University of Oviedo

Sustainability and development perspectives of low energy buildings in Asturias

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SUSTAINABILITY AND DEVELOPMENT PERSPECTIVES OF LOW-ENERGY BUILDINGS IN ASTURIAS

DOCTORAL THESIS

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Declaration

I declare that the present Doctoral Thesis entitled "Perspectives of sustainability and development of low-energy buildings in Asturias", presented by Daniel González Prieto to obtain the degree of Doctor, has been carried out under my direction within the framework of the Doctorate Program in Energy and Control of Processes, in the line of research "Resources, Technology and Energy Management" of this University, and that it meets all the requirements to qualify for the Doctorate Award.

Gijón, April, 2021

Doctoral Thesis Supervisor

Prof. Dr Yolanda Fernández Nava

This doctoral thesis is dedicated
to my beloved parents and
my brother Ángel.

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Abstract

Worldwide, net emissions of greenhouse gases from human activities increased by 35% from 1990 to 2010. An increase in the atmospheric concentrations of greenhouse gases produces a positive climate forcing, or warming effect. From 1990 to 2015, the total warming effect from greenhouse gases added by humans to the Earth's atmosphere increased by 37%. As greenhouse gas emissions from human activities increase, they build up in the atmosphere and warm the climate, leading to many other changes around the world—in the atmosphere, on land, and in the oceans, as is summarized by the EPA, Environmental Protection Agency of the United States.

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. The need to reduce the energy consumption of buildings led in Europe to Directives to get nearly zero-energy buildings in 2020. However, new amending Directives on Energy Efficiency agreed to update the policy framework to 2030 and beyond. Besides, Energy and Climate Policy Framework for 2030 establishes ambitious Union commitments to reduce greenhouse gas emissions further by at least 40% by 2030 as compared with 1990, to increase the proportion of renewable energy consumed.

Regulations establish a long-term goal of accomplishing neutrality of greenhouse gas (GHG) emissions by 2050, which means achieving a 100% renewable electricity system by that date. To reach this objective in Spain, the authorities presented the National Integrated Energy and Climate Plan, which 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.

Bearing in mind the foreseeable changes in the Spanish energy mix aimed at contributing to the energy decarbonisation of Europe, as well as present-day and future climate changes, a first study was carried out in order to know

the impact that these changes will have on a single-family house that uses panels of lightweight concrete in the envelope. This house, designed with a high energy performance envelope, has been placed in different locations (Oviedo, Bilbao, Valladolid, Madrid, Zaragoza, Barcelona, Valencia and Seville) and climates in Spain. In order to analyse the environmental changes as power mix varies, life cycle assessment using SimaPro IMPACT 2002+ software was carried out. The weather forecast in each of the eight Spanish cities chosen for this study was obtained using the Meteonorm database. Heating demands will diminish as a consequence of the increase in temperature. The total demand (heating and cooling) generally decreases in 2030 with respect to 2018, by a percentage that depends on the location. The most significant variations occur in Oviedo, Bilbao and Valladolid, with 21%, 16% and 15%, respectively, while at the remaining locations the percentage decrease is less than 7%. However, there is a slight increase of 3% in the total demand for Barcelona, due to the increase in cooling demand.

As a consequence of climate change and the Energy and Climate Plan, the categories of damage will decrease (to a greater or lesser extent, depending on the location): Human Health, from 59% to 68%; Climate Change, from 57% to 67%; and Resources, from 54% to 65%.

Asturias presents a variety of microclimates, since the mountains are close to the coast and there are strong variations in altitude. Thermal behaviour in the use of energy and incorporated energy are analysed for different insulation thicknesses, for two designs of single-family houses with different form factors and for different locations in the Principality of Asturias. The impacts on primary energy (embodied and use) and on greenhouse gas emissions (embodied and use) are obtained. Regarding the impacts due to the energy used to cover the thermal demand, three supply scenarios are considered: (i) electricity only; (ii) heat pump plus electricity; and (iii) natural gas boiler. Finally, the influence on future impacts of the planned Spanish electricity mix in the 2030 horizon is analysed when using electricity only. The findings demonstrate that the electricity-only scenario can be very suitable versus the gas boiler. However, the impacts of the electricity-only scenario will always be greater than those of the heat pump scenario, since if the electricity mix is improved, the improvement will also have a favourable effect on the heat pump impacts. One of the aspects in which the heat pump could be disadvantageous compared to the electricity-only

scenario, would be damage to the ozone layer, which is a very important impact to consider.

EU Directives encourage Member States to increase the number of high energy performance buildings and new rules for greener and smarter buildings are foreseen to increase the quality of life for all European. However, the majority of the buildings will be still in use the next 70 years. Therefore, most of the energy reductions will have to be achieved by deep retrofitting of existing buildings. This thesis 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 itself. The aim is to achieve significant reductions in cumulative energy demand (CED), global warming potential (GWP) and other environmental impacts. The work includes a scenario with the Spanish electricity mix for 2018 (which is taken as a reference) and two scenarios based on the electricity mixes of 2020 and 2030, to take into account the medium-term environmental policy in which it is framed the decarbonisation plan proposed by the Spanish Government. The impacts will decrease up to 54% for GWP and 61% for CED in 2030 compared to 2018 if photovoltaic panels are implemented in combination with a heat pump.

Finally, the thesis proposes the extensive use of economic indicators for environmental assessment, as an aid in choosing the most suitable materials for the construction of the building and energy supply systems. Such assessment covers not only the economic aspects of potential interventions for the improvement of the energy performance of a building, but also the environmental effects of such interventions, so that these indicators (quick and easy to calculate) can be utilized as a useful tool to select the "best investment". Specifically, the indicators used in the present study are the payback period (PBP), the net present value (NPV) and the return on investment (ROI).

Keywords: Energy transition, Decarbonisation, Climate change, Energy demand for heating and cooling, Low-energy single-family houses, Sub-regional Atlantic climates, Lightweight concrete, Life cycle assessment, Retrofit of non-residential buildings, Renewable energy in the building itself, Indicators of investment.

Resumen

A nivel mundial, las emisiones netas de gases de efecto invernadero de las actividades humanas aumentaron un 35% entre 1990 y 2010. El incremento de las concentraciones atmosféricas de gases de efecto invernadero produce un efecto positivo de calentamiento o forzamiento del clima. Desde 1990 hasta 2015, el efecto de calentamiento total de los gases de efecto invernadero agregados por los humanos a la atmósfera de la Tierra aumentó un 37%. A medida que crecen las emisiones de gases de efecto invernadero de las actividades humanas, estos gases se acumulan en la atmósfera y calientan el clima, lo que provoca muchos otros cambios en todo el mundo: en la atmósfera, en la tierra y en los océanos, como lo resume la EPA, la Agencia de Protección Medioambiental de Estados Unidos.

Los edificios en la Unión Europea representan el 40% del consumo de energía final, el 36% de las emisiones de CO_2, el 30% del consumo de materias primas, el 12% del consumo de agua potable y son productores del 30% de los residuos destinados a vertedero. La necesidad de reducir el consumo de energía de los edificios llevó en Europa a Directivas encaminadas a conseguir edificios de consumo de energía casi cero en 2020. Sin embargo, nuevas Directivas de enmienda sobre Eficiencia Energética acordaron actualizar el marco político para 2030 y más allá. Además, el Marco de Políticas de Energía y Clima para 2030 establece ambiciosos compromisos de la Unión para reducir aún más las emisiones de gases de efecto invernadero, al menos un 40% para 2030 con respecto a 1990, aumentando la proporción de energía renovable consumida.

Las regulaciones establecen como objetivo a largo plazo lograr la neutralidad de las emisiones de gases de efecto invernadero (GEI) para el 2050, lo que significa disponer de un sistema eléctrico 100% renovable para esa fecha. Para alcanzar este objetivo en España, las autoridades presentaron el Plan Nacional Integrado de Energía y Clima, que incluye una serie de medidas que permitirán obtener los siguientes resultados en 2030: reducción del 23% de las emisiones de GEI respecto a 1990; 42% de participación de renovables en el uso final de la energía; mejora del 39,5% en la eficiencia energética; y 74% de participación de las energías renovables en la generación de electricidad.

Teniendo en cuenta los cambios previsibles en el mix energético español destinados a contribuir a la descarbonización energética de Europa, así como los cambios climáticos actuales y futuros, se ha realizado un primer estudio para conocer el impacto que estos cambios tendrán en una vivienda unifamiliar que utiliza paneles de hormigón aligerado en la envolvente. Esta vivienda, diseñada con una envolvente de alto rendimiento energético, se ha situado en diferentes ubicaciones (Oviedo, Bilbao, Valladolid, Madrid, Zaragoza, Barcelona, Valencia y Sevilla) y climas de España. Para analizar los cambios medioambientales a medida que varía el mix energético, se realizó una evaluación del ciclo de vida utilizando el software SimaPro IMPACT 2002+. La previsión meteorológica en cada una de las ocho ciudades españolas elegidas para este estudio se obtuvo mediante la base de datos Meteonorm. Las demandas de calefacción disminuirán como consecuencia del aumento de temperatura. La demanda total (calefacción y refrigeración) generalmente disminuye en 2030 con respecto a 2018, en un porcentaje que depende de la ubicación. Las variaciones más significativas se dan en Oviedo, Bilbao y Valladolid, con un 21%, 16% y 15%, respectivamente, mientras que en el resto de localidades la disminución porcentual es inferior al 7%. Sin embargo, hay un ligero aumento del 3% en la demanda total de Barcelona, debido al aumento de la demanda de refrigeración.

Como consecuencia del cambio climático y del Plan de Energía y Clima, las categorías de daños disminuirán (en mayor o menor medida, según la ubicación): Salud Humana, del 59% al 68%; Cambio climático, del 57% al 67%; y Recursos, del 54% al 65%.

Asturias presenta una variedad de microclimas, ya que las montañas están cerca de la costa y hay fuertes variaciones de altitud. Se analiza el comportamiento térmico en el uso de la energía y la energía incorporada para diferentes espesores de aislamiento, para dos diseños de viviendas unifamiliares con diferentes factores de forma y para diferentes ubicaciones en el Principado de Asturias. Se obtienen los impactos sobre la energía primaria (incorporada y de uso) y sobre las emisiones de gases de efecto invernadero (incorporadas y de uso). En cuanto a los impactos debidos a la energía utilizada para cubrir la demanda térmica, se consideran tres escenarios de suministro: (i) solo electricidad; (ii) bomba de calor más electricidad; y (iii) caldera de gas natural. Finalmente, se analiza la influencia que sobre los impactos futuros producirá el mix eléctrico español planificado para el horizonte 2030, en caso de que se utilice únicamente electricidad. Los resultados demuestran que el escenario de solo electricidad puede ser muy adecuado frente a la caldera de gas. Sin embargo, los impactos del escenario solo eléctrico serán siempre mayores que los del escenario de la bomba de calor, ya que, si se mejora el mix eléctrico, la mejora también tendrá un efecto favorable sobre los impactos de la bomba de calor. Uno de los aspectos en los que la bomba de calor podría ser desventajosa en comparación con el escenario de solo electricidad, sería el daño a la capa de ozono, que es un impacto muy importante a considerar.

Las Directivas de la UE alientan a los Estados Miembros a aumentar el número de edificios de alto rendimiento energético, estando previstas nuevas normas sobre edificios más ecológicos e inteligentes, para aumentar la calidad de vida de todos los europeos. Sin embargo, la mayoría de los edificios seguirán en uso durante los próximos 70 años. Por lo tanto, la mayor parte de las reducciones de energía deberán lograrse mediante una profunda remodelación de los edificios existentes. Esta tesis analiza el ciclo de vida completo de un edificio de oficinas catalogado como sujeto a protección cultural y discute las implicaciones ambientales del uso de diferentes materiales de construcción para modernizar la envolvente y de la adopción de sistemas de energía activa renovable en el propio edificio. El objetivo es lograr reducciones significativas en la demanda de energía acumulada (CED), el potencial de calentamiento global (GWP) y otros impactos medioambientales. El trabajo incluye un escenario con el mix eléctrico español de 2018 (que se toma como referencia) y dos escenarios basados en los mix eléctricos de 2020 y 2030, con el fin de tener en cuenta la política medioambiental a medio plazo en la que se enmarca el plan de descarbonización propuesto por el Gobierno de España. Los impactos en 2030 disminuirán con respecto a 2018 si se implementan paneles fotovoltaicos en combinación con una bomba de calor: hasta un 54%, en el caso de GWP, y un hasta un 61%, en el caso de CED.

Finalmente, la tesis propone el uso extensivo de indicadores económicos para la evaluación medioambiental, como ayuda para la elección de los materiales más adecuados para la construcción del edificio y de los sistemas de suministro energético. Dicha evaluación cubre no solo los aspectos económicos de las posibles intervenciones para la mejora del rendimiento

energético de un edificio, sino también los efectos medioambientales de dichas intervenciones, de modo que estos indicadores (rápidos y fáciles de calcular) se pueden utilizar como una herramienta útil para seleccionar la "mejor inversión". En concreto, los indicadores utilizados en el presente estudio son el período de amortización (PBP), el valor actual neto (NPV) y el retorno de la inversión (ROI).

Palabras clave: Transición energética, Descarbonización, Cambio climático, Demanda energética de calefacción y refrigeración, Viviendas unifamiliares de bajo consumo energético, Climas atlánticos subregionales, Hormigón aligerado, Evaluación del ciclo de vida, Rehabilitación de edificios no residenciales, Energía renovable en el propio edificio, Indicadores de inversión.

Conclusiones y Trabajo Futuro

Los estudios realizados muestran la importancia de los efectos combinados del plan de descarbonización y el cambio climático, a partir de los impactos ambientales provocados por la electricidad necesaria para satisfacer las demandas térmicas. Los efectos combinados para los climas españoles y las viviendas unifamiliares conducen a un pronóstico de reducción de daños en Salud Humana (59-68%), Cambio Climático (57-67%) y Recursos (54-65%). Sin embargo, el daño a la Calidad del Ecosistema se incrementará (5-28%), como resultado del mayor impacto en esta categoría de daño del escenario de producción de energía para 2030, aun a pesar de los menores requerimientos térmicos esperados en los hogares para ese año.

Los microclimas atlánticos del norte de España pueden modificar los requisitos para conseguir un aislamiento adecuado y, en consecuencia, la energía de uso operacional. Sin embargo, incluso para las casas con un buen nivel de aislamiento, las ratios de impacto de uso respecto a impacto total varían significativamente: del 46% al 87% para la energía primaria y del 31% al 75% para el potencial de calentamiento global, dependiendo del factor de forma de la casa, el microclima y el escenario de suministro de calor. Aplicando futuras políticas medioambientales, la electricidad puede convertirse en una opción más respetuosa con el medio ambiente que el gas natural.

La evaluación del ciclo de vida (LCA) previo a la rehabilitación de un edificio de oficinas catalogado como de interés cultural, revela la posibilidad de ser respetuosos con el medio ambiente, incluso con el mix energético actual, si se implantan sistemas activos en el propio edificio. Para el mix eléctrico español de 2018, los resultados de este trabajo destacan la posibilidad de reducir el potencial de calentamiento global (GWP) del 59 al 25% y la demanda energética acumulada (CED) del 69 al 31%, combinando las medidas anteriores.

