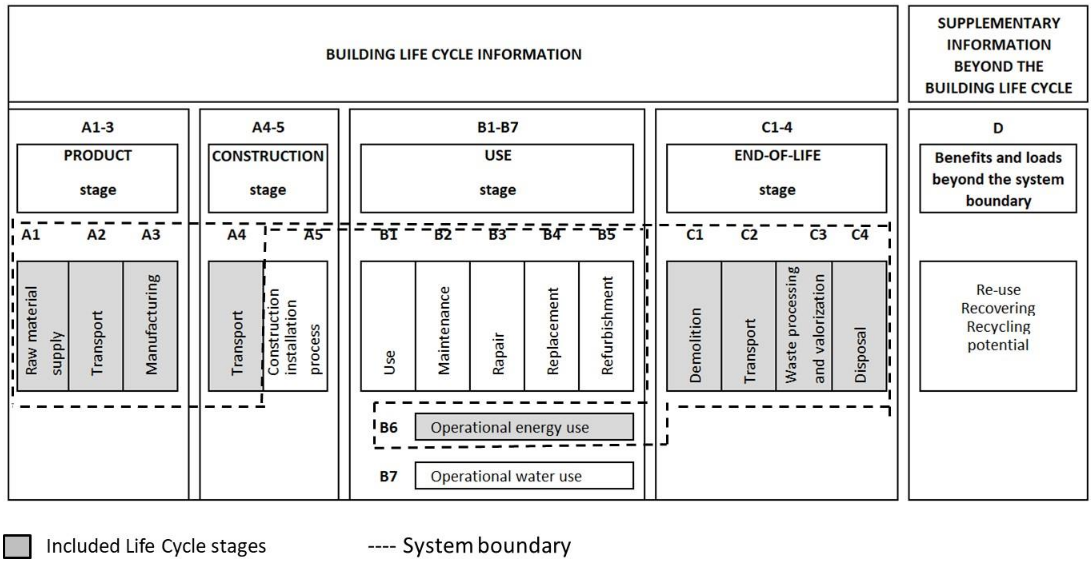

Figure 2. Considered life-cycle stages for the office building, according to EN 15978 (2011)

The functional unit considered was the net floor area of the listed building. As to the lifespan, although in many LCA studies, as in Eurocode EN 1990 (2002/A1:2005) (EN 1990, 2002), the indicative design service life has a period of 50 years, this can be greatly extended with proper maintenance and considering structural characteristics. A lifespan period of 100 years was considered for this particular listed building, as in other LCA studies (Leskovar et al., 2019).

Description of the scenarios

The scenarios of this study were proposed on the basis of the five types of studies that were carried out and are summarized in Figure 3.

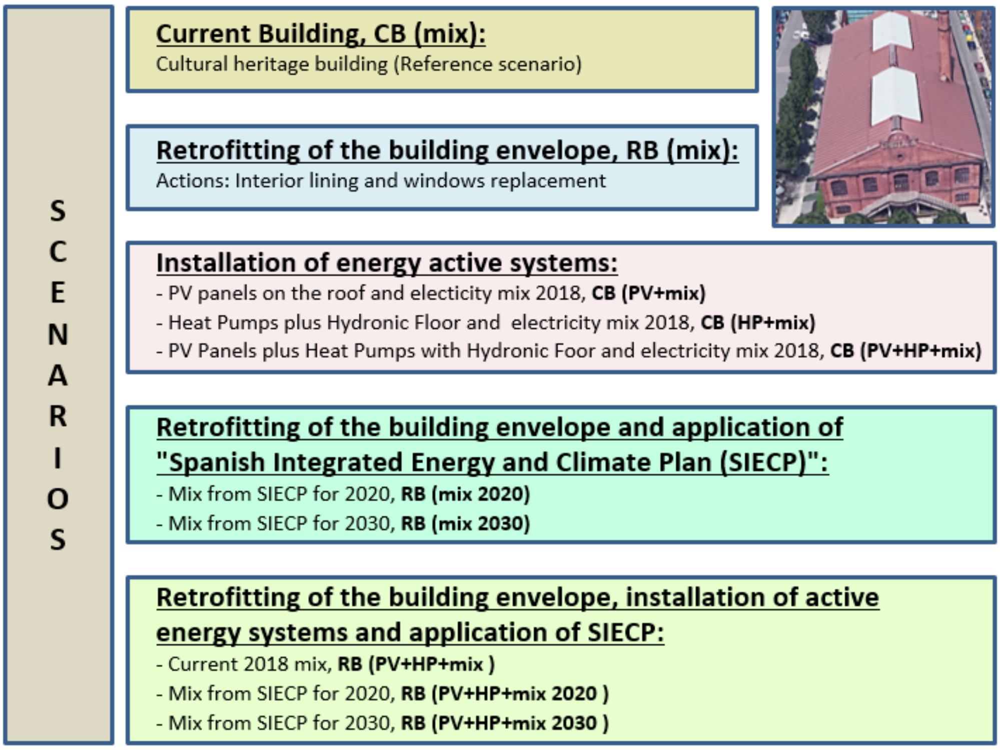

Figure 3. Studied scenarios.

Baseline scenario: Current Building, CB (mix)

The building has a floor area of 2782 m^2 and is divided into three storeys: the ground, first and second floors, with an interior layout distributed around a large central atrium occupying the full height of the building, connecting all three floors and allowing natural light to enter through the skylight that takes up a major part of the roof. Figure 4 shows the interior of the building (only the ground and second floor plans, since the first-floor plan is very similar to the second) and an exterior view with façades provided with large windows. The distribution of the windows with respect to the total amount of openings is: North 8 %; East 38 %; South 15 % and West 38 %. The building has an overall length of 50 metres and a width of 25.4 metres. The roof is gabled, with a crest height of 14 metres. The pitch of the gable roof is 26 degrees, with one plane of the roof facing west and the other facing east.

The building has a mechanical exhaust ventilation system, the heating consisting of an electrical radiant floor, while the domestic hot water is heated by means of a thermoelectric element. The energy demand was calculated based on this current building, this energy being covered by the Spanish electricity mix for the peninsula for the year 2018.