Para el escenario en el que la demanda de energía está totalmente cubierta por el mix eléctrico, los impactos en 2030 disminuirán en un 40% para GWP y en un 15% para CED, en comparación con 2018. Estas reducciones aumentarán aún más, hasta 54% y 61%, respectivamente, si se implementan paneles fotovoltaicos en combinación con una bomba de calor.

El uso de indicadores económicos para la evaluación ambiental se ha mostrado en este trabajo como una herramienta muy útil para seleccionar la mejor intervención a la hora de elegir los sistemas activos y los elementos constructivos de la envolvente de los edificios. Se han realizado dos estudios de rehabilitación de un edificio de oficinas, con múltiples escenarios cada uno. Los indicadores (payback, valor actual neto y retorno de la inversión) permiten, cuando se utilizan en conjunto, tener una visión global de la mejor opción (para la rehabilitación, en este caso), incluso cuando se consideran tantos casos, cada uno teniendo en cuenta no solo la inversión económica, sino seis impactos ambientales (en los pocos antecedentes de la literatura se suele estudiar uno o dos indicadores, con uno o dos impactos, aplicados a un número reducido de casos). Para el edificio de oficinas analizado, la intervención más recomendada sería la instalación formada por paneles fotovoltaicos y bomba de calor, sin mejorar la envolvente.

En cuanto a las futuras líneas de investigación, hay que tener en cuenta que los procesos del ciclo de vida relacionados con la explotación de residuos a través de la reutilización o fabricación de nuevos productos que puedan ser reincorporados en edificios o utilizados para otros fines aún están poco analizados. Esto también se debe a la escasez de datos sobre los procesos de tratamiento, así como a la baja tasa de generación de materiales de deconstrucción. Por tanto, se propone como un posible trabajo futuro, la incorporación a los estudios de la etapa D del ciclo de vida, según su definición en UNE-EN 15978: 2012: Información complementaria - Beneficios y cargas más allá del límite del sistema, que incluye la subetapas del potencial de reutilización, recuperación y reciclaje.

Otra posible línea de trabajo sería extender el estudio de ciclo de vida a un barrio de Gijón (Asturias), incluyendo la deconstrucción y rehabilitación de edificios, y de tal forma que, en su conjunto, se obtenga un barrio de energía casi nula. En cuanto a los sistemas energéticos propios, se propone la instalación de placas solares a nivel de barrio en las cubiertas actuales, así como la inclusión de bombas de calor centralizadas con calefacción y suministro de ACS para todo el barrio.

Los núcleos urbanos con alta compacidad edificatoria y envolventes con alta capacidad de absorción y reflexión del calor, sin elementos de regulación climática en el entorno urbano, deben ser reconsiderados en el futuro. El aumento de temperatura en el planeta incrementará cada vez más el efecto isla de calor, por lo que el confort en la ciudad será relevante y dará lugar a la necesidad de proyectos de diseño de confort térmico a nivel de barrio. Cada vez se introducirán más elementos para reducir el calentamiento: sombreados estratégicos, áreas verdes o sistemas que mejoren el enfriamiento evaporativo, depósitos de agua artificiales, etc. Todos estos aspectos también deberían ser objeto de futuras investigaciones.

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Chapter 1. Introduction and Thesis Objectives

1.1 Introduction

Sustainability is a broad term describing a desire to carry out activities without depleting resources or having harmful impacts. An international group of environmental experts, politicians and civil servants convened by the UN General Assembly (Brundtland Commission 1987) defined the sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

Sustainable construction can be defined as one that has special respect and commitment to the environment. Consequently, it implies the efficient use of energy, water and resources. In addition, it uses materials that are less harmful to the environment, are healthier and aim to reduce environmental impacts. Sustainable construction intends conceptually to rationalize, save, conserve and improve processes. Broadly speaking, the requirements that sustainable buildings must meet include a rational consumption of energy and water throughout their life cycle and the use of materials that are not harmful to the environment and meet the three "Rs": recyclable, recoverable and reusable. It also requires the minimization of waste during construction, the rational use of the land and natural integration into the environment, the satisfaction of the present and future needs of the users / owners, so that the buildings are flexible, adaptable and with intrinsic quality (definition in Ramírez 2002). The term sustainable construction encompasses not only the buildings themselves, but also takes into account the environment and the way in which they are integrated to form cities. Sustainable urban development aims to create an urban environment that does not harm the environment, and that provides sufficient urban resources, not only in terms of integration of forms and energy and water efficiency, but also for its functionality, as the best place to live. This entails a change in the mentality of the industry and economic strategies, in order to prioritize the recycling, reuse and recovery of materials over the traditional trend of extraction of natural materials and promote the use of construction and energy processes based on less polluting processes and products and the use of renewable energies (Sola et al. 2005).

1.1.1 Climate Change

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 and greenhouse gases from human activities are the most significant driver of observed climate change since the mid-20th century. Major long-lived greenhouse carbon gases are dioxide, methane, nitrous oxide and fluorinated gases, as stated by the Working Group I (WGI) in the Fifth Assessment Report (AR5) of IPCC (the Intergovernmental Panel on Climate Change, IPCC 2014), concerning the physical science basis.

Worldwide, net emissions of greenhouse gases from human activities increased by 35 percent from 1990 to 2010 (see Figure 1.1). Emissions of carbon dioxide, which account for about three-fourths of total emissions, increased by 42 percent over this period. An increase in the atmospheric concentrations of greenhouse gases produces a positive climate forcing, or warming effect. From 1990 to 2015, the total warming effect from greenhouse gases added by humans to the Earth's atmosphere increased by 37 percent. The warming effect associated with carbon dioxide alone increased by 30 percent. As greenhouse gas emissions from human activities increase, they build up in the atmosphere and warm the climate, leading to many other changes around the world—in the atmosphere, on land, and in the oceans, as is summarized by the EPA, Environmental Protection Agency of the United States (EPA 2021).

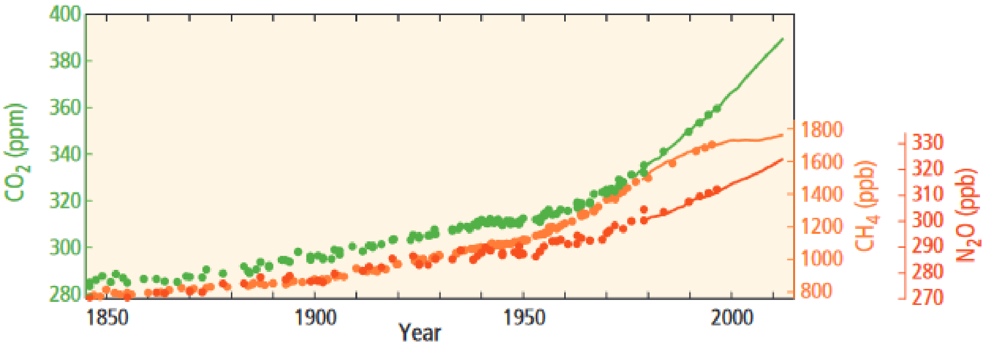


Figure 1.1. Globally averaged greenhouse gas concentrations (IPCC 2014).

The evidence for human influence on the climate system has grown since the IPCC Fourth Assessment Report AR4 (Solomon et al. 2007). It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcing together.

Anthropogenic GHG emissions are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy. The Representative Concentration Pathways (RCPs), which are used for making projections based on these factors, describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use (see Figure 1.2). The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ("baseline scenarios") lead to pathways ranging between RCP6.0 and RCP8.5. RCP2.6 is representative of a scenario that aims to keep global warming likely below 2°C above pre-industrial temperatures.

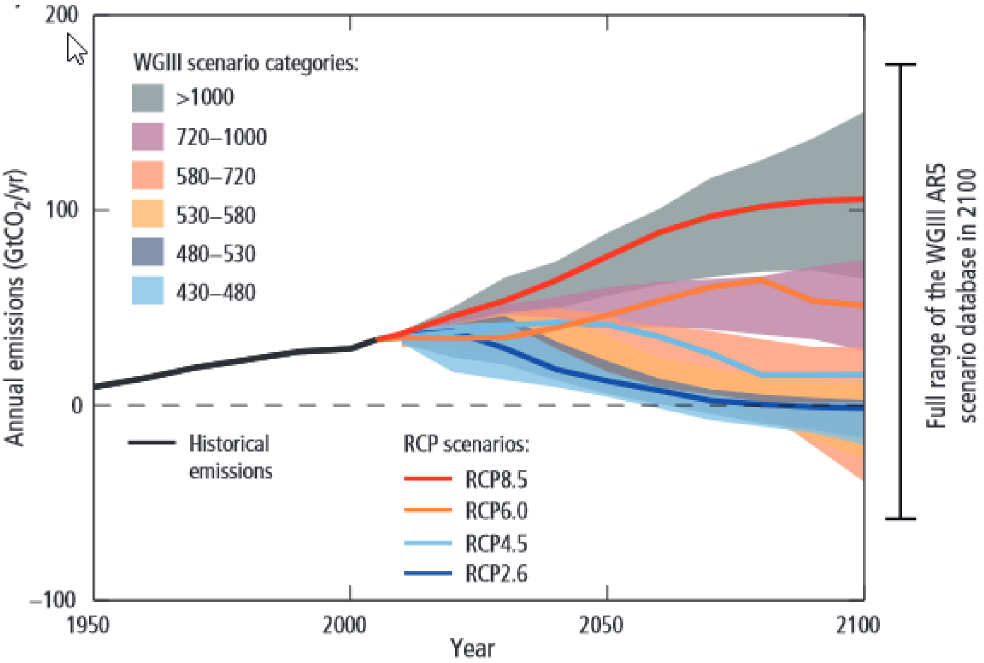


Figure 1.2. Annual anthropogenic CO_2 emissions (IPCC 2014).

The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.5.

Climate change will amplify existing risks and create new risks for natural and human systems. Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development.

Figure 1.3 (from IPCC 2014) shows the total anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2- equivalent per year, $GtCO_2$-eq/year) from economic sectors in 2010. The circle shows the shares of direct GHG emissions (in % of total anthropogenic GHG emissions) from five economic sectors in 2010. The pull-out shows how shares of indirect CO_2 emissions (in % of total anthropogenic GHG emissions) from electricity and heat production are attributed to sectors of final energy use. “Other energy” and “Electricity and heat production” refer to all GHG emission sources in the energy sector as defined in the contribution of the Working Group III (WGIII) to the Fifth Assessment Report (AR5) of IPCC in Annex II.9 (Krey et al. 2014). The emission data on agriculture, forestry and other land use (AFOLU) includes land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from the sub-sectors of forestry and other land use (FOLU) of the WGIII report. Emissions are converted into CO_2-equivalents based on 100-year Global Warming Potential (GWP100y).

The environmental impacts due to human activity, including the greenhouse gases that are leading to global warming, together with the decrease in the potential use of fossil fuels, have led to the emergence of numerous energy and environmental content directives. 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).

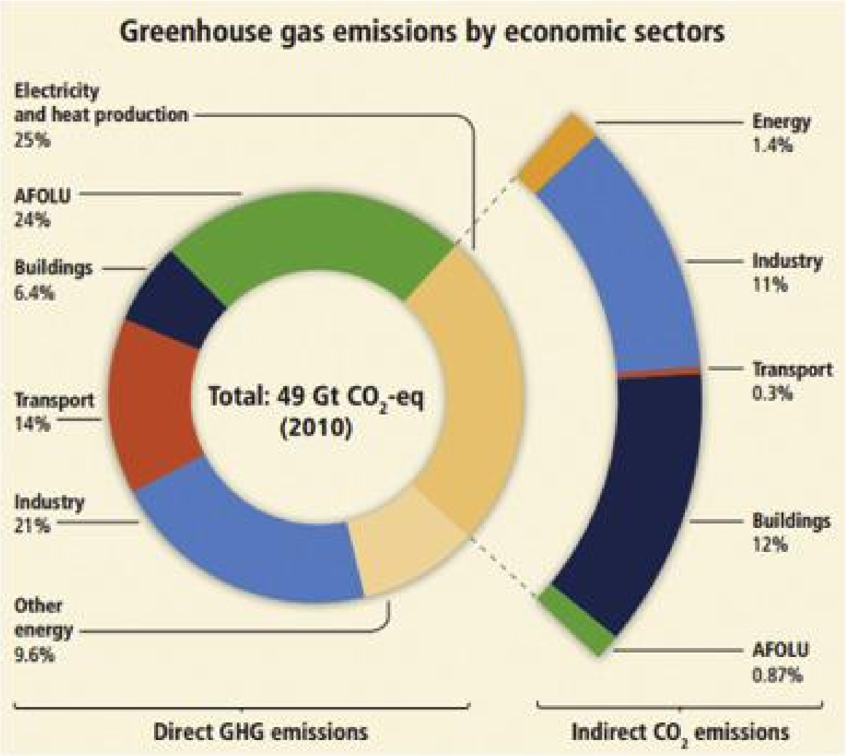


Figure 1.3. Total anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2 equivalent per year, $GtCO_2$-eq/year) from economic sectors in 2010 (IPCC 2014).

1.1.2 European Directives

The need to reduce the energy consumption of buildings led in Europe to directives to get nearly zero-energy buildings in 2020. In 2002, the European Directive 2002/91/EC on the energy performance of buildings was published, which was later joined by Directive 2010/31/EU and Directive 2012/27/EU. Directive 2002/91/EC focused on the methodology for calculating the energy efficiency of buildings and on the definition of the minimum requirements to be met by new buildings and by those existing buildings that were subject to a deep renovation. Directive 2010/31/EU introduced the concept of nearly zero-energy buildings and established the end of 2020 as the deadline to implement such buildings in new constructions. Afterwards, additional directives continued this process. Directive 2012/27/EU establishes a set of binding measures to help the EU reach its 20% energy efficiency target by

2020. A number of important measures have been adopted throughout the EU to improve energy efficiency in Europe: EU countries making energy efficient renovations to at least 3% per year of buildings owned and occupied by central governments; national long-term renovation strategies for the building stock in each EU country; mandatory energy efficiency certificates accompanying the sale and rental of buildings; etc. The new amending Directive 2018/2002/EU on Energy Efficiency was agreed to update the policy framework to 2030 and beyond. The key element of the amended directive is a headline energy efficiency target for 2030 of at least 32.5%. The target, to be achieved collectively across the EU, is set relative to the 2007 modelling projections for 2030. The directive allows for a possible upward revision in the target in 2023, in case of substantial cost reductions due to economic or technological developments. Directive 2018/844/EU, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy and efficiency, is written to take into account the facts that: the European Union is committed to developing a sustainable, competitive, secure and decarbonised energy system by 2050; the Energy and Climate Policy Framework for 2030 establishes ambitious Union commitments to reduce greenhouse gas emissions further by at least 40% by 2030 as compared with 1990, to increase the proportion of renewable energy consumed; and to meet that goal, Member States and investors need measures that aim to reach the long-term greenhouse gas emission goal and that decarbonise the building stock, which is responsible for approximately 36% of all CO_2 emissions in the Union, by 2050.

Under the Regulation 2018/1999/EU of the European Parliament on the Governance of the Energy Union and Climate Action for 2021-2030, Member States are required to draw up integrated 10-year national energy and climate plans (NECPs) outlining how they intend to meet the energy efficiency and other targets for 2030. Updated measures relating to national long-term renovation strategies are now covered under the amended Energy Performance of Buildings. Regulation 2018/1999/EU 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 National Integrated 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% in 2018 and is foreseen to represent 44% of gross electricity generation in 2020 and 78% in 2030.

1.1.3 Transposition of Directives Concerning Buildings in Spain

In Spain, these directives have been transposed through the Spanish Technical Building Code (STBC) (Spanish Ministry of Housing 2006) and its subsequent modifications: Spanish Ministry of Housing 2009; Spanish Ministry of Development 2013; and Spanish Ministry of Infrastructure 2017. Recently, on December 20, 2019, Royal Decree 732/2019 was approved, which modifies the Spanish Technical Building Code by introducing a new series of changes. The main ones are included in the new Basic Energy Saving Document (DB-HE) and intends the reduction of greenhouse gas emissions by promoting the quality of the envelope through passive measures that improve the performance of the building and increase the weight of energy from renewable sources in the building. The first section of the DB HE, the HE0, collects the most global aspects of the document and determines the total and non-renewable primary energy consumption, as well as the definition of a building with nearly zero-energy consumption. Buildings are designed to consume little energy and preferably to be of renewable origin, to minimize the emission of greenhouse gases and the ecological footprint. Energy consumption from fossil sources and energy dependence are minimized. It is aimed at new buildings and interventions in existing buildings.

1.1.4 Environmental, Social and Economic Regulations

Human activity produces consumption of materials, water, and pollutants harmful to our environment and finally to our health. Therefore, sustainability has become synonymous with reduction of invasion and degradation of the environment. The concern about environmental aspects has led to a greater use of the life cycle assessment (LCA) following the criteria of ISO 14040:2006 and ISO 14044:2006 standards. The aspects that must be considered have been increased, as well as the impacts reflected in the environmental product declaration (UNE-EN 15804:2012+A1:2014) and in the assessment of the environmental performance of buildings (UNE-EN 15978:2012) (typically: embodied energy, global warming potential, ozone layer depletion potential, acidification potential and eutrophication potential), so other economic, social and cultural ones have been added. In this way, to the requirements that obey the technical and functional needs defined by the client, other more general ones are added, which are set out in specific regulations and that pursue environmental, social and economic interests, expanding the perspective of the customers. These regulations seek to generate tools that facilitate the assessment and communication of sustainability. Figure 1.4 shows a scheme for the evaluation of the sustainability of buildings from UNE-EN 15643-1:2012, the standard that provides the general framework.

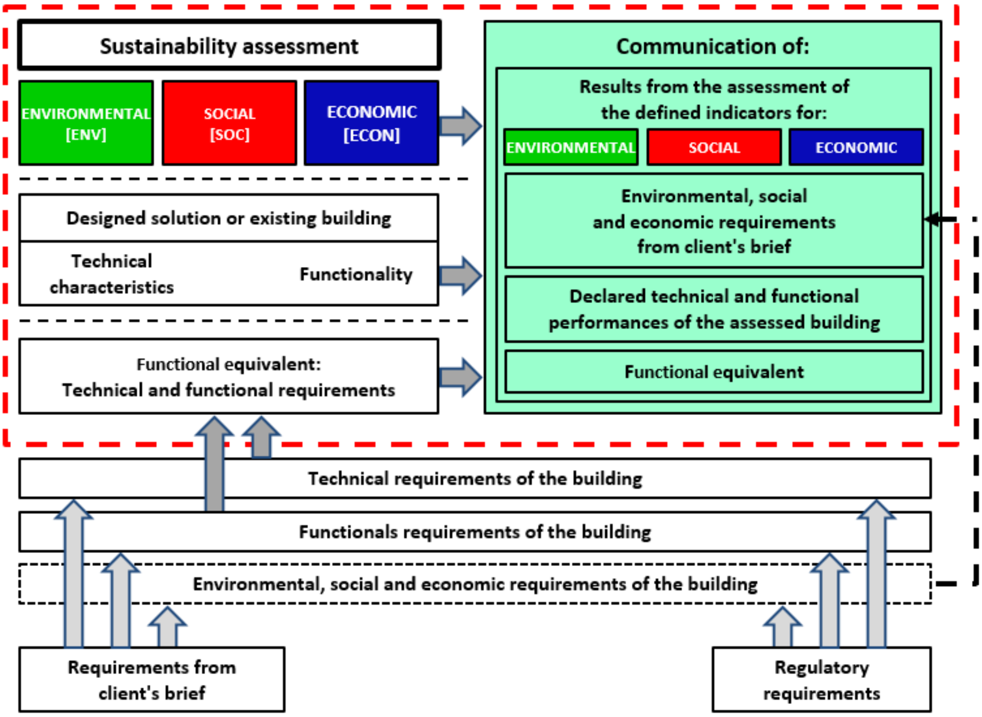
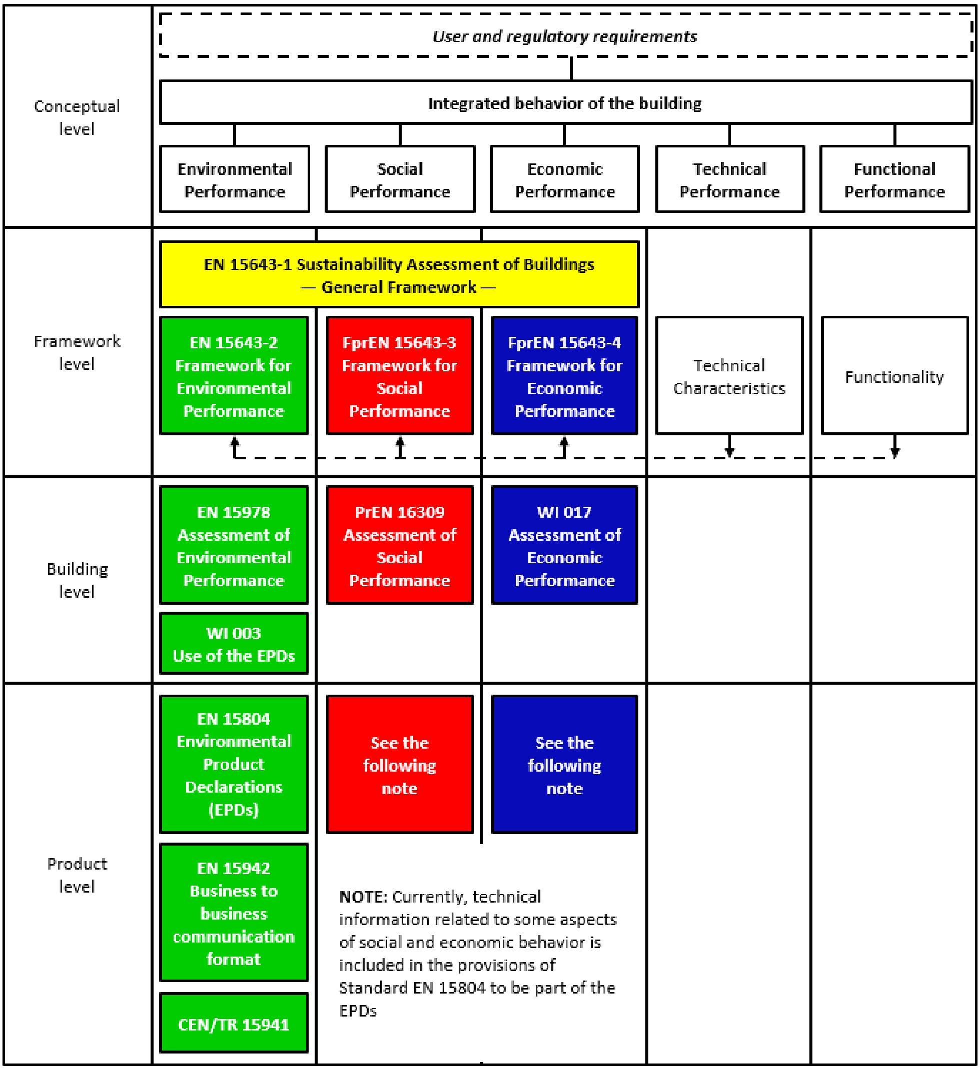


Figure 1.4. Scheme for the evaluation of the sustainability of buildings from UNE-EN 15643-1:2012 (Own elaboration).

Regulations are supplemented by works from others entities, as the European Committee for Standardization (CEN), whose monitoring and development is being carried out by the Technical Committee on "Sustainability of construction works", CEN/TC 350 (European Committee for Standardization 2013). Figure 1.5 gives a scheme proposed by this Committee for the assessment of sustainability of buildings.



NOTE: Currently, technical information related to some aspects of social and economic behavior is included in the provisions of Standard EN 15804 to be part of the EPDs

Figure 1.5. Scheme of the regulations for the assessment of sustainability of buildings, with proposed nomenclature, from CEN/TC 350 Seminar in European Committee for Standardization 2013 (Own elaboration).

As it was previously mentioned, in addition to the environmental aspect, the economic, social and cultural aspects are being added, which obey the economic possibilities and functionalities defined by the customers and their economic and social surrounding. It is also required to adapt the costumers needs to create inclusive socio-economic environments that favour the work of local suppliers and builders. The social aspects are stablished in UNE-EN 16309+A1:2015 and the economic ones in UNE-EN 16627:2016.

For the environmental assessment of buildings, methodologies based on the life cycle assessment (LCA) focus in detail on stages (see Figure 1.6) that consider the production of the elements or components for the building (extraction of raw materials, transportation to the factory and manufacturing), the construction of the building itself (transport from the factory and on-site construction and installation), the use of the building (including maintenance, renovation and energy consumption, also called operational energy) and, finally, the end of the building live (deconstruction and reuse of parts). The environmental impacts have indicators that are quantified by calculations based on the composition, weight and processes applied (UNE-EN 15804:2012+A1:2014 and UNE-EN 15978:2012). The evaluation of environmental, social and economic impacts is carried out in each of the stages.

The first stage is the product stage, which comprises: extraction of raw materials (A1), transport to the factory (A2) and manufacturing (A3). Subsequently, the components produced are transported (A4) and assembled in factory (modules) or in the place where the building will be erected, forming larger parts (A5). Once the building has been built, the use stage begins, which includes: initial use (B1), maintenance (B2), repair (B3), replacement (B4), rehabilitation (B5), use of operational energy (B6) and use of operational water (B7). Finally, when life is over, the building is demolished (C1) and the materials are transported to a sorting plant where they are processed and recovered (C3) or, finally, taken to landfill (C4).

In UNE-EN 15978:2012 one more stage is still considered, beyond the life cycle of the building: stage D (not represented in Figure 1.6), which takes into account the benefits and environmental burdens of going beyond the limits of the building, considering the reuse, recovery of components and potential recycles.

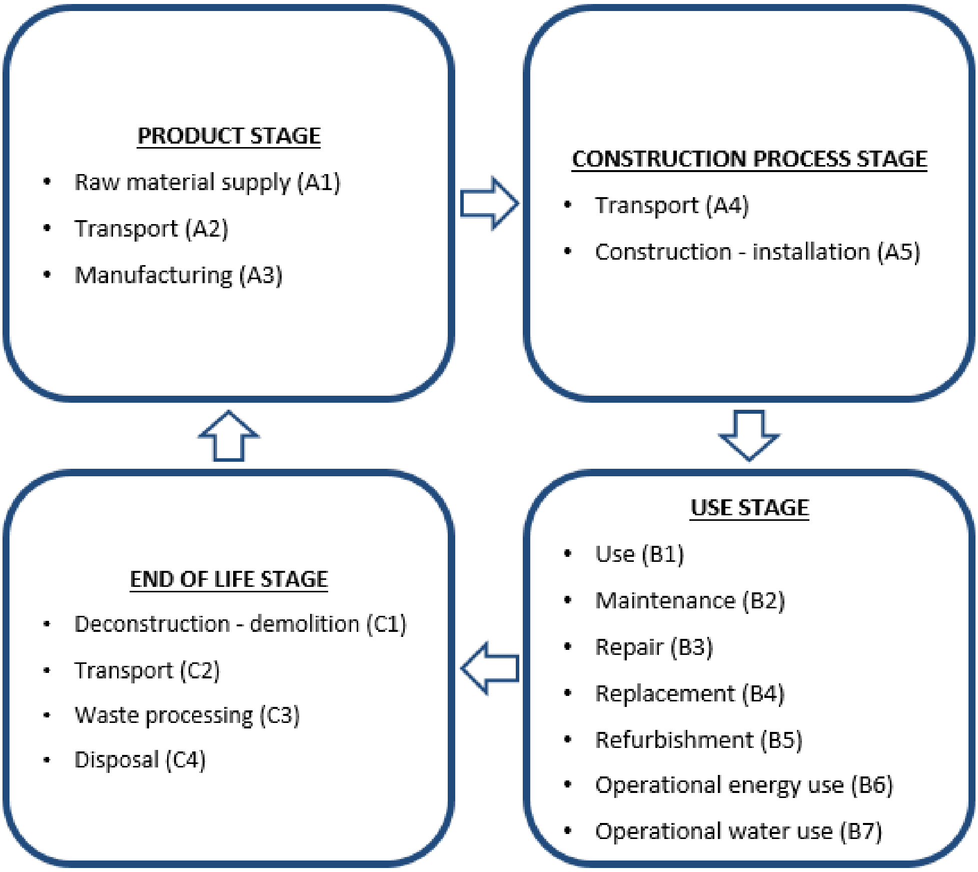


Figure 1.6. Stages for the assessment of environmental performance of buildings in UNE-EN 15978:2012 (Own elaboration).

1.1.5 Other Sustainability Aspects

The regulations in the scheme in Figure 1.5 mainly focus on the physical part of the building itself and its impacts, and although they consider some social aspects of accessibility and access to transportation from the building, these aspects could be expanded. Figure 1.7 shows some of these other aspects, which have been added to those indicated in UNE-EN 16309+A1:2015 for the sustainability assessment. These components have been grouped in families (circles), around a central circle that represents the social aspect. It is proposed: 1st) a greater consideration of the surroundings of the building and a greater possibility of changing the design to meet future needs, since a suitable home for a family with young children may not be suitable when the couple grows older or has special needs, so the role of adaptive designs should be increased; 2nd) greater emphasis on the immediate surroundings of the building, so that not only easy accessibility to transport from the building is contemplated, but also that the building has nearby infrastructures to cover the needs that favour physical, educational, health and social relationships; 3rd) inclusive socio-economic environments, created to favour the work of local suppliers and builders; 4th) and 5th) comfort and health, which are components that are already contemplated, but whose evaluation is still considered poorly defined.