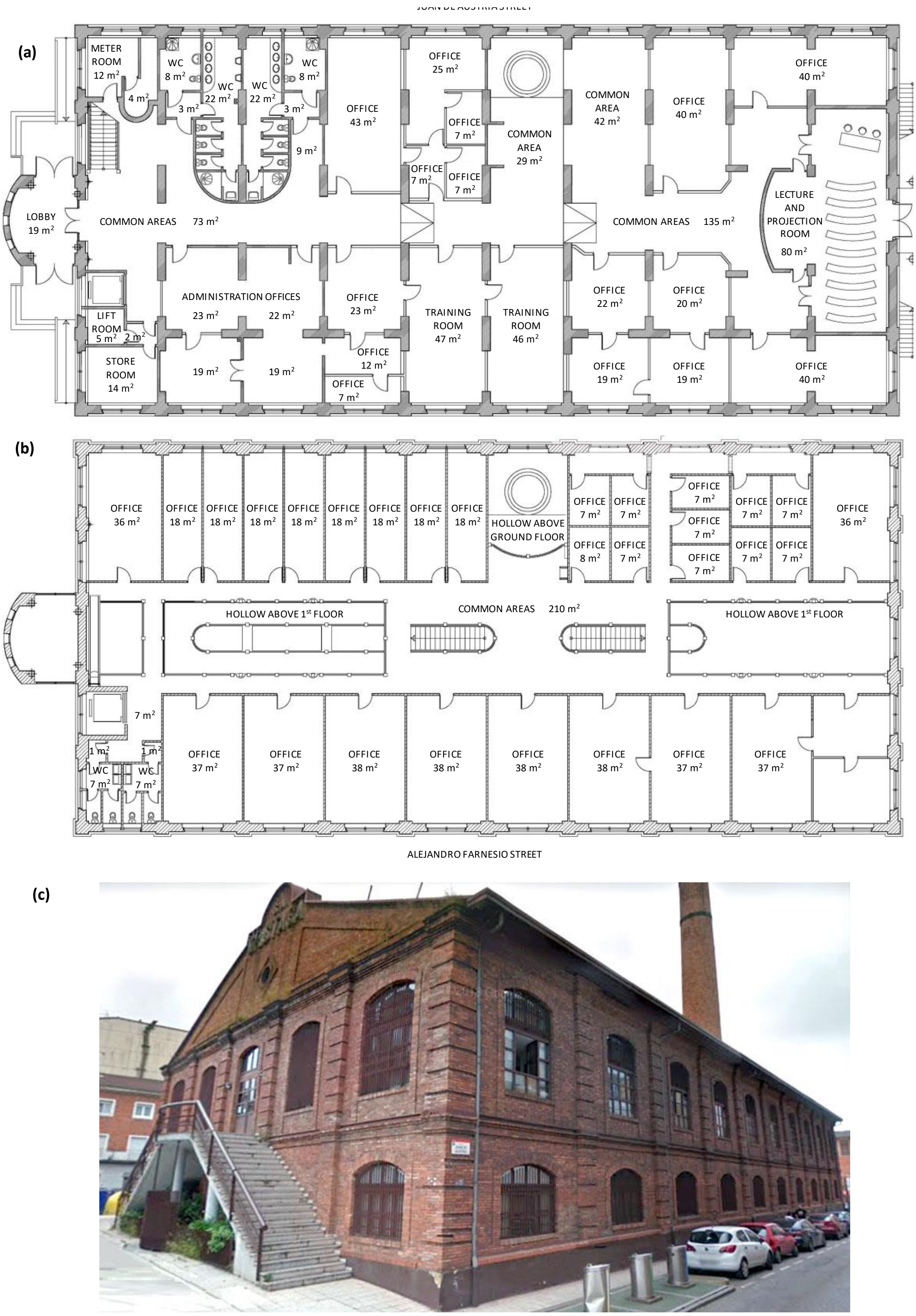

Figure 4. Ground and second floor plans (a, b) and main perspective (c) of the building under study

Scenario with retrofitting actions in the envelope: Retrofitted Building, RB (mix)

The proposed retrofitting actions for the walls and windows consist in: 1) installing interior lining (three types of insulating materials were studied: mineral fibre, glass wool and expanded polystyrene, EPS), with gypsum plasterboard being added to the interior brick lining; and 2) replacing windows by changing the wooden frames and double glazing by aluminium and triple glazing. The energy demand of the retrofitted building was calculated on the basis of the Spanish electricity mix for the peninsula for the year 2018.

Scenarios with installation of energy active systems

The effects of the implementation of PV panels and a heat pump were studied, both separately (scenarios CB (PV+mix) and CB (HP+mix)), and in combination (scenarios CB (PV+HP+mix) and RB (PV+HP+mix)).

Scenarios with retrofitting actions in the envelope and application of the decarbonisation plan

The effect on the retrofitted building of the implementation of the Spanish Integrated Energy and Climate Plan for 2020 and 2030 horizons was studied. Two new scenarios were defined: RB (mix 2020) and RB (mix 2030).

Scenarios with retrofitting actions in the envelope, installation of energy active systems and application of the decarbonisation plan

The effect of these actions was studied in three further scenarios: RB (PV+HP+mix), RB (PV+HP+mix 2020) and RB (PV+HP+mix2030).

Life cycle inventory (LCI)

Inventory analysis was carried out in order to quantify the environmentally relevant inputs and outputs of the studied scenarios by means of a mass and energy balance of each of the stage considered within the life cycle of the building.

<u>Product Stage (A1-A3)</u>

The materials considered in modules A1 to A3 included those of the current building and those planned to be introduced in the future (depending on the studied scenario). Replacements of retrofitting materials and energy systems materials according to the corresponding years of service life of the lining materials, windows and energy systems were considered in these stages.

In the current building, the exterior façade has a solid double-face brick finish, while the interior is lined with a single brick wall. There is a 20 mm air chamber between these two walls, containing 20 mm of projected polyurethane insulation. The windows have double glazed panes (4/6/4) filled with air and have wooden frames.

Retrofitting for the walls consisted in installing interior lining: 100 mm of mineral fibre insulation and 13 mm of gypsum plasterboard. The insulating material used for the retrofit is of major interest because it can represent an important contribution to the environmental impact of the resulting building. In the present study, the use of glass wool and expanded polystyrene was considered as alternative options to mineral fibre.

Regarding the retrofitting of the windows, aluminium frame windows with thermal bridge breaking were considered. Argon-filled triple glazing was chosen for the glass area.

Table 1 shows the inventory of the construction elements and the components of the envelope. For each element and component, calculations were made of the distances by road from the construction site to the main suppliers of each material that are located near the construction site. All of the suppliers considered are in Asturias, normally less than 100 km distance from the construction site. The distance from the building to the sorting plant was considered to be 20 km. A 16 tonne diesel lorry was considered for transportation purposes (freight lorry). Table 1 also shows the treatment applied at the end of life of the components of the envelope elements, taking into account the proportion at which the component will be recycled or sent to landfill. These data were considered bearing in mind current legislation (European Commission, 2008; Spanish Ministry of Agriculture, Food and Environment, 2015), which identifies construction and demolition waste (CDW) as a priority waste stream in the European Union and establishes a target of 70% CDW to be recycled by 2020, although it does not specify individual targets for the different materials. Source separation has to be enhanced to remove hazardous waste and facilitate material recovery (European Commission, 2018; Turner et al., 2015). The degree of recycling and material recovery of CDW varies greatly (from below 10% to above 90%) across the EU (Piccardo et al., 2020; Cuéllar-Franca and Azapagic, 2012; International Energy Agency, 2016). In the present study, the recycling values were established considering the existing CDW plants for material recovery in

Spain and data from different industrial sectors (cement, metals, glass, plastics) (Lázaro et al., 2012; Ihobe, 2016). Distances were calculated from sorting plant to the location of the main recyclers of each material. Some of these recyclers are located outside Asturias, and distances were greater.