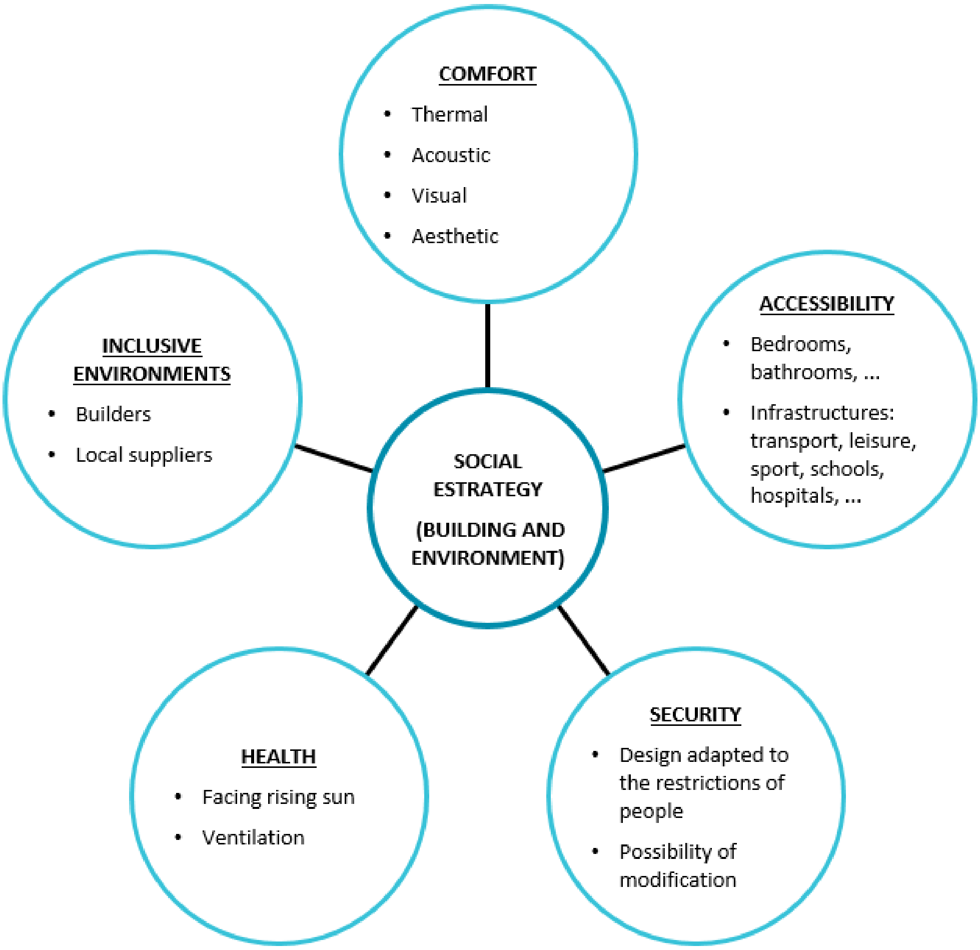


Figure 1.7. Social aspects with reference to the building and its surroundings (Own elaboration).

In Figure 1.8, the components in the regulations are represented inside hexagonal forms: cost of the land and cost to obtain the connection services; maintenance of the building and its interior and exterior components; reuse and adaptation of the building and its parts (centred above all in repair and replacement); generation of waste and its processing; and energy and water consumption.

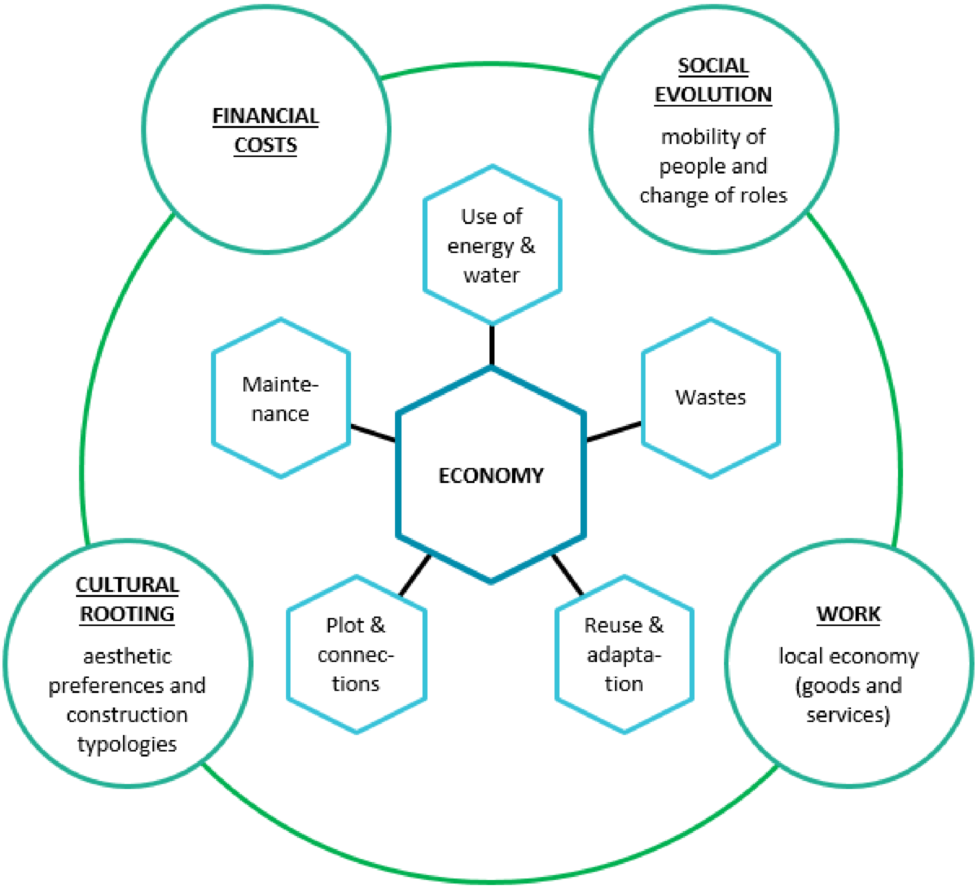


Figure 1.8. Economic aspects of the building: relationship with the social and labour panorama and the financial costs (Own elaboration).

These aspects are included in stages B of the life cycle of the building. In the economic framework is also important the stages related to deconstruction, transport of waste and disposal or recycling, which are associated to stages C. However, other aspects are not taken into account: cultural aspects, population (evolution of roles and configuration of family units), financial costs and labour provision. Therefore, surrounding the hexagonal cells of the interior of Figure 1.8, a circular frame has been drawn to include those aspects that determine decisions about if building users want or can afford the cost of a building: cultural aspects (local aesthetic tastes and inclination for certain constructive typologies of buildings), social evolution (mobility of people between regions, attachment to the land and change of roles of the family components) and economic aspects (related to the monetary policies—financial costs, the abundance or scarcity of workforce for the local economy etc.)

Summarizing, the three aspects or lines that characterize sustainability are typically: environment, society and economy, and that is why the term "Triple Bottom Line" (TBL) is widely used to indicate it. These three lines are those marked in Figure 1.4 and Figure 1.5 with the colours green, red and blue, respectively. However, in order to facilitate the application of more extensive sustainability concepts, software programs have been developed to label sustainability based on credit systems that define the quality of buildings: in USA, the tool Leadership in Energy and Environmental Design (LEED) (Green Building Council 2000); in UK, the Building Research Establishment Environmental Assessment Method (BREEAM) (Yates et al. 1998); in Germany the German Society for Sustainable Building (DGNB) (German Sustainable Building Council); in Japan, the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) (Japan Sustainable Building Consortium (JSBC) and Institute for Building Environment and Energy Conservation (IBEC)); in Canada, Raymond GBTool, pub iiSBE (Cole et al. 2002), etc. These certification systems progressively incorporate aspects and components, including some that are also highlighted in this work, which make sustainability a complex concept and consider four or more lines. An example is SPeAR® (Sustainable Project Appraisal Routine 2012), which was developed by Arup in 2000, as a way of incorporating and assessing sustainability factors in development plans for their clients. It is a decision-making tool that allows developers and other stakeholders to investigate the impacts of a development on a wide range of subjects, such as air quality, water use, employment, culture etc. It communicates the results of the appraisal visually through a unique diagram, which uses a traffic light system to indicate performance in each area, considering natural resources, environment, society and economy. Although these efforts to establish sustainability are very positive, Gou et al. 2017 warn that they may not help to promote sustainability in practical construction and propose to evolve towards a more adequate selection of insulation and an increase in efficiency, promoting the real comparison of solutions.

1.1.6 Energy and Environmental Trends

The above mentioned energy directives and transpositions in counties have led to the improvement of the energy performance of buildings toward Zero Energy Buildings. Nevertheless, the impacts derived from the production of building materials and equipment can overcome the impacts related to the use phase. It also can be noticed that not all the energy efficiency strategies, including the regulatory ones, lead to an overall reduction of the environmental impacts. In fact, while in old buildings the ratio of impacts between the production of materials and the impact of energy consumption on the use phase is 1:10, in low-energy buildings the embodied energy can represent 45% of the lifecycle energy (Sartori et al. 2007), being the ratio of embodied energy to energy use highly influenced by climate. These facts have been remarked in several life cycle assessments studies, which, in addition, have evidenced the increasing role of impacts in stages of life cycle such as maintenance and end-of-life. These conclusions can be observed both for new low-energy buildings and in the case of the refurbishment of old buildings.

The software programs to label sustainability give a major importance to the use of Life Cycle Assessment (LCA) as the main tool to obtain the environmental performance of buildings. Besides, LCA plays a strategic role in identifying critical aspects and potential impacts of the current situation and possibilities the identification of actions, policies and strategies that can help to reduce environmental impacts, verifying their environmental effectiveness and considering the entire life cycle and several environmental impact categories. Moreover, the majority of studies for new and refurbished buildings have centred in impacts as primary energy, use energy and CO_2 emissions, which is very restrictive, since buildings are responsible also of other resource consumption (such as land, water, minerals and metals) and of other emissions (causing, for example, acidification, eutrophication, and ecotoxicity).

The concerns about climate change have led in Europe to national energy and climate plans. In the case of Spain, the result is the already mentioned Spanish National Integrated Energy and Climate Plan (NIECP), which will affect the impacts due to energy consumption. The repercussion of the plan is of particular importance, because of the changes in gross electricity generation (electricity mix) that it implies. The energy consumption in residential buildings in Spain is distributed according to the energy sources as follows: electricity, 43.5%; natural gas, 18.5%; oil, 18.6%; renewable energies, 19.0%; and coal, 0,5% (IDAE 2018a). Concerning the non-residential sector (offices, hotels, restaurants, education, services and others), the distribution according to the energy sources is: electricity, 59.4%; natural gas, 26.3%; oil, 12.5%; and renewable energies, 1.8% (IDAE 2018b). Therefore, the distribution on gross electricity generation using different energy sources planned by Spain for the horizons 2020 and 2030 will introduce important changes in the potential environmental impacts according the electricity mix planned.

1.2 Objectives of the Thesis

The *main objective* of this doctoral thesis is to analyse the behaviour of low energy consumption buildings in Asturias using tools that measure sustainability. This study is of interest, since Asturias presents highly varied climatic characteristics due to its mountainous orography and its longitudinal geographic development, along the Atlantic coast. This study will improve the knowledge on how the climate and energy policies affect the most suitable isolation levels in different climatic subzones.

Sustainability analysis techniques (such as LCA) still have a low penetration rate in building design, in part due to the scarcity of examples. The findings of this thesis will contribute to the expansion of the use of these tools in the building sector, particularly in the Asturian context.

To accomplish the main objective of this thesis, the following specific objectives are set:

- The variation of the environmental impacts due to the application of the planned decarbonisation policies in Spain for the gross production of electricity in horizons 2020 and 2030 needs also to be investigated.

- Two cases of very different buildings are proposed to be analysed: in the residential sector, a typology of a newly built single-family housing; in the non-residential sector, an office building declared of cultural and public interest to be rehabilitated. In both cases, the repercussions on the environmental impacts of these buildings due to the introduction of policies of decarbonisation need to be studied.

- The prefabricated single-family houses have become very important in Spain in recent years due to the demystification of the presumed loss of quality due to the industrialization of housing. To define the single-family home design, social and economic aspects are added to those concerning energy and sustainability. The prefabricated construction with concrete panels lightened with expanded clay in single-family homes is one of the systems that is being widely developed in the north of Spain. Therefore, the single-family house to be analysed has been designed considering this constructive system. The variation of the building performance according the insulation level and the use of different energy supply systems will be investigated for several locations in Asturias.

- For the single-family house, the variation of the energy demand according the climate change affectation will be analysed, together with the decarbonisation policies, for several climates in different locations in Spain, including one in Asturias (Oviedo), and for different locations in Asturias.

- For the building declared of public and cultural interest, different materials to be used for the rehabilitation of the envelope will be considered, to find their repercussion on the environmental sustainability of the building. In addition, it is also necessary to propose the implementation of active renewable systems in the building itself and investigate the consequent environmental variation of impacts.

- Economic indicators will be applied to the study of the very different scenarios considered for the building declared of public and cultural interest. In addition, it is proposed to analyse the consequent repercussion of changes in environmental impacts adopting an extended application of economic indicators.

1.3 Structure of the Thesis

In the first chapter, it has been defined the context of climate change and energy transition in which this doctoral thesis is developed. Then, the role and the objectives of European Directives in energy and environment is exposed, as well as the development of environmental social and economic regulations. The life cycle assessment and several software programs to analyse the sustainability are also introduced. Some general values of ratios between stages of LCA and observed trends are also enunciated. It is then followed by a description of the overall and specific objectives of the thesis. The remaining chapters of the thesis are organized as follows:

- **Chapter 2**: Effect of Decarbonisation Policies and Climate Change on Environmental Impacts Due to Heating and Cooling in a Single-Family House. This chapter discusses the environmental impacts of the decarbonisation plan proposed by the Spanish Government, comparing the current situation with those foreseen for 2020 and 2030. Furthermore, climate change will vary the thermal demands of buildings. The chapter thus investigates the heating and cooling demands of a type of single-family house located in eight Spanish cities with very different climates and altitude. The combined effects of the decarbonisation plan and climate change are analysed based on the environmental impacts caused by the electricity required to meet thermal demands.

- **Chapter 3**: Influence of Atlantic Microclimates in Northern Spain on the Environmental Performance of Lightweight Concrete Single-Family Houses. In this chapter, single-family houses with different shape factors and window-to-wall ratios are analysed from both a thermal and environmental perspective using Passive House Planning Package (PHPP) software to calculate the energy demand. The study has been carried out for different Atlantic microclimates (coastal, inland and mountain) in northern Spain. Operational energy for heating has decreased greatly via the use of high degree of insulation and hence the next task is to decrease the total energy consumed taking into account the embodied energy. Impacts on Primary Energy and Global Warming Potential are calculated using a cradle-to-grave approach. The energy use for heating and domestic hot water is analysed for different thicknesses of insulation under three energy supply scenarios: electricity only (for 2018 and with the Spanish decarbonisation plan for 2030); heat pump plus electricity; and natural gas boiler.

- **Chapter 4**: Environmental Life-Cycle Assessment of a Nineteenth-Century Building Retrofitting in Electricity Decarbonisation Scenarios. The aim of this chapter is to estimate the environmental impacts associated with modernization measures that improve the energy efficiency of an office building listed as being of cultural interest. A life cycle assessment (LCA) is carried out considering the retrofitting of the envelope by introducing interior lining using different insulating materials and changing the windows while preserving their appearance. The study considers different energy supply scenarios: employing only electricity from the electricity mix (scenario in 2018, and decarbonisation scenarios proposed by the Spanish Government for 2020 and 2030) and the installation of renewable energy systems in the building itself (heat pump and photovoltaic panels).

- **Chapter 5**: Use of Economic Indicators for Environmental Assessment of a Refurbished Building. This chapter is dedicated to consider different improvement scenarios with respect to a reference scenario, with the final objective of selecting the best possible intervention. The study includes several possible energy mix scenarios (present and future) for each possible intervention, with several variables in each case (the economic cost and various environmental impacts), which are calculated in turn for each stage of the life cycle. The resulting amount of information is so great that it makes it very difficult to compare the potential interventions on the building. To solve this problem, in this chapter it is proposed the use of some of the indicators that are common in the analysis of economic investments for the assessment not only of the economic aspects of potential interventions for the improvement of the energy performance of a building, but also of the environmental effects of such interventions.

- **Chapter 6**: This chapter gives the overall conclusions obtained in this doctoral thesis. Additionally, it is given a remark of the remaining research gaps that could be addressed in future studies and new research directions.

After the chapters and the bibliographic references, there is a series of appendices, each of which corresponds to a specific chapter and contains supplementary material for that chapter. This material constitutes, almost entirely, information prepared by the author that has been extracted from the body of each chapter to make it more legible and that can be considered reference material (for example, tables and figures showing some results, starting information, etc.)

Chapter 2. Effect of Decarbonisation Policies and Climate Change on Environmental Impacts Due to Heating and Cooling in a Single-Family House

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Major parts of this Chapter have been published in the following article:

González-Prieto, D.; Fernández-Nava, Y.; Marañón, E.; Prieto, M.M. 2020. Effect of Decarbonisation Policies and Climate Change on Environmental Impacts due to Heating and Cooling in a Single-Family House. *Sustainability*. 12, 3529, https://doi.org/10.3390/su12093529.

2.1 Introduction

Climate change associated with global warming and decreasing fossil fuel reserves has led to the need to increase the use of renewable sources and to stricter environmental regulations.

The energy policy framework in Spain is highly conditioned by the European Union (EU), which is affected by the global context. The Framework Convention on Climate Change, internationally known as the Paris Agreement, held in 2015 (United Nations 2015), resulted in the most ambitious response to date to the effects of climate change. The EU ratified the Agreement in 2016, thus establishing the starting point for energy policies in the scenario of climate change in the near horizon.

The three key legislative pieces of the "Clean energy for all Europeans" package (European Union 2018) came into force on 24 December 2018 with the aim of reducing greenhouse gas emissions, increasing the proportion of renewable energy in the system and improving energy efficiency in the EU by 2030: i) Directive 2018/2002/EU on energy efficiency, mainly related with the increase in the efficiency of electricity generation and use, sets the objective of improving energy efficiency by 32.5% by 2030; ii) Directive 2018/2001/EU, for the promotion and use of renewable energy, sets a mandatory objective for the EU to increase the renewable energy contribution to at least 32% of the total final energy consumption by 2030; iii) and Regulation 2018/1999/EU, on the Governance of the Energy and Action Union for Climate, defines the design of the electricity market.

To this should be added the Communication COM/2018/773 by the European Commission (European Communication 2018), which constitutes its roadmap towards a systematic decarbonisation of the economy by 2050. Regarding Spain, the policy of decarbonisation was proposed in the National Integrated Energy and Climate Plan (Spanish Ministry of Ecological Transition 2019), which proposes scenarios for the evolution of electricity production and energy sources from now until 2030.

Several studies have addressed future scenarios of electricity production, both for EU countries and for non-EU countries, analysing a number of environmental impacts: Portugal (Fortes et al. 2019); Spain (García-Gusano et al. 2017); Turkey (Atilgan et al. 2016); Germany (Ruhnau et al. 2019); Japan (Kato et al. 2019); and, employing a more local approach, at the city level, the USA (Deetjen et al. 2018).

2.1.1 Energy Demand and Sustainability for Space Conditioning in a Context of Energy Decarbonisation

Operational energy comprises the building's energy requirements during its useful life, from commissioning to demolition (not including maintenance or renovations). It includes the energy used for space heating and cooling, appliances, domestic hot water and electricity use for lighting, fans and pumps. Previous regulations focus to a great extent on reducing energy demand for the thermal conditioning of buildings (heating and cooling), and these demands are greatly affected both by the design (geometry, materials and orientation) of the building and by climate data; therefore, these aspects will form an important part of this work.

The climate is currently undergoing major changes. Variations in the climate affect the dataset underlying the tools to calculate building demand.

Although life cycle analysis (LCA) was first applied to energy use during the life cycle of buildings in 1997 (Adalberth 1997), LCA studies have not been extensively applied to the building industry until more recently (Khasreen et al. 2009; Buyle et al. 2013; Rashid et al. 2015; Vilches et al. 2017).

Due to the large amount of data required to perform an LCA, it is advisable to use a software application that makes the study much more efficient. SimaPro and Gabi software are some of the most widely used applications in studies of this kind (Goedkoop et al. 2001; Guinee et al. 2002; Lewandowska et al. 2013: Szamosi et al. 2020), although there are also specific building life cycle assessment tools (Bribian et al. 2009). As for the impact assessment methodologies used in the different LCA studies applied to buildings, these are varied and depend on the objective and scope of the study. However, the method employed must be consistent with

International Standard Organization (ISO) recommendations for impact assessment methods (ISO 14040:2006; ISO 14044:2006).

The scope of LCA studies in buildings is also variable and can be applied to the entire life cycle of the building (Zhang et al. 2019; Buyle et al. 2014), to some stages (Schlegl et al. 2019), or focus solely on the manufacturing of construction materials (Szamosi et al. 2020). The energy and annual operational CO_2 emissions of early decisions regarding the design of buildings in a scenario of climate change is considered for a residential building in Turkey (Gercek et al. 2019). Other studies refer to the energy demand variation until 2050 in renovated buildings in a district in Portugal (Andric et al. 2016) and to the impact of climate change on related CO_2 emissions (Andric et al. 2015). The calculation of the LCA in different types of residential buildings, both passive houses and traditional constructions, is studied using SimaPro and the IMPACT 2002+ method (Lewandowska et al. 2013). The impact of the rehabilitation stage has also been analysed in different contributions to the literature (Vilches et al. 2017), and the extension of life and duration, comparing new and renovated buildings, have also been addressed (Palacios-Muñoz et al. 2019).

Bearing in mind the foreseeable changes in the Spanish energy mix aimed at contributing to the energy decarbonisation of Europe, as well as present-day and future climate changes and the major impact of buildings as energy consumers, mainly due to their thermal conditioning, this study was carried out in order to know the impact that these changes will have on a typical single-family house with high thermal performance.

This work analyses: (1) the environmental impacts of the decarbonisation policy in the National Integrated Energy and Climate Plan for Spain (NIECP), focusing more specifically on electricity generation; (2) the impacts of the proposed electricity generation on the energy used for the thermal conditioning of a single-family reference house. This house is designed with a high energy performance envelope and has been placed in different locations and climates in Spain. Moreover, the conditioning demands are calculated taking into account climate evolution models with a 2020 and 2030 horizon, which is as far as the NIECP currently covers.

2.2 Materials and Methods

The impacts of current electricity production available for 2018 as well as those of future electricity production are studied. Two scenarios for electricity generation in Spain are proposed for the future (2020 and 2030) based on EU guidelines regarding decarbonisation policies. Eight different weather locations in Spain were selected, calculating the heating and cooling demands for the same building at the different locations. The weather data considered were obtained from the database of Meteonorm v7.2 2017. For 2010, these data are still in use in current demand calculation programmes, while for 2020 and 2030 the forecasted climate data were used. The climate data for the future were implemented in software tools officially approved by the Spanish authorities for calculating the thermal demand (heating and cooling) of the buildings for each location and year of calculation. Finally, the way in which the decarbonisation proposal concerning electricity generation will affect the impacts that occur in the building because of the thermal energy demand, which were calculated following the method implemented in SimaPro IMPACT 2002+ software (PRè Consultants, Amersfoort, The Netherlands) is studied. It was considered that the thermal demand will be supplied using electricity. A scheme with the sequence of the steps followed in this research is shown in Figure 2.1.

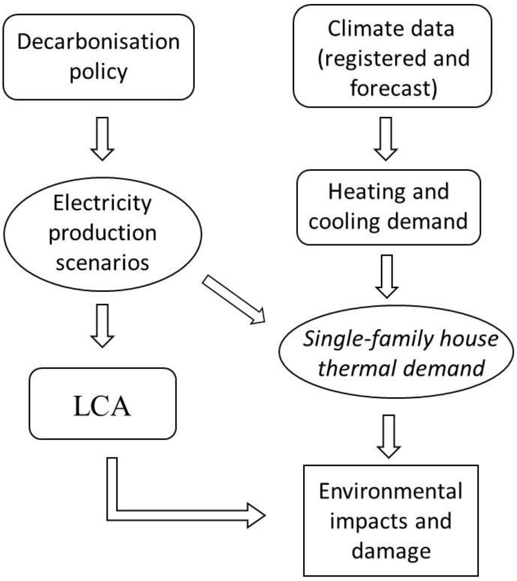

Figure 2.1. Scheme of the steps followed in this study.

2.2.1 Proposal for Future Scenarios of Electricity Production

The evolution of the Spanish electrical energy mix proposed in the NIECP (Spanish Ministry of Ecological Transition 2019) reflects the government's intentions to contribute to decarbonisation in terms of electricity production and the primary energy sources to be used. These data for the years 2020 and 2030 have been adapted to define the structure of the primary energy sources used in this study. The data for 2018 were obtained from those compiled by the Spanish Grid Operator 2019 (Red Eléctrica de España, REE) and were adapted to have the same primary energy structure as that considered for the data for 2020 and 2030. The data in REE were also compared with those collected for the same year for Spain by the International Energy Agency (IEA Monthly Electricity Statistics 2019) to ensure that the difference between sources is not significant. Using these data and the aforementioned NIECP, Table 2.1 shows the evolution of the net energy generated.

Table 2.1. Gross electricity generation (GWh) in 2018 and proposal for 2020 and 2030 according to the target scenario in Spain (Spanish Ministry of Ecological Transition 2019).

			2018	**%**	**2020**	**%**	**2030**	**%**
Renew.	Hydro	Hydropower	34,106	33	28,288	23	28,351	10
		Pumped-storage	2,009	2	4,594	4	11,960	4
	Wind	Hydro-wind	24	0	0	0	0	0
		Wind	49,570	48	60,670	50	119,520	44
	Solar	Solar photovoltaic	7,759	8	16,304	13	70,491	26
		Solar thermal	4,424	4	5,608	5	23,170	9
	Others	Others renewables (1)	0	0	0	0	301	0
		Renewable waste (2)	4,431	4	6,823	6	17,596	6
Total Renewables			102,324	100	122,287	100	271,389	100
Non-Renew.	Nuclear	Nuclear	53,198	34	58,039	37	24,952	32
	Coal	Coal	37,274	23	33,160	21	0	0
	Oil	Oil + Gas	6,683	4	10,141	7	5,071	7
	Natural gas	Combined cycle	30,044	19	29,291	19	32,725	42
		Cogeneration (3)	29,016	18	24,845	16	15,179	19
	Others	Non-renewable waste	2,435	2	0	0	0	0
Total Non-Renewables			158,650	100	155,476	100	77,927	100
Total Renewables + Non-Renewables			260,974		277,763		349,316	

(1) Geothermal and marine energies

(2) Renewable cogeneration, biomass, waste cogeneration and municipal waste

(3) Gas and oil products (no coal)

2.2.2 Single-Family House

2.2.2.1 Building Geometry

At present, single-family housing is increasing significantly in Spain, representing around 35% of homes. However, it still does not reach the average value in the EU-28, where it represents around 59% of housing (35% detached and 24% semi-detached) (Berndgen-Kaiser et al. 2016). Figure 2.2 shows the reference single-family house with the glazed openings facing South and North and the locations for the house made with lightweight concrete panels of expanded clay for the entire envelope and all the inner walls. The typology chosen for the reference building is a traditional one-storey house with three bedrooms that fulfils consumer demands, considering 1.3 children per couple (González-Prieto et al. 2018). The house is oriented North-South, the envelope has a high energy efficiency and the heating and cooling demands are very low. The one-storey house has a net floor area of 98 m^2 and is planned to be inhabited by three occupants. The house consists of a living room/kitchen, two bathrooms, three bedrooms, a corridor and a facilities room (Figure 2.2 (a)). The map of Spain in Figure 2.2 (b) shows the climate zones according to their level of irradiation (Spanish Ministry of Infrastructure 2013) and the locations of the eight Spanish cities representing the studied scenarios: Oviedo, Bilbao, Valladolid, Madrid, Zaragoza, Barcelona, Valencia and Seville. These locations are plotted on the irradiation map for Spain, obtained from the STBC, which classifies Spain in five zones according to their level of solar irradiation.

2.2.2.2 Materials and Properties

Table 2.2 shows the materials and thicknesses used for the exterior walls, floor and roof, as well as the thermal conductance values obtained. The characteristics of the envelope elements and the properties of the building materials are also detailed. The properties were taken from the Building Elements Catalogue recommended by the Spanish Technical Building Code (STBC) (Spanish Ministry of Infrastructure 2013). For the exterior walls, floor and roof, the thickness of the lightweight concrete is 140 mm; the partitions are made of the same concrete, but are 80 mm thick. The thickness of the Extruded Polystyrene (XPS) insulation is 140 mm in the walls and floor, and 200 mm in the roof. Argon-filled triple glazing is used, with a central-glass

U-value (Ug) of 0.56 W/(m²·K) and a solar factor (g) of 0.51. The glazing frames are made of aluminium with thermal bridge breaking and a frame U-value (Uf) of 0.83 W/(m²·K), absorptivity = 0.4 and infiltration class = 4. The overall U-value of the opaque building elements is 0.164 W/(m²·K) and the average U-value of all windows is 0.80 W/(m²·K).

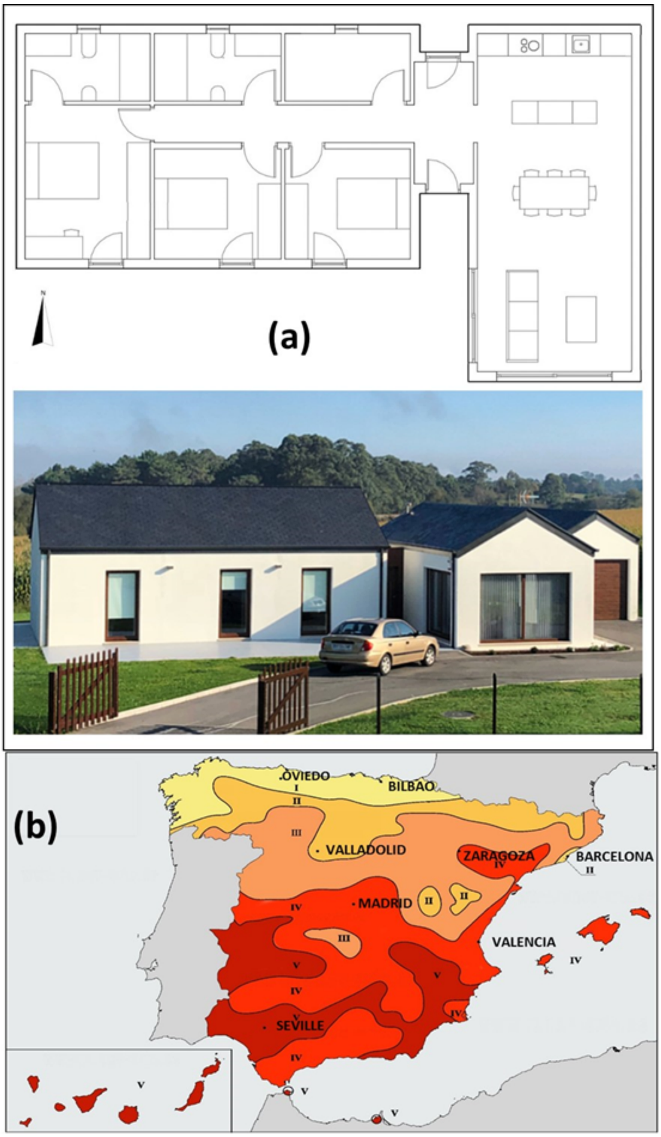

Figure 2.2. House constraints: (a) views of the single-family house with the glazed openings facing South and North and (b) climate zones in Spain according to their level of irradiation (Spanish Ministry of Infrastructure 2013) and locations of the studied cities.