Table 1. Building construction elements, components, thickness, transport distance and end-of-life treatment of components.

Elements and components	Thickness (m)	Transport distance to construction site (km)	Transport distance for recycling or disposal (km)	Recycling [(2)]	Disposal [(3)]
Exterior walls (1138.42 m²)					
Clay brick [(1)]	0.370	83	80	48%	Landfill (52%)
Polyurethane foam	0.020	21	-	-	Incinerator (100%)
Lining inside (1138.42 m²)					
Gypsum plasterboard	0.013	8	430	19%	Landfill (81%)
Mineral fibre	0.100	21	-	-	Landfill (100%)
Ground floor (1186.71 m²)					
Ceramic floor tile	0.010	83	-	-	Landfill (100%)
Cement mortar	0.020	12	80	70%	Landfill (30%)
Polystyrene, extruded	0.020	21	267	50%	Landfill (50%)
Steel rebars	0.008	32	7	100%	
Concrete	0.400	12	80	70%	Landfill (30%)
Polyester resin	0.002	21	-	-	Landfill (100%)
Epoxy resin	0.001	21	-	-	Landfill (100%)
Bitumen seal	0.004	21	-	-	Landfill (100%)
Lean concrete	0.100	12	80	70%	Landfill (30%)
Roof (1236.64 m²)					
Steel, unalloyed	-	32	7	100%	-
Galvanized steel sheet	0.0015	32	7	100%	-
Plywood	0.016	47	-	-	Landfill (20%), incinerator (80%)
Gypsum plasterboard	0.013	8	430	19%	Landfill (81%)
Polycarbonate	-	8	267	100%	-
Polystyrene, extruded	0.140	21	267	50%	Landfill (50%)
Other floors (2119.33 m²)					
Ceramic floor tile	0.010	83	-	-	Landfill (100%)
Cement mortar	0.040	12	80	70%	Landfill (30%)
Polystyrene, extruded	0.020	21	267	50%	Landfill (50%)
Concrete	0.040	12	80	70%	Landfill (30%)
Interior walls (1379.49 m²)					
Wooden boards	0.100	21	-	-	Landfill (100%)
Base plaster	-	21	-	-	Landfill (100%)
Glass fibre	0.030	21	-	-	Landfill (100%)
Clay brick	0.120	83	80	48%	Landfill (52%)
Wooden window frames (168.53 m²)					
Gypsum plasterboard	0.026	8	430	19%	Landfill (81%)
Window frame, wood	0.140	103	-	-	Landfill (20%), incinerator (80%)
Polybutadiene	-	103	-	-	Landfill (100%)
Silicone product	-	103	-	-	Landfill (100%)
Aluminium window frames (212.40 m²)					
Aluminium frame		5	10	100%	-
Polybutadiene	-	5	-	-	Landfill (100%)
Silicone product	-	5	-	-	Sanitary landfill (100%)
Glazing for wooden windows (184.83 m²)					
Flat glass	-	30	16	78%	Landfill (22%)
Polybutadiene	-	30	-	-	Landfill (100%)
Silicone product	-	30	-	-	Landfill (100%)
Glazing for aluminium windows (140.96 m²)					
Flat glass	-	30	16	78%	Landfill (22%)
Polybutadiene	-	30	-	-	Landfill (100%)
Silicone product	-	30	-	-	Landfill (100%)
Doors (222.46 m²)					
Glued laminated timber	-	47	-	-	Landfill (20%), incinerator (80%)
Steel, low-alloyed	-	103	7	100%	-

[(1)] Include three layers of brick

[(2)] Calculated as a percentage of the material from the construction: 7% material loses; 93% to the following treatment stage

[(3)] Calculated as a percentage of the material originated from the previous treatment stage

A solar panel installation was designed for the two planes of the roof of the building, slightly altering the aesthetics, but without affecting the large central skylight that provides external light to the building. In all, 240 panels were planned to be installed on the west-facing roof plane and another 240 panels on the east-facing roof plane, each polycrystalline silicon solar panel (340W, 24V) having a 17.5% module efficiency. The panels cover a roof area of 926.64 m^2. The energy that would be produced annually by these panels was evaluated, their orientation and inclination being the same as those of each respective roof.

Installation of hydronic underfloor heating (placed on top of the current electrical radiant floor) assisted by a 70 kW heat pump capable of supplying heating and domestic hot water up to a temperature of 45°C was also considered. This change supposes a considerable reduction in the environmental impacts of energy use, as it is estimated that the pump will have a seasonal coefficient of performance of 2.42.

Table 2 shows the inventory for the building energy systems, the service life of the components and the recycling and disposal considered. The heat pump was considered renewable to a certain extent, as it uses heat from the environment, although it needs electricity to drive the compressor. The replacements of the considered energy systems were: 50 years (2 changes for the service life of the building) for the hydronic floor; 20 years (5 changes) for the solar panels and the heat pump; and 30 years (4 changes) for the solar installation. The distance from the production site of the active systems to the building was considered to be 20 km. A 16 tonne diesel lorry was considered for transportation purposes (freight lorry).

Table 2. Systems, components, years of service life and end-of-life treatment for the different energy system scenarios.

Energy system	Component	SER. LIFE	Recycling	Disposal
PV Panels Instalation				
480 Panels (158.4 kWp)	Silicon (as SiH_4)	30	-	Landfill (100%)
	Steel	30	100%	-
	Polystyrene	30	100%	-
	Aluminium	30	100%	-
	Cooper	30	100%	-
	Polyethylene	30	100%	-
Aerothermal Heat Pump				
Heat Pump (70 kW)	PVC	20	-	Landfill (100%)
	Copper	20	100%	-
	Refrigerant R-134a	20	Market	-
	Mineral oil	20	-	Incineration with fly ash extraction (100%)
	Steel	20	100%	-
	Rubber	20	-	Incineration with fly ash extraction (100%)
Hydronic floor (2782.5 m^2)	Polystyrene	50	-	Landfill (100%)
	Polyethylene	50	-	Landfill (100%)
	Aluminium	50	-	Landfill (100%)
	Concrete	50	-	Landfill (100%)
PV Panels plus Heat Pump				
Combined system	Steel	20/30(1)	100%	-
	Polyethylene	20/50(1)	27%	Landfill (73%)
	PVC	20/30(1)	95%	Landfill (5%)
	Copper	20/30(1)	100%	-
	Aluminium	30/50(1)	17%	Landfill (83%)
	Refrigerant R-134a	20	Market	-
	Mineral oil	20	-	Incineration with fly ash extraction (100%)
	Rubber	20	-	Incineration with fly ash extraction (100%)
	Polystyrene	50	-	Landfill (100%)
	Concrete	50	-	Landfill (100%)

PVC: Polyvinyl chloride; (1) Depends on the active system to which the component belongs

Transport stage (A4)

Transportation of the components of the building from the production site to the building was taken into account (Table 1).