Table 2.2. Characteristics of the envelope elements and properties of the building materials.

Building Element	Material	Thickness (m)	Conductivity (W/m K)
External wall (with internal lining)	Plaster	0.013	0.250
	Mineral wool	0.047	0.035
	Lightweight concrete	0.140	0.680
	XPS	0.140	0.034
	Coat of cement	0.018	0.459
	Total	0.358	
Floor slab	Wood	0.020	0.130
	Conductive cement mortar	0.040	2.000
	XPS with acoustic protection	0.040	0.034
	Lightweight concrete	0.140	0.680
	XPS	0.140	0.034
	Cement mortar	0.050	1.050
	Concrete slab	0.200	2.100
	Total	0.630	
Roof	Lightweight concrete	0.140	0.680
	XPS	0.200	0.034
	Oriented strand board (OSB)	0.024	0.120
	Air layer	0.060	0.180
	Slate	0.018	2.200
	Total	0.442	
Horizontal partition	Plaster	0.013	0.250
	Mineral wool	0.040	0.035
	Total	0.053	
Vertical partition	Gypsum plaster	0.015	0.540
	Lightweight concrete	0.080	0.680
	Expanded polystyrene	0.080	0.035
	Total	0.175	
External wall (without internal lining)	Lightweight concrete	0.140	0.680
	XPS	0.140	0.034
	Coat of cement	0.018	0.459
	Total	0.298	

2.2.2.3 Operational Conditions

The building operational conditions are given in Table 2.3: profiles of occupancy, lighting and other equipment, set point of heating and cooling, as well as the ventilation flow rates defined in the STBC adding infiltrations.

Table 2.3. Internal contributions due to persons, lighting and other equipment, set point of heating and cooling, ventilation and infiltration rates.

Schedule	1 h–7 h	8 h	9 h–15 h	16 h–18 h	19 h	20 h–23 h	24 h
Persons (W/m^2)							
- Working day (sensible)	2.15	0.54	0.54	1.08	1.08	1.08	2.15
- Working day (latent)	1.36	0.34	0.34	0.68	0.68	0.68	1.36
- Holiday (sensible)	2.15	2.15	2.15	2.15	2.15	2.15	2.15
- Holiday (latent)	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Lighting (W/m^2)	2.2	1.32	1.32	1.32	2.2	4.4	4.4
Other equipment (W/m^2)	2.2	1.32	1.32	1.32	2.2	4.4	4.4
Heating set point (°C)	17	20	20	20	20	20	17
Cooling set point (°C)	27	25	25	25	25	25	27
Ventilation + infiltration rate (/h) (1)							
- Winter	1.468	1.468	1.468	1.468	1.468	1.468	1.468
- Summer	4	4	1.468	1.468	1.468	1.468	1.468

(1) Minimum air renewals required by STBC regarding the Basic Document on Health (DB HS 3).

2.2.3 Climate Data

The climate and altitude corresponding to the cities considered in this study are: Oviedo (Oceanic, 339 m); Bilbao (Oceanic, 39 m); Valladolid (Continental, 735 m); Madrid (Continental, 582 m); Zaragoza (Continental / Mediterranean, 258 m); Barcelona (Mediterranean, 6 m); Valencia (Mediterranean, 62 m); and Seville (Mediterranean / Subtropical, 31 m).

The climate datasets used in this study were obtained using the Meteonorm software, which allowed us to forecast the global weather climate. The software was applied under Intergovernmental Panel on Climate Change (IPCC) scenario B1, to obtain the data corresponding to 2010 and the predicted data for 2020 and 2030 for each of the eight locations. The radiation model was the one proposed by default (Pérez et al. 1991). All data were estimated on an hourly basis. The hourly data were exported to a spreadsheet and processed to obtain the average monthly data. This software package is also used extensively in the scientific literature, and in all the works that use the standard Passive House (PHPP v9 2015).

To illustrate the climate diversity of Spain, Figure 2.3 shows average monthly values of dry temperature and global horizontal irradiation, obtained for 2020 at the locations studied.

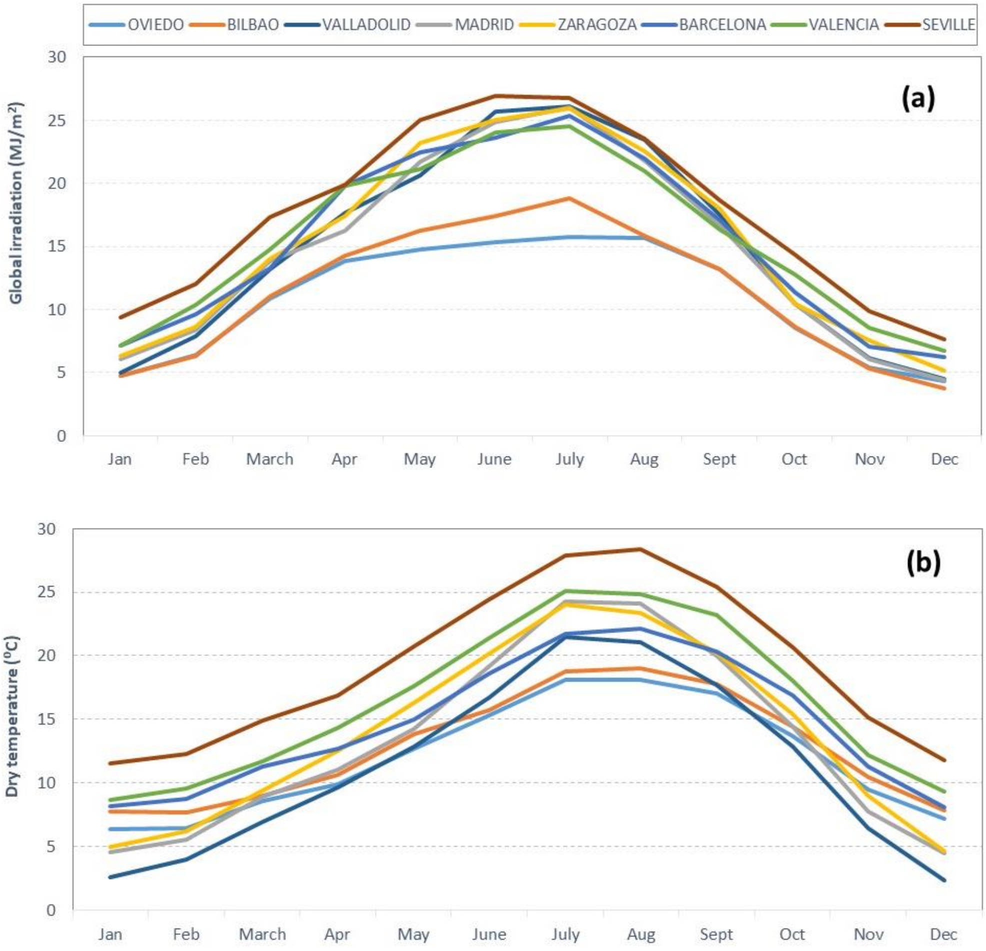

Figure 2.3. Average monthly values for dry temperature and global horizontal irradiation for 2020.

2.2.4 Calculation of the Thermal Demand

The heating and cooling demand of houses at all the locations for the years under study was calculated using a software programme officially approved in Spain (CYPECAD MEP 2019) that applies the STBC with a dynamic base time procedure described in ISO 52016-1:2017. The calculation performs a dynamic simulation on a time basis following an equivalent resistance-capacitance model. The software CYPETHERM HE PLUS 2019, which uses the calculation engine from Energy Plus (through hourly-based weather data files, city-year.epw, obtained from Meteonorm) and allows the inputting of customised climatic datasets, was also used. Using this software, it was possible to implement data for 2010, 2020 and 2030 from the Meteonorm software.

The heating and cooling demands are considered as fully electric. However, if we consider the use of a heat pump (HP) and, assuming that the average efficiency in Spain for HP in winter is approximately 2.75 and in summer 2.25, this will lead to a reduction in electricity consumption of 56% in summer and 64% in winter.

2.2.5 Life Cycle Analysis

The LCA methodology was based on ISO 14040:2006 and ISO 14044:2006 standards. The objective of the LCA was to analyse the environmental impacts of the electricity production scenarios proposed in the NIECP for the following time horizons: 2018, 2020 and 2030. The results of the study were used to calculate and compare the environmental impacts associated with the use of electrical energy for the thermal conditioning of the reference single-family house, based on its location in areas with different climates, for the same time horizons. The functional unit used was the total kWh of consumed electric energy in a year in Spain. For the software and data quality, SimaPro version 8.3.0 was used to carry out the LCA, along with its associated database (Professional). Regarding the inventory analysis, the Ecoinvent v3.3 (2016) database was used to obtain the environmental loads associated with energy production and with high, medium and low voltage energy consumption in Spain. All stages, from raw material extraction to dismantling, have been considered.

The energy mix was updated with the contribution of each of the types of energy production, according to the scenarios proposed in the NIECP for the 2018, 2020 and 2030 time horizons (Table 2.1). The distances over which the electricity was distributed were also updated, taking into account the subsequent losses in the network.

For the LCA, impact categories were selected in order to evaluate the environmental impacts (midpoint categories), as well as the damage caused (endpoint categories). The chosen assessment method was IMPACT 2002+, version 2.14 (Jolliet et al. 2003), which is a combination of four methods: IMPACT 2002 (Pennington et al. 2005), Ecoindicator 99, CML (Guinee et al. 2002) and IPCC. The approach defines midpoint impact categories that can be combined into four endpoint damage categories: Human Health, Ecosystem Quality, Resources and Climate Change.

The Human Health damage category includes impact categories that contribute to human health damages: Carcinogenic and Non-Carcinogenic effects, Respiratory effects (Inorganics and Organics), Ionising Radiation and Ozone Layer Depletion. It is expressed in DALYs (Disability-Adjusted Life Years).

The Ecosystem Quality damage category takes into account the Aquatic Ecotoxicity, Terrestrial Ecotoxicity, Terrestrial Acidification/Nutrification and Land Occupation. It is expressed as PDF·m^2·year (Potentially Disappeared Fraction over a certain area and during a certain time).

The Climate Change damage category only includes the mid-point scores for Global Warming and is expressed as kg CO_2 equivalent.

The Resource Depletion category includes the midpoint impact categories for Non-Renewable Energy and Mineral Extraction and measures the amount of energy extracted or needed to extract the resources. It is expressed as MJ.

Figure 2.4 lists the categories included in the IMPACT 2002+ method, as well as the factors used to transform the midpoint impact categories into the endpoint damage categories and units.

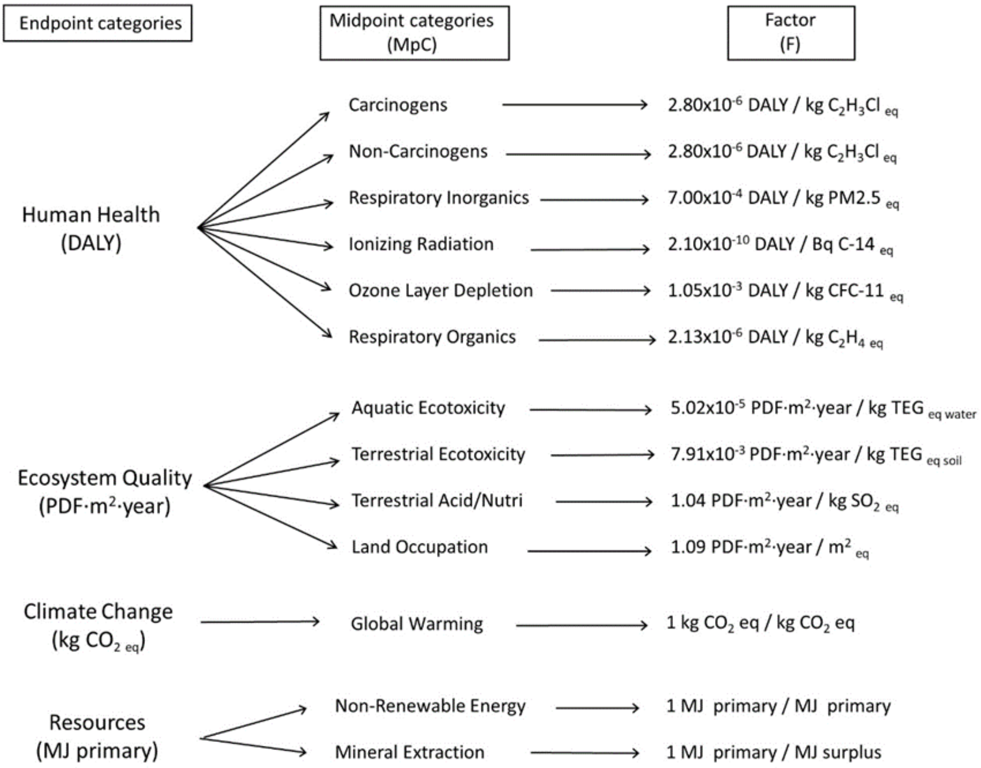

Figure 2.4. Overall schema of the IMPACT 2002+ framework, linking the impact categories to damage categories.

To analyse the respective contribution of each damage or impact to the overall considered category, a normalisation of the obtained data was performed by dividing the corresponding values by their respective normalisation factor.

The IMPACT 2002+ assessment method uses the total impact of all the substances in each specific category per person per year for Western Europe as the normalisation factor.

2.3 Results and Discussion

2.3.1 Effect of Decarbonisation Policies on the Impacts Associated with Electricity Production

In 2018, according to the data of the International Energy Agency (IEA) (IEA Monthly Electricity Statistics 2019), non-renewable energy in the Organisation for Economic Co-operation and Development (OECD) for the European Union electricity production represents 63%, while renewable energy represents 37%. In Spain, these figures have a similar percentage—60% and 40%, respectively.

In general, the most important renewable sources are wind and hydroelectric power. Currently, the contribution of solar energy is not very high, but it is expected to increase substantially in the near future (International Renewable Energy Agency 2018).

For the present study, electricity generation figures were obtained using 2018 data from REE and the future values proposed by the Spanish government (NIECP), previously shown in Table 2.1. The values are: 260,974 GWh (2018), 277,763 GWh (2020) and 349,316 GWh (2030). The figure for this last year represents an increase of 34% with respect to the 2018 data. The final electricity demand values, considering transmission losses and the electricity grid in Spain, are: 243,577 GWh (2018), 259,701 GWh (2020) and 331,338 GWh (2030).