Operational energy use stage (B6)

The energy demand of the building is broken down as follows: heating, DHW, and lighting and other electrical consumption.

The energy consumed according to the different scenarios is shown in Table 3. For scenarios other than the baseline scenario, the table breaks down the part of the demand covered by each active system and the part covered by the electricity mix. The energy consumption for the current building was based on real data obtained during a year. The energy savings due to improvements in the envelope have been calculated using cypecad mep software (Cypecad, 2019), whose calculation engine is energy plus, previously calibrated using occupation profiles.

The quality of the envelope greatly influences the thermal conditioning demand. This quality is summarized by the thermal conductance and the area associated with each envelope element. The window's conductance differs according to the orientation of the walls. Therefore, the area of frame, glass and total of the windows for each wall were calculated according to orientation. The thermal properties of frames and glass also need to be added. The average conductance of the windows was obtained by taking into account the characteristics of all the windows at each orientation and averaging according to the areas. The conductance of the opaque elements of the envelope was obtained in a similar way, considering the geometry and properties of the material components of the envelope.

The thermal conductance data ~~of~~ for the current building were the following:

- Vertical walls in the current building, conductance $U_{wall,CB}$=0.46 W/m^2 K.
- Ground, conductance $U_{ground,CB}$=0.86 W/m^2 K
- Roof, conductance $U_{roof,CB}$=2.27 W/m^2 K.
- Windows with wooden frame, conductance $U_{frame,CB}$=2.5 W/m^2 K and double glass panes, solar factor of 0.75 and conductance $U_{glass,CB}$=3.3 W/m^2 K. The average window conductance $U_{window,CB}$=2.90 W/m^2 K.

While the data obtained for the retrofitted building were:

- Vertical walls, conductance $U_{wall,RB}$=0.21 W/m^2 K.
- Windows with aluminium frames, conductance $U_{frame,RB}$=0.83 W/m^2 K and triple glass panes, solar factor of 0.51 and conductance $U_{glass,RB}$=0.56 W/m^2 K. The average window conductance of $U_{window,avg,RB}$=0.70 W/m^2 K.

The PV panels provide 46% of the energy demand of the CB and 63% of the energy demand of the RB considering all the energy to be supplied by the electricity mix. The heat pump provides 32% of the thermal demand of the CB and 22% of the thermal demand of the RB. Hence, renewable energy systems cover 78% of the demand for the CB and 86% of the demand for the RB, which has a lower demand.

Table 3. Energy consumed according to the different scenarios regarding the envelope and energy systems (electricity mix from year 2018).

Energy system scenarios	Envelope scenarios	
	CB	RB
(mix): All energy demand covered from electricity mix	164740	119758
Heating	80661	35679
DHW	9840	9840
Lighting and other electricity consumption	74238	74238
(PV+mix): PV Panels + electricity mix	164740	119758
PV Panels supply	76030	76030
Electricity grid supply (electricity mix)	88710	43728
Renewable-to-total ratio	0.46	0.63
(HP+mix): Heat pump + electricity mix	164740	119758
Aerothermal heat pump thermal supply	53089	26702
Electricity grid supply (electricity mix)	111651	93056
Renewable-to-total ratio	0.32	0.22
(PV+HP+mix): PV Panels + Heat pump + electricity mix	164740	119758
PV Panels supply	76030	76030
Aerothermal heat pump thermal supply	53089	26702
Electricity grid supply (electricity mix)	35621	17026
Renewable-to-total ratio	0.78	0.86

Energy values in kWh/year

<u>End-of-life stage (C1-C4)</u>

The end of life of all the materials used in the building and of those old materials that were removed from the building in the retrofitted measures was taken into account in this study. Demolition, transport to the treatment plant, waste processing (including recycling) and disposal were thus considered.

Life cycle impact assessment

In order to assess the energy and environmental impacts of the retrofitted measures, eight impact categories were selected (Table 4) in accordance with the main environmental indices and characterization factors included in the “Environmental Product Declaration” scheme (UNE-EN 15978, 2011; UNE-EN 15804, 2012). Besides, they are applied by other authors (Beccali et al., 2013; Piccardo et al., 2020; Morales et al., 2019; Sözer and Sözen, 2019).

Seven of the eight categories were calculated using the EPD 2013 V1.03 method, included in SimaPro 8.3.0 software. In this method, most of the impact categories are taken directly from the CML-IA baseline method (eutrophication, global warming, ozone depletion and abiotic resource depletion), acidification is taken from the CML-IA non baseline method and photochemical oxidation is based on ReCiPe 2008.

Life-cycle primary energy consumption was calculated according to the Cumulative Energy Demand (CED) Method, also included in SimaPro 8.3.0 software. The CED includes non-renewable (fossil and nuclear) and renewable (biomass, wind, solar, geothermal, water) energy source categories (International EPD System, 2013; Pré Sustainability, 2020)].

Table 4. Environmental impact categories and indicators used in the LCIA.

Environmental impact category	Indicator - Unit	LCIA reference
Acidification Potential (AP)	kg SO_2 eq	EPD (2013)
Eutrophication Potential (EP)	kg PO_4^{3-} eq	EPD (2013)
Global Warming Potential for a 100 year horizon (GWP-100y)	kg CO_2 eq	EPD (2013)
Photochemical Oxidant Creation Potential (POCP)	kg ethylene eq	EPD (2013)
Ozone Layer Depletion (ODP)	kg CFC-11 eq	EPD (2013)
Abiotic Depletion Potential (non-fossil resources) (ADP-n)	kg Sb eq	EPD (2013)
Abiotic Depletion Potential (fossil resources) (ADP-f)	MJ	EPD (2013)
Cumulative Energy Demand (CED)	MJ	CED V1.09

Results and discussion

Comparison of impacts for different insulating materials

Environmental impacts contribution of the components of the exterior walls and, specially, insulating materials, were investigated for the retrofitted building. Mineral fibre, glass wool and expanded polystyrene (EPS) were selected as insulating materials to compare their environmental effect. Table 5 shows the values of the different impact categories, given per year and unit of surface of the exterior wall, considering the product stage (A1-A3). The last column in the table shows the increase in the impacts due to the installation of insulating material. The values, expressed in percentage, were calculated by dividing the impact associated with each insulating material by the total impact of the non-insulating materials that make up the exterior walls (clay brick, polyurethane foam and plasterboard).