As for the evolution of the different types of non-renewable energies, an appreciable decrease is expected in nuclear power and a moderate decrease in energy from mineral oils. Furthermore, a substantial decrease in energy from coal is proposed, reaching zero in 2030, while, in parallel, a very significant increase in wind and solar energy is proposed. The percentage of generation using non-renewable sources decreases from 60.8% in 2018 to 22.5% in 2030, whereas the contribution of renewable energies increases from 39.2% in 2018 to 77.5% in 2030.

With regard to the distribution of renewable primary energy, likewise comparing 2018 and 2030, it is observed that: i) the percentage of wind energy decreases slightly (from 48% to 44%), although the amount of energy produced increases until reaching a figure more than double that of 2018; ii) hydroelectricity hardly varies in amount, although its percentage decreases from 35% to 14%; and iii) the amount of solar energy increases more than sevenfold, and the percentage increases from 12% to 35%.

As to non-renewable sources: i) the percentage of nuclear power generation decreases moderately (from 34% to 32%), although the amount of this type of energy decreases more than a half compared to 2018; ii) the contribution of natural gas increases significantly (from 37% to 61%), although the amount of this type of energy is expected to decrease in 2030; iii) the contribution of mineral oils in electricity generation is expected to increase slightly (from 4% to 7%), although the amount of this type of energy will decrease in 2030.

Possible scenarios taking into account the European Commission Directives on emissions of atmospheric pollutants were proposed and studied in García-Gusano et al. 2017 and in Lechón et al. 2018, using the TIMES-Spain power model. TIMES-Spain is a techno-economic energy optimisation software that implements the TIMES family of models developed by the International Energy Agency (IEA, Paris, France) in the Energy Technology Systems Analysis Programme (ETSAP) (http./iea-etsap.org/).

Although both studies report similar trends, they show some differences with respect to the NIECP plan presented by Spain. There is a growth in the gross electricity generation, which is justified in Lechón et al. 2018 by considering the trends towards an increase in population and the gross domestic product of Spain. The reference scenario discussed is known as Business as Usual (BaU). Among others, the BaU scenario includes subsidies for investments in renewable technologies and commitments in force related to Directive 2009/28/EC on the promotion of the use of energy from renewable sources, Directive 2009/29/EC to improve and extend the greenhouse gas emissions allowance trading scheme of the Community and Directive 2001/81/EC on national emission ceilings for certain atmospheric pollutants.

Table 2.4 shows the estimations for the mix of gross electricity generation for the NIECP scenario, used in this study, and for the BaU scenario.

Table 2.4. Comparison scenarios: mix of gross electricity generation (%).

Energy sources	**2020**		**2030**	
	NIECP	**BaU** (1)	**NIECP**	**BaU** (1)
Hydro	11.8	13.4	11.5	11.8
Wind	21.8	16.0	34.2	32.4
Solar PV	5.9	2.6	20.2	2.1
Solar Thermal	2.0	1.5	6.6	8.8
Other Renewables	2.5	2.1	5.0	3.6
Nuclear	20.9	24.9	7.1	0.0
Coal	11.9	0.0	0.0	0.0
Oil + Gas	3.7	8.5	1.5	5.1
Natural Gas (heat and power)	19.5	30.9	13.7	36.2

(1) García-Gusano et al. 2017.

The contribution of renewable energies is higher in the NIECP scenario (44% and 77.5% by 2020 and 2030, respectively) than in the BaU scenario (35.6% and 58.7% by 2020 and 2030, respectively). Natural gas will have a smaller contribution to the mix in the NIECP scenario, even if decreasing from 2020 to 2030, as opposed to the BaU scenario, which presents an increase in this period of time. Coal will still be used in 2020 in the NIECP scenario, but there will be no contribution of coal by 2030. The contribution of nuclear power will decrease by 2020, but it will still be used in 2030 according to the NIECP scenario, whereas there will be no contribution according to the BaU scenario. As for the behaviour of renewable energies, the use of solar powers will rise significantly by 2030, the figures being much higher in the NIECP scenario.

In the present study, the NIECP scenarios were implemented in SimaPro to calculate the impact and damage associated with the different time horizons. The results of the life cycle impact assessment for the three studied horizons are shown in Table 2.5 and Figure 2.5. Table 2.5 summarises the values of the selected damage and impact categories, and Figure 2.5 shows the normalised values of those categories. The normalisation is carried out with respect to the total impact of all the substances in each specific category per person per year for Western Europe.

Table 2.5. Summary of the damages and impacts associated to each power generation scenario.

Damage Categories (Endpoint Categories)				
Categories	**Unit**	**2018**	**2020**	**2030**
Human Health	DALY	$8.65 \times 10^{+04}$	$8.28 \times 10^{+04}$	$4.73 \times 10^{+04}$
Ecosystem Quality	PDF·m^{2}·year	$2.31 \times 10^{+10}$	$2.65 \times 10^{+10}$	$3.92 \times 10^{+10}$
Climate Change	kg CO_2 eq	$8.46 \times 10^{+10}$	$8.11 \times 10^{+10}$	$4.81 \times 10^{+10}$
Resources	MJ primary	$1.87 \times 10^{+12}$	$1.90 \times 10^{+12}$	$1.14 \times 10^{+12}$
Impact Categories (Midpoint Categories)				
Categories	**Unit**	**2018**	**2020**	**2030**
Carcinogens	kg $C_2H_3Cl_{eq}$	$1.63 \times 10^{+09}$	$1.48 \times 10^{+09}$	$1.60 \times 10^{+09}$
Non-Carcinogens	kg $C_2H_3Cl_{eq}$	$1.03 \times 10^{+09}$	$1.13 \times 10^{+09}$	$1.73 \times 10^{+09}$
Respiratory Inorganics	kg PM2.5$_{eq}$	$1.12 \times 10^{+08}$	$1.06 \times 10^{+08}$	$0.53 \times 10^{+08}$
Ionising Radiation	Bq C-14$_{eq}$	$4.58 \times 10^{+12}$	$5.02 \times 10^{+12}$	$2.49 \times 10^{+12}$
Ozone Layer Depletion	kg CFC-11$_{eq}$	$1.36 \times 10^{+04}$	$1.46 \times 10^{+04}$	$1.22 \times 10^{+04}$
Respiratory Organics	kg $C_2H_{4\,eq}$	$1.37 \times 10^{+07}$	$1.23 \times 10^{+07}$	$1.53 \times 10^{+07}$
Aquatic Ecotoxicity	kg TEG water	$7.70 \times 10^{+12}$	$8.56 \times 10^{+12}$	$10.8 \times 10^{+12}$
Terrestrial Ecotoxicity	kg TEG soil	$2.36 \times 10^{+12}$	$2.67 \times 10^{+12}$	$3.81 \times 10^{+12}$
Terrestrial Acid/Nutri	kg SO_2 eq	$1.67 \times 10^{+09}$	$1.67 \times 10^{+09}$	$0.94 \times 10^{+09}$
Land Occupation	m^{2}org.arable	$2.09 \times 10^{+09}$	$2.89 \times 10^{+09}$	$6.93 \times 10^{+09}$
Aquatic Acidification	kg SO_2 eq	$5.78 \times 10^{+08}$	$5.60 \times 10^{+08}$	$2.62 \times 10^{+08}$
Aquatic Eutrophication	kg PO_4 P-lim	$1.73 \times 10^{+07}$	$1.78 \times 10^{+07}$	$1.78 \times 10^{+07}$
Global Warming Potential	kg CO_2 eq	$8.46 \times 10^{+10}$	$8.11 \times 10^{+10}$	$4.81 \times 10^{+10}$
Non-Renewable Energy	MJ primary	$1.87 \times 10^{+12}$	$1.89 \times 10^{+12}$	$1.14 \times 10^{+12}$
Mineral Extraction	MJ surplus	$4.50 \times 10^{+09}$	$4.90 \times 10^{+09}$	$7.14 \times 10^{+09}$

In view of the results (Figure 2.5 (a)), it may be concluded that the categories most affected by the electricity production scenarios are Human Health, Resource Consumption and Climate Change. The damage categories in 2020 undergo only a slight variation with respect to 2018. The Human Health and Climate Change damage categories decrease around 4%, and Resources Consumption increases 1.6%, whereas the damage to Ecosystem Quality experiences an increase of 14.7%. The increase in this damage category is much higher in 2030 (70%), but the damage to the other three categories decreases significantly compared to the 2018 values. The effects observed on each of these damage categories are discussed below, through an individual analysis of the impact categories that contribute to each of the damage categories.

Figure 2.5 (b) shows that the effect on Human Health is mainly due to the effect of the Respiratory Inorganics impact category and, to a lesser extent, to the Carcinogenic and Non-Carcinogenic impacts.

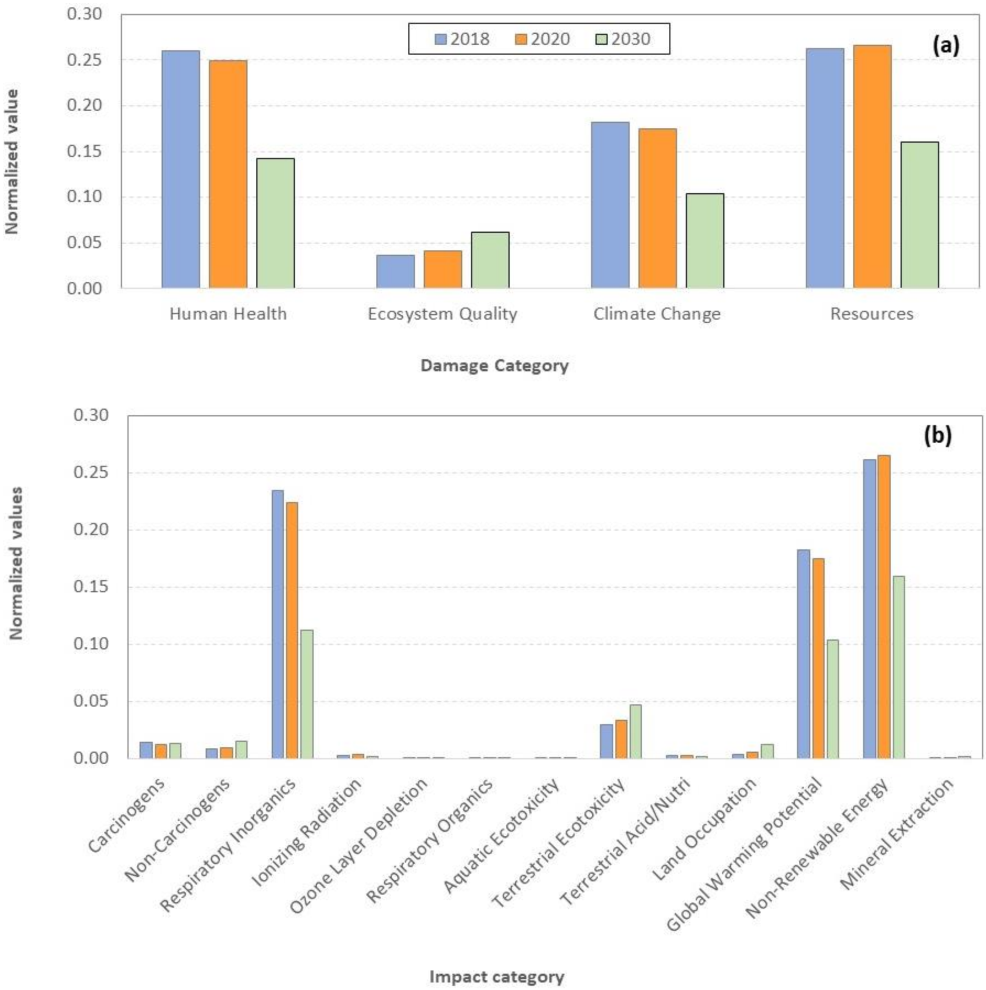

Figure 2.5. Contribution of each power generation scenarios to the damage (a) and impact (b) categories (normalised values).

In the following discussion, the substances and processes that contribute to the different impact and damage categories can be seen in the supplementary material of Appendix B.

2.3.1.1 Human Health

As regards the impact of Respiratory Inorganics, and taking the energy production scenario of 2018 as reference, a decrease of 4% was observed in this impact category in 2020 and of up to 45% in the 2030 scenario. According to the employed methodology, the emission to the air of fine particulate matter (particle diameter < 2.5 microns), sulphur dioxide and nitrogen oxides is mainly responsible for the effect on this impact category. These substances are associated with the use of coal as an energy source in the generation of electricity; hence, the elimination of coal in the 2030 scenario could explain the observed decrease in this category.

In the case of Non-Carcinogens, there is a significant increase (68%) in the contribution of the proposed scenario for 2030 with respect to the 2018 scenario, whereas the increase for 2020 is much lower (9.5%). The substances that have the greatest effect on this category are the arsenic emitted to the air, water and soil, dioxins emitted to the air and zinc emitted to the soil. These substances are associated with biomass combustion processes (including waste combustion). As can be seen in Table 2.1, the generation of electricity from waste is foreseen to increase considerably in 2030, from 4431 GWh in 2018 to 17596 GWh. This increase may justify the behaviour observed in this impact category.

As regards the effect on the Carcinogens impact category, this is not very significant, with slight decreases in the contribution of the proposed scenarios for 2020 (9%) and 2030 (1.7%) compared to that of 2018. The substances with the greatest contribution to this impact category are aromatic hydrocarbons emitted into the air, which are associated with various processes, such as the production of natural gas at high pressure or the use of biomass and waste for electricity production, amongst others. Therefore, it is difficult to associate the expected decreases with the variation in the processes for the proposed scenarios.

The effect of the electricity generation scenario on this damage category was studied by García-Gusano et al. 2017. Values of 3.11×10^{-7} DALY/kWh and 3.07×10^{-7} DALY/kWh were obtained for the BaU scenario proposed in 2020 and 2030, respectively. In the present study, the value obtained in 2020 is similar (2.98×10^{-7} DALY/kWh), but the value for 2030 (1.35×10^{-7} DALY/kWh) is much lower. The difference could be attributed to the different contribution of coal and natural gas in both the BaU and NIECP electricity generation scenarios (Table 2.4). Even though coal is not present in the BaU scenario in 2020, the high value obtained in the Human Health damage category may be explained by the greater contribution of natural gas in this scenario compared to the NIECP scenario used in the present study. Concerning 2030, even though coal is not present in either scenario, the contribution of natural gas is higher in the BaU scenario. This fact could explain the higher value of the Human Health damage category obtained by García-Gusano et al. 2017.

2.3.1.2 Ecosystem Quality

It can be seen in Figure 2.5 (a) that there is a significant increase (70%) in damage to Ecosystems Quality in 2030. The Terrestrial Ecotoxicity impact category presents the greatest contribution to this damage category, followed by Land Occupation and Terrestrial Acidification/Nutrification (Figure 2.5 (b)).

As regards Terrestrial Ecotoxicity, an increase of 61% is observed in 2030 (Table 2.5). Copper, aluminium, chromium and zinc emitted to the soil are the substances with the greatest influence on this impact category. On the other hand, the process with the greatest contribution to this impact category in 2030 appears to be the treatment by landfarming of wood and ash mixtures, which could be associated with the use of biomass and waste in electricity production. Energy sources of this type are foreseen to increase up to 17,596 GWh in 2030 (Table 2.1).