Table 5. Contribution to impact categories of the components of the exterior walls and the different insulating materials

Impact category, indicator unit	**Value**					**Impact increase due to insulation (%)**
	Clay brick	Polyurethane foam	Gypsum plasterboard	Insulating material		
AP, kg SO_2 eq/m^2·year	$6.27x10^{-3}$	$1.50x10^{-4}$	$2.72x10^{-4}$	*Mineral fibre*	$1.01x10^{-3}$	15%
				Glass wool	$1.87x10^{-3}$	28%
				EPS	$1.48x10^{-3}$	22%
EP, kg PO_4^{3-} eq/m^2·year	$1.36x10^{-3}$	$4.03x10^{-5}$	$6.21x10^{-5}$	*Mineral fibre*	$1.99x10^{-4}$	14%
				Glass wool	$5.89x10^{-4}$	40%
				EPS	$2.46x10^{-4}$	17%
GWP100y, kg CO_2 eq/m^2·year	$16.5x10^{-1}$	$3.61x10^{-2}$	$4.30x10^{-2}$	*Mineral fibre*	$1.37x10^{-1}$	8%
				Glass wool	$2.75x10^{-1}$	16%
				EPS	$4.13x10^{-1}$	24%
POCP, kg C_2H_4 eq/m^2·year	$3.60x10^{-4}$	$7.46x10^{-6}$	$1.24x10^{-5}$	*Mineral fibre*	$6.12x10^{-5}$	16%
				Glass wool	$9.66x10^{-5}$	25%
				EPS	$5.94x10^{-4}$	157%
ODP, kg CFC-11 eq/m^2·year	$1.48x10^{-7}$	$4.11x10^{-10}$	$2.41x10^{-9}$	*Mineral fibre*	$8.01x10^{-9}$	5%
				Glass wool	$2.53x10^{-8}$	17%
				EPS	$1.24x10^{-8}$	8%
ADP-n, kg Sb eq/m^2·year	$3.77x10^{-6}$	$3.99x10^{-8}$	$6.62x10^{-8}$	*Mineral fibre*	$2.70x10^{-7}$	7%
				Glass wool	$5.81x10^{-7}$	15%
				EPS	$9.12x10^{-8}$	2%
ADP-f, MJ/m^2·year	$180x10^{-1}$	$6.13x10^{-1}$	$4.59x10^{-1}$	*Mineral fibre*	$15.1x10^{-1}$	8%
				Glass wool	$38.2x10^{-1}$	20%
				EPS	$88.3x10^{-1}$	46%
CED, MJ/m^2·year	$197x10^{-1}$	$7.32x10^{-1}$	$5.96x10^{-1}$	*Mineral fibre*	$16.8x10^{-1}$	8%
				Glass wool	$46.6x10^{-1}$	22%
				EPS	$94.8x10^{-1}$	45%

In all impact categories, the major contribution is due to clay bricks, followed to a lesser extent by insulating materials. The impact increase due to insulation ranges from 5 to 16% for mineral fibre, from 15 to 40% for glass wool and from 2 to 157% for EPS. Mineral fibre is the insulating material that produces the lowest impact in all impact categories, except in abiotic depletion potential for non-fossil resources (ADP-n), where expanded polystyrene has a somewhat smaller contribution. As for glass wool, it produces a higher impact on acidification potential (AP), eutrophication potential (EP), ozone layer depletion (ODP) and abiotic depletion potential for non-fossil resources (ADP-n). In the cases of global warming potential (GWP100y), cumulative energy demand (CED) and abiotic depletion potential for fossil resources (ADP-f), the use of glass wool causes increases in impacts whose values are between those associated with mineral fibre and those of EPS. As can be seen, the use of EPS produces significant increases of 157%, 46% and 45% in the photochemical oxidant creation potential (POCP), abiotic depletion potential for fossil resources (ADP-f) and cumulative energy demand (CED) impact categories, respectively. These impacts are associated with the process of manufacturing EPS, which is produced from oil refining by-products that involve ethylene and benzene.

Comparison of impacts according to the envelope components for the current building and the retrofitted building

Figure 5 shows the percentage contribution to the environmental impact categories due to the manufacture of building components, grouped according to the different construction elements. Two scenarios are considered: the building in its current state and the building with a retrofitted envelope. For this study, in both scenarios the energy demand is considered to be fully covered by the 2018 electricity mix (baseline). Only the product stage (A1 + A2 + A3) has been included, as the study focuses on the variation in the elements of the building envelope.

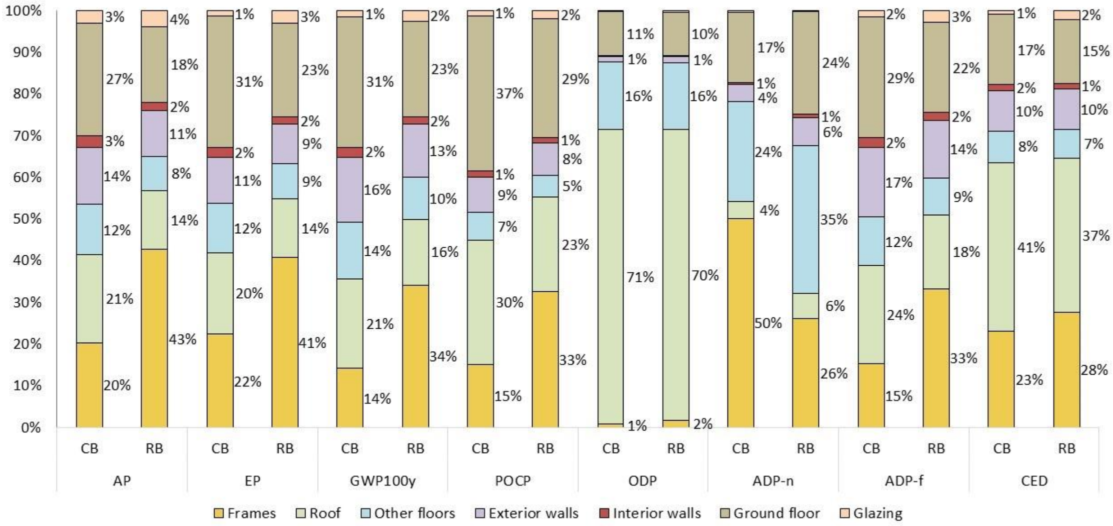

Figure 5. Contribution to the impact categories of the construction elements of the building (product stage) in the current and retrofitted building

With respect to the current building, the elements with the greatest contribution to environmental impact in most impact categories (AP, EP, GWP, POCP and ADP-f) are the ground floor, roof and frames, followed by the exterior walls and the other floors. The interior walls and glazing have a minor contribution. The material production processes that contribute the most to these impact categories are the production of steel, plywood and extruded polystyrene (XPS). In the retrofitted building, the frames stand out in terms of their contribution to the aforementioned impact categories due to the use of aluminium. Concerning to other impact categories, the roof represents around 70% of the contribution to the ozone depletion potential (ODP), both in the CB (mix) and the RB (mix). This impact can be attributed to the presence of XPS in the roof, due to the use of chlorofluorocarbons as blowing agents in the manufacturing process, although these chemicals are currently being greatly reduced or completely substituted by hydrofluorocarbons, which do not cause damage to the ozone layer, although they do have a greenhouse effect. As to cumulative energy demand (CED), the roof represents 41% and 37% and the frames 23% and 28% in the CB (mix) and RB (mix), respectively. The high contribution of the roof may be related to the great energy demand in steel production. The use of wood in the CB (mix) has a major contribution to the abiotic depletion potential for non-fossil resources (ADP-n), which accounts for 50%, as all the exterior window and door frames are made of this material, whereas in the RB the contribution to the impacts is more balanced among other elements, including aluminium, which is not present in the current building.

Comparison of impacts for active systems and envelope retrofitting

Figure 6 shows the results of the environmental impact values per year and unit of net floor area of the building for the different stages of the life cycle in the studied scenarios. Values for most impact categories decrease when implementing renewable active energy systems and when retrofitting the envelope, except for the ozone depletion potential when using the heat pump, and for the abiotic depletion potential for non-fossil resources when using PV solar panels.

When using the heat pump, the impact on ozone depletion potential can be attributed to the refrigerants used in this technology, and in particular to the use of R-134a during the manufacturing stage. According to Greening and Azapagic (2012), although R-134a does not contain chlorine, other substances emitted during its life cycle contribute to this impact, including monochlorotetrafluoroethane (R-124) and trichlorotrifluoroethane (R-113).

When using PV solar panels, the impact on ADP-n can be attributed to the high consumption of materials required in their manufacture. Using the ReCiPe methodology, Desideri et al. (2013) and Zhong et al. (2011) reported that the manufacture of the panels and the inverter produces significant impacts on human health, especially in the categories of climate change and human toxicity. Kabakian et al. (2015), who also employed the ReCiPe methodology, likewise reported that these elements (panels and inverter) have a great impact on the metals depletion category.

This category could be considered equivalent to the ADP-n category that has been evaluated in the present study by means of the EPD 2013 methodology.

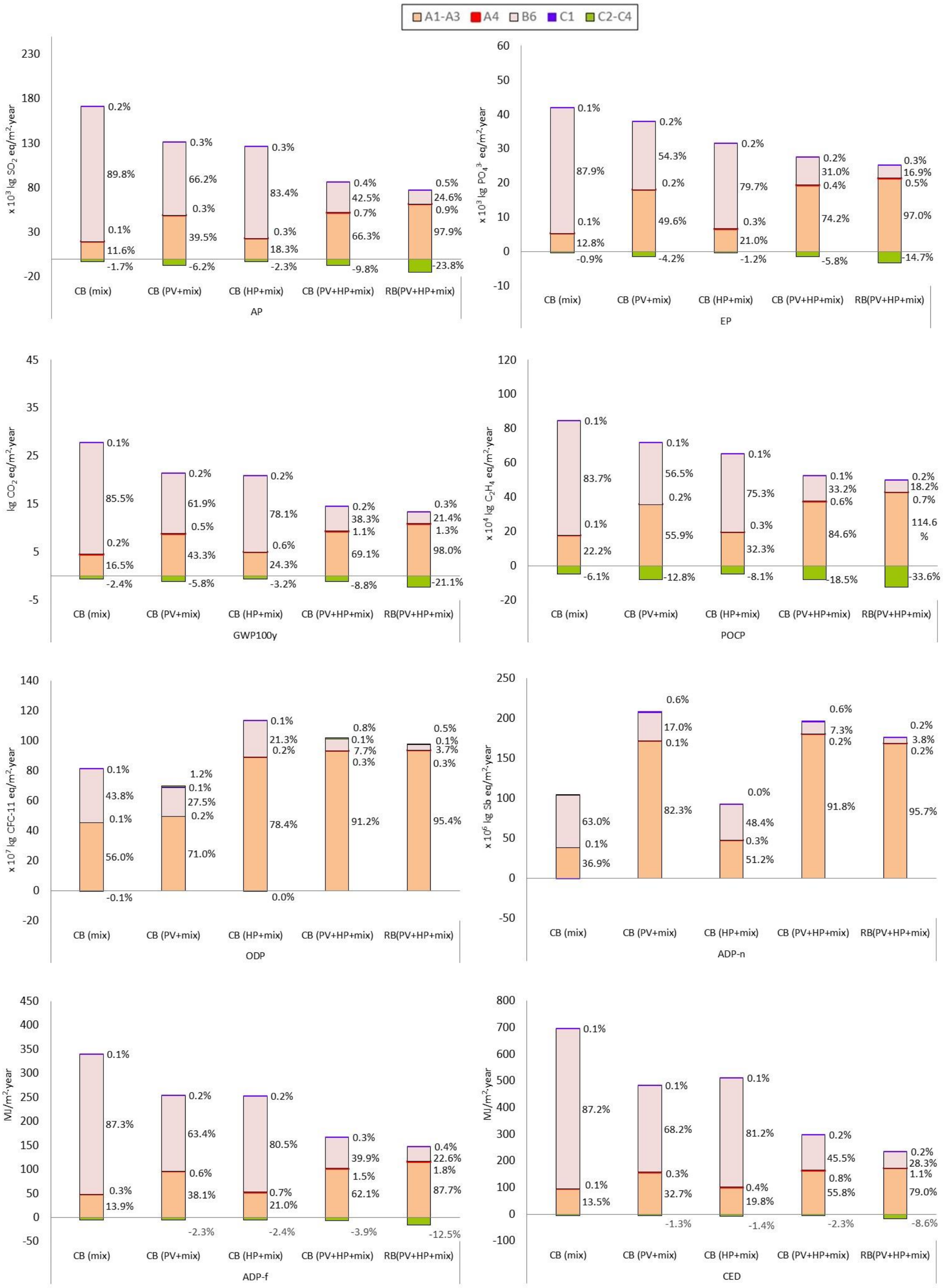

Figure 6. Contribution to the impact categories of the product (A1-A3), construction (A4), use (B6) and end-of-life (C1-C4) stages for the different scenarios.

The installation of the heat pump does not substantially increase the impacts at the manufacturing stage compared to the scenario in which the total energy demand is covered only by the electricity mix, except for the ODP category. However, the use of PV panels increases the contribution to all impact categories at the manufacturing stage. The use stage is the one that has the greatest impact for the CB (mix) scenario, the percentage impact contributions for this stage ranging between 83.7 and 89.8%, according to the following order of categories: POCP, GWP, CED, ADP-f, EP and AP. The impacts of this stage decrease for the ADP-n (63%) and ODP (43.8%) categories, whose contribution is greater in the materials manufacturing stage (A1 + A2 + A3).

The introduction of renewable photovoltaic energy in the current building greatly reduces the share of the use stage in the different impact categories, with percentages ranging between 54.3 and 68.2% for the following order of categories: EP, POCP, GWP, ADP-f, AP and CED. As in the scenario in which only the electricity mix was considered, the material manufacturing stage has a major contribution to the ODP and ADP-n impact categories, with values of 71.0 and 82.3%, respectively.

When both active energy systems are used, the contribution of the use stage decreases in all of the impact categories, with contributions ranging from 7.1% for ODP or 7.3% for ADP-n to 39.9% for ADP-f, 42.5% for AP or 45.5% for CED.

When comparing the environmental impacts of the retrofitted building with those of the current building, including the two active energy systems (PV and HP) in both scenarios, the values are lower for all impact categories, the contribution of the energy use stage decreasing, but the contribution of the product stages increasing as a result of the greater consumption of material in the retrofitted building. For the current building with both active energy systems, the contribution of the embodied energy is greater than that of the energy use for all the impact categories. The difference is more significant for the retrofitted building, as a result of its lower energy use. For the ADP-n impact category, all the scenarios, except the CB (mix), have higher embodied energy than energy use. For the ODP impact category, the embodied energy exceeds the energy use in all scenarios.

For the current building, the impact due to GWP decreases to approximately less than a half when active systems are implemented and the use-to-total ratio decreases from 86% to 38%, while the embodied-to-total ratio increases from 14% to 61% (Table 6). Additionally, carrying out retrofitting of the envelope together with the implementation of both active systems (PV panels + heat pump) would further decrease the use-to-total ratio to 21%, while the embodied-to-total ratio would increase~~s~~ to 78%. The same trends can be observed for the impact due to CED: the total impact decreases from 688 a

MJ/m^2·year when the active systems are implemented in the current building (57.9% reduction). If only the use-to-total ratio is considered, a decline of 47% was achieved (from 87% to 46%). For the RB (PV+HP+mix), this ratio decreases to 28%.

Table 6. Greenhouse warming potential and cumulative energy demand for the current building and the retrofitted building considering the Spanish electricity mix for 2018: total values, impact variations and impact ratios.

Impact category	Scenario (mix 2018)	Total impact	Impact variation (%)	Impact Ratios (%)	
				use to total	Embodied to total
GWP100y kg CO_2 eq/m^2·year	CB (mix)	27		86	14
	CB (PV+mix)	20	-25.3	62	38
	CB (HP+mix)	20	-25.6	78	22
	CB (PV+HP+mix)	13	-50.9	38	61
	RB (PV+HP+mix)	11	-59.4	21	78
CED CED MJ/m^2·year	CB (mix)	688		87	13
	CB (PV+mix)	475	-30.9	68	32
	CB (HP+mix)	503	-26.9	81	19
	CB (PV+HP+mix)	290	-57.9	46	54
	RB (PV+HP+mix)	216	-68.7	28	71

NOTE: Stages A1-A4 + C1-C4 are considered for the embodied energy

In line with our results, Asdrubali et al. (2013) applied LCA to a multi-story office building built in Italy in 2008 with 3353 m^2 net flow area, including all the life cycle stages. The results showed that the environmental impact of the construction phase, as measured by the Cumulative Energy Demand method, was 13.7% of the total impact for an office building; the operational stage impact was 85% and end of life was less than 2%. They carried further analyses to evaluate the influence of various optimizations, i.e., more efficient envelopes and facilities and recognized that their results confirm the fact that in these future scenarios, with more energy-efficient buildings and materials, the selection of low embodied energy construction materials will become more important. They reinforce the idea that the particularities of each building case have great weight. Particular attention also was paid to analysing the equipment system, both for its performance and embodied energy (i.e., installing a photovoltaic system on the roof). This last optimization significantly reduces impact throughout the entire life cycle (−12%), even though it may slightly increase embodied energy (+3.8%), the impact values being greater in our case (-25. 3%) but these values are very dependent on the number of PV panes used, building orientations and location irradiation.

Compared to the results of Ramesh et al. (2010) for total primary energy for the life cycle and the embodied energy, our results are rather lower, with the total primary energy in the range from 59.8 to 191 KWh/ m^2 year, limit values that correspond to the cases RB (PV+HP+mix) and CB (mix) respectively. The embodied energy values for these same cases were 41.9 and 24.8 KWh/ m^2 year. The differences between our results and those of Ramesh et al. (2010) may be related to different climate, building materials and building practices.

Effect of the variation in the electricity mix on environmental impacts

The effects of national policies on the different impact categories for the energy use stage of the retrofitted building in the 2020 and 2030 horizons are presented in Figure 7: (i) in the scenario in which energy is supplied only from the electricity mix, RB (mix); and (ii) in the scenario in which energy is supplied from the active energy systems plus the electricity mix, RB (PV + HP + mix). The figure also shows the values of the impact categories for RB (mix) in the 2018 electricity mix scenario with the aim of analysing the percentage variations with respect to this scenario.

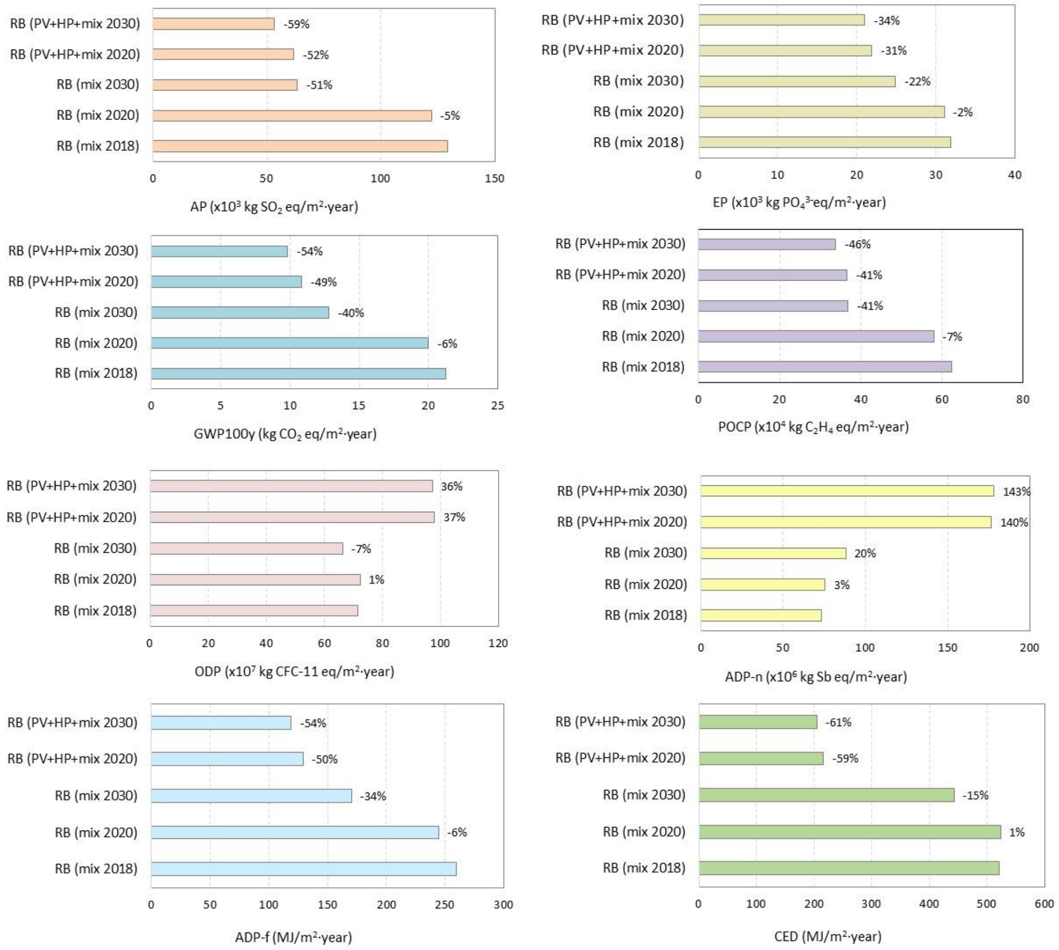

Figure 7. Effect of the variation in the electricity mix in the 2020 and 2030 horizons on a building with a retrofitted envelope when the energy is supplied only by the electricity grid and when a combination of renewable systems (PV+HP) is added.

The contribution of the GWP and CED impact categories to the energy use stage decreases in the 2020 and 2030 horizons, and occurs for both the RB (mix) and the RB (PV+HP+mix) scenarios. For the RB (mix), the expected decreases in 2030 compared to 2018 are 40% for GWP, and 15% for CED. The rest of the impact categories also decrease, in different proportions, except in the impact ADP-n, where there is an increase of 20%. This may be due to the negative effect in this impact category of the increase in photovoltaic energy in the electricity mix, which may be related to silver mining, as silver is one of the most important metals used in the photovoltaic panel manufacturing process, along with lead, zinc and copper (Apergis and Apergis, 2019; Silver Institute, 2018).

Regarding the influence of the energy supply system, the use of a combination of PV panels and a heat pump, which covers a large part of the building's energy consumption, reduces the environmental impact by 54% for GWP and 61% for CED in 2030 compared to 2018. However, the ADP-n and ODP impact categories increase 143% and 36%, respectively. These changes are not caused only for the effect of electricity mix, but they are produced mainly by the use of the active systems: PV panels (ADP-n) and heat pumps (ODP).

Table 7 presents the total impact values (per unit of net floor area and year) and impact ratios in the GWP and CED categories for the retrofitted building, considering the planned electricity mix for 2020 and 2030 in Spain.

Table 7. Greenhouse warming potential and cumulative energy demand for the retrofitted building considering the mix of 2020 and 2030: total value and impact ratios.

Impact category	Scenario	Total impact	Indicator unit	Impact Ratios (%) use to total	Impact Ratios (%) embodied to total
GWP100y	RB (mix 2020)	20	kg CO_2 eq/m^2·year	78	22
	RB (mix 2030)	13		66	34
	RB(PV+HP+mix 2020)	11		20	80
	RB(PV+HP+mix 2030)	10		12	88
CED	RB (mix 2020)	524	CED MJ/m^2·year	84	16
	RB (mix 2030)	443		81	19
	RB(PV+HP+mix 2020)	216		28	71

RB(PV+HP+mix 2030)	205	25	75

Comparing the 2030 horizon with that of 2020, the use-to-total ratio for the GWP category in the RB (mix) scenario decreases from 78 to 66%, while the embodied-to-total ratio increases from 22 to 34%. For the RB (PV+HP+mix) scenario, the use-to-total ratio decreases from 20 to 12%, while the embodied-to-total ratio increases from 80 to 88%. As regards the results for the cumulative energy demand (CED), the use-to-total impact ratio for the RB (mix) scenario decreases from 84 to 81%, while the embodied-to-total ratio increases from 16 to 19%. For the RB (PV+HP+mix) scenario, the use-to-total ratio decreases from 28 to 25%, while the embodied-to-total ratio increases from 71 to 75%.

Tenants, policy makers, researchers and civil society generally need to know the environmental benefits resulting from the decisions that each of them may make to improve the sustainability of buildings. Our research provides evidence on the need to consider jointly the effects not only of the environmental implications of using different building materials to retrofit the envelope and of adopting renewable active energy systems in the building itself, but also the changes in the electric mix derived from the decarbonisation policies that are adapted in each country.

For instance, comparing the results of Tables 6 and 7, it is important to note that, without considering the effect of the change in the reference energy mix, with the adoption of active systems in the current and retrofitted building, the effect on GWP100y is reduced up to 13 and 10 kg CO_2 eq/m^2·year, respectively. However, when the electricity mix considered is that of the 2030 horizon, with no more than the improvement of the building envelope, the effect on GWP100y reaches the same value as that achieved without any retrofitting actions in the envelope but adopting active systems and with the mix of reference (13 kg CO_2 eq/m^2·year). Therefore, it is clear that for this impact category, the effect produced by the change in the mix is greater than the implementation of active systems in the building itself.

Regarding CED, it is observed that the introduction of active energy systems in the building always reduces the impact. Thus, without adopting any retrofitting actions in the envelope and with the reference mix, the impact reaches 688 MJ/m^2·year and it diminishes to 290 MJ/m^2·year when active systems are implemented and still more, to 216 MJ/m^2·year, if the envelope is improved too. However, when the electricity mix considered is that of the 2030 horizon, if only the envelop is retrofitted, the effect on CED is merely reduced to 443 MJ/m^2·year. This shows that the effect of the electricity mix is not that important for this impact category.

Conclusions

The main conclusions focus on CO_2 equivalent emissions, via the variation in the global warming potential, and on primary energy, via the variation in cumulative energy demand.

In the scenario of the building supplied by electricity generated from the 2018 electricity mix without the envelope being retrofitted, the implementation of active energy systems in the building itself (photovoltaic panels and a heat pump) produces a decrease in the use-to-total impact ratios. These ratios can fall from 86% (GWP) and 87% (CED), when using only electricity from the electricity mix, to 38% (GWP) and 46% (CED), when using active systems complemented with electricity from the electricity mix. If, in addition to this change, the envelope is retrofitted, the ratios drop even further, to 21% (GWP) and 28% (CED).

If the envelope is retrofitted and all the demand for energy use is supplied by the electricity mix, when comparing the results of the 2030 mix with those of the 2018 mix, decreases are foreseen in acidification (51%), eutrophication (22%), global warming (40%), photochemical oxidant creation potential (41%), ozone depletion (7%), abiotic depletion potential for fossil fuels (34%) and cumulative energy demand (15%). However, there will be a 20% increase in the abiotic depletion potential for non-fossil fuels.

The joint consideration of the effects of different actions to improve the sustainability of the building and of the changes in the electricity mix derived from the decarbonisation policies, allows us to weigh more accurately the environmental benefits of decisions that we may adopt. Thus, in this paper, it is highlighted that for the global warming potential the effect produced by the change in the electricity mix is greater than that of the implementation of active systems in the building.

This study has some limitations: (i) it focuses on a listed building, in northern Spain with an Atlantic climate, (ii) the available surface for the placement of photovoltaic panels is limited because of the need to preserve the appearance of the building, (iii) the decarbonisation scenarios are working objectives which could be subject to changes in the future that would require their modification. Nevertheless, the results achieved can be extrapolated to a large number of listed buildings both in Spain and in other parts of Europe.

Declaration of competing interest

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

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