The production of photovoltaic panels is the process with the greatest contribution to the Land Occupation impact category. An increase of 232% in 2030 with respect to 2018 can be observed in this impact category (Table 2.5). This fact is in keeping with the variation in solar photovoltaic energy, which is foreseen to increase from 7759 GWh in 2018 to 70491 GWh in 2030.

The Terrestrial Acidification/Nutrification impact category does not change in 2020 but a decrease of 44% can be observed for 2030 (Table 2.5). Nitrogen oxides, sulphur dioxide and ammonia emitted to the air are the substances with the greatest contribution to this impact category. These substances are mainly associated with the use of solid fossil fuels in energy production. The use of coal as an energy source decreases in 2020 with respect to 2018, and no coal will be used in 2030 for electricity production, in line with the observed trend in the Terrestrial Acidification/Nutrification impact category.

2.3.1.3 Climate Change

Carbon dioxide is the substance with the greatest contribution to the Climate Change damage category, followed by methane and, to a lesser extent, dinitrogen monoxide. Carbon dioxide and methane are mainly associated with the use of coal and natural gas (both in combined cycle and conventional power plants) in electricity production. The Climate Change category decreases 4% in 2020 and 43% in 2030 with respect to 2018 due to the elimination of coal and the reduction in oil and gas as energy sources.

Comparing the values of the present research for this damage category with those obtained using the BaU scenario (García-Gusano et al. 2017), significant variations are observed, mainly in 2020. An impact of around 0.19 kg CO_2/kWh was obtained for the aforementioned scenario, which is lower than the value obtained in the present study (0.29 kg CO_2/kWh). This could be attributed to the fact that, in the electricity generation scenario proposed in this study, coal will still be used in 2020, while it will not in the BaU scenario. For the year 2030, the differences are smaller (0.18 kg CO_2/kWh in the BaU scenario compared to 0.14 kg CO_2/kWh in this study). This difference could be attributed to the greater contribution of oil, gas and natural gas in the BaU scenario.

2.3.1.4 Resources Consumption

Resources Consumption increases slightly (1.6%) in 2020 with respect to 2018, but is seen to decrease 39% in 2030 (Table 2.5). This reduction is mainly due to the decrease in Non-Renewable Energy, as this impact category is the one presenting the greatest contribution to the damage in Resources Consumption. Uranium, natural gas, coal and oil are the resources that mainly affect this impact category, and the use of these types of energy sources is seen to decrease very significantly in 2030.

2.3.2 Heating and Cooling Demands

The data for the eight selected locations represent a wide spectrum of climatic conditions, as can be seen in Figure 2.2. The lowest value for the average monthly temperature in the winter period (from October to May) was found for Valladolid (2.34°C in December) and the highest value for Seville (20.75°C in May). In the summer period (from June to September), the lowest value was found for Oviedo (15.35°C in June) and the highest value for Seville (28.38°C in September). Concerning the levels of the monthly global solar irradiation on a horizontal plane, a wide spectrum of values can also be observed. In winter, the lower values correspond to Bilbao (3.77 MJ/m^2 in December) and Oviedo (4.34 MJ/m^2 in December), while the highest value corresponds to Seville (24.99 MJ/m^2 in May). As regards summer, the lowest monthly global horizontal irradiation value corresponds to Oviedo (13.16 MJ/m^2 in September), which is followed by Bilbao (13.20 MJ/m^2 in September); while the highest value is found for Seville (26.92 MJ/m^2 in June)

Figure 2.6 shows a comparison of the heating demands (from October to May), and Figure 2.7 shows a comparison of the cooling demands (from June to September) corresponding to the years 2018, 2020 and 2030 for all the locations under study. The heating demand in all places was less than 22 kWh/m^2 per year, and this value was obtained for Valladolid in 2018. However, some of the buildings at the locations under study have low demand, such as Barcelona, in all three years under analysis. With respect to cooling demand, this remains below 18 kWh/m^2 per year, the value obtained for Barcelona in 2030, while some of the buildings have zero cooling demand, such as Oviedo, in the three years analysed.

With regards to heating demand, in 2020, compared to 2018, there is generally a reduction. The largest decrease is 48%, which occurs in Valencia, which has a Mediterranean climate, although this location has low heating demand values. The average decrease in cities with an oceanic/continental climate (Oviedo, Bilbao, Valladolid, Madrid and Zaragoza), which have a higher heating demand, ranging from 4% to 21%. The exception to this decrease is observed in Seville, which has a Mediterranean/subtropical climate, where the demand for heating increases 132%.

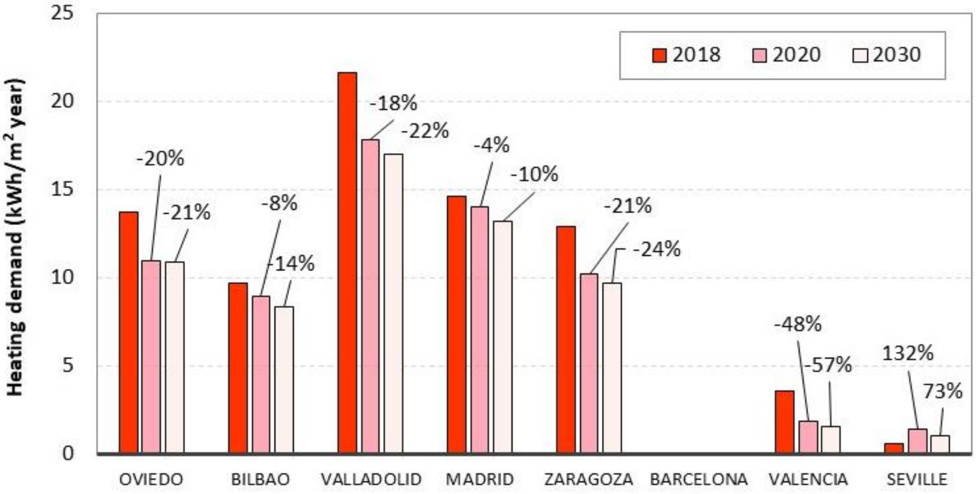

Figure 2.6. Heating demands (values and percentage variation).

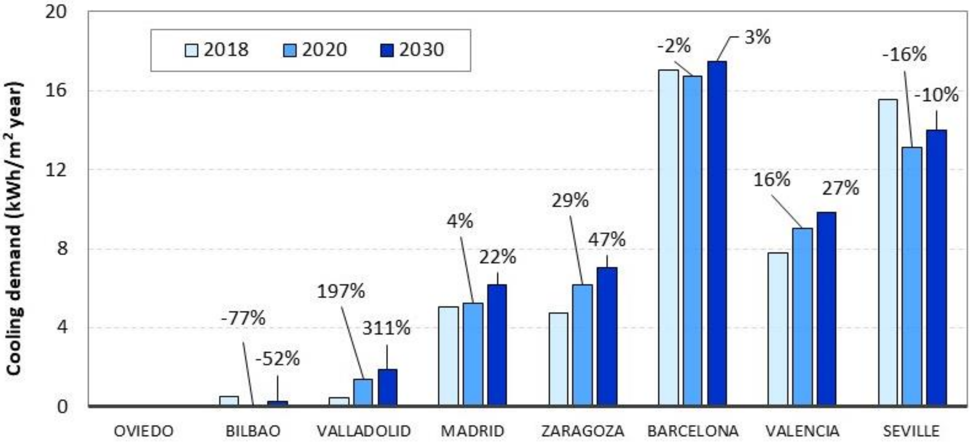

Figure 2.7. Cooling demands (values and percentage variation).

However, as heating demand values are very low, the increase is not significant from the point of view of energy consumption. The trend is similar in 2030, although the values vary. In Valencia, the decrease is 57%; in the cities with an oceanic/continental climate, the decrease ranges from 10% to 24%, while in Seville demand increases 73%. In values, the most affected demand is that of Valladolid, where, in addition to presenting the highest demand, the percentage decrease is the second highest (22%).

Regarding the demand for cooling, this increases at all locations, except for Bilbao, which has very low demands, and Seville, which presents relatively high demand values, although in this latter case the variation is small. This trend is consistent with the general increase in temperature caused by climate change. Of the locations studied, the greatest change occurs in Valladolid, where the demand for cooling increases almost 197% in 2020 and more than 310% in 2030, and the demands are also substantial. In other places, increases in 2030 are observed in Madrid, 22%; Zaragoza, 47%; and Valencia, 27%.

The total demand (heating and cooling) generally decreases in 2030 with respect to 2018, with the percentage decreases depending on the location. The most significant variations occur in Oviedo, Bilbao and Valladolid, with 21%, 16% and 15%, respectively, while at the remaining locations the percentage decrease is less than 7%. However, there is a slight increase of 3% in the total demand for Barcelona, due to the increase in cooling demand.

It can be seen that the values of thermal demand are largely dependent on the climate of the cities under study and, in this respect, Spain has a significant climatic variation. These results are consistent with those reported by Karimpour et al. 2014 for single-family homes in different geographical locations with a high level of insulation and similar net floor areas to those in this study, such as Auckland (New Zealand), which presents values of 19 and 32 kWh/m^2 per year, and Hamar (Norway), with values of 63 kWh/m^2.

As for the behaviour of the thermal demand in buildings, taking climate change in future horizons into consideration, the results are consistent with the findings of other authors. The variation in thermal demand in future horizons and under a Mediterranean climate was studied by Gercek et al. 2019 in a residential block of buildings in Izmir (Turkey). Although the type of construction is different to that considered in this study, the trends are in agreement: the demand for heating is predicted to decrease in 2020 (13.6%) and 2050 (26.7%) with respect to the current data; however, the demand for cooling will increase by 2020 (23.2%) and 2050 (49.5%). Andric et al. 2016 studied the evolution of demand according to different time horizons at the district level in Lisbon (Portugal), also under a Mediterranean climate. Different renovation scenarios were proposed for buildings, in high-rise flats and single-family one-storey houses, also considering different shading levels. In agreement with the present work, the thermal heating demand is foreseen to decrease within the range of 22.3–52.4% in 2050 compared to 2010, depending on the building and renovation scenario studied.

The variations in heating and cooling demands were analysed in southern Spain for a theoretical reference single-family house in Suárez et al. 2018, built in 2006 in accordance with Spanish regulations. Calculations were performed for the current scenario (climate data in software tools valid for 2018) and for the predicted scenario in 2050. Different passive conditioning strategies (envelope modification, solar gain protection and night-time natural ventilation) and two building orientations were studied. The results showed that demand values depend very much on the strategy employed, with a moderate decrease in heating demand and a potential twofold increase in cooling demand when comparing the current scenario and that of 2050. Therefore, these findings are also in agreement with those of this study.

2.3.3 Impacts Associated with the Operational Energy for Heating and Cooling

The estimated values for the damage categories (in terms of m^2 of housing and year at different locations in Spain) are shown in Figure 2.8 to Figure 2.11. Both the decarbonisation process proposed for Spain and the climate change that will occur at the different locations have been taken into account.

Figure 2.8 presents the damage to Human Health, with calculated values and percentage of variation. It can be seen that the damage decreases in 2020 compared to 2018 at all locations. The changes in 2030 are very significant, the decrease in this damage category ranging between 59% and 68%.

Regarding the damage to Ecosystem Quality (Figure 2.9), this category decreases in some locations but increases in others in 2020, the reductions being mainly at the locations in northern Spain: Oviedo, Bilbao and Valladolid. In 2030, this damage increases in all cases except for Oviedo, where it decreases slightly (1%), a finding that may be associated to a relatively higher decrease in total thermal demand than at other locations. It can also be seen that the increase in this damage category is substantial for the locations in the centre of Spain: Madrid, 23%; and Zaragoza, 18%; in the Mediterranean area: Barcelona, 28%; and Valencia, 25%; and in southern Spain: Seville, 16%. The increases in damage are lower than those obtained by applying the proposed energy policy, as the thermal demand for buildings generally decreases.

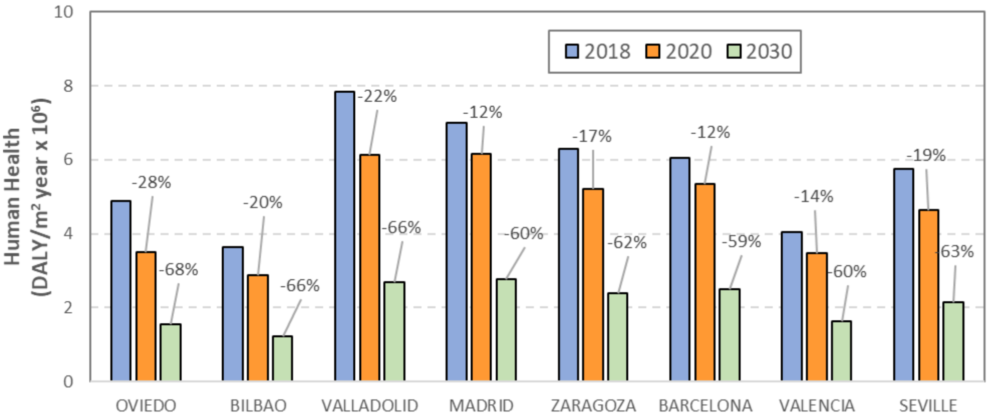

Figure 2.8. Damage category: Human Health (values and percentage variation).

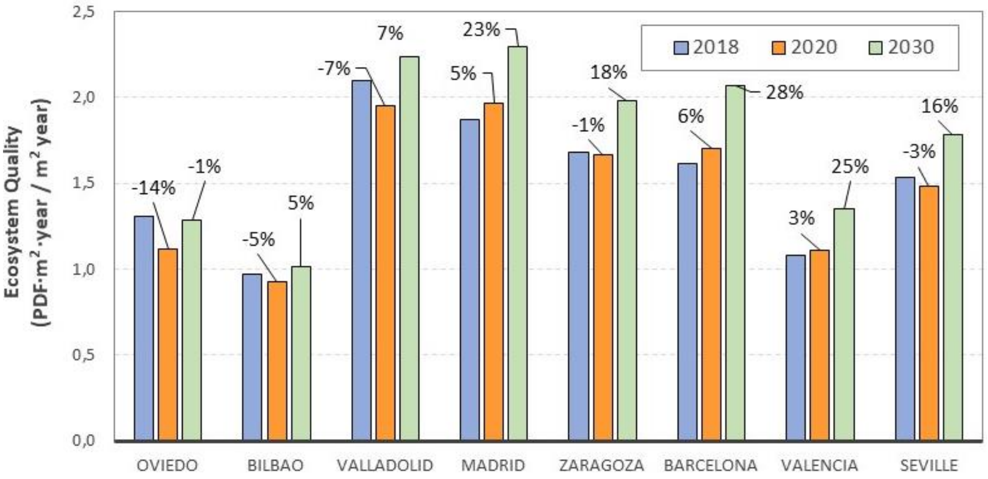

Figure 2.9. Damage category: Ecosystem Quality (values and percentage variation).

The impact on Climate Change (Figure 2.10) is seen to decrease at all locations and in both time scenarios (2020 and 2030). In 2020, the reduction ranges from 12% to 28% and in 2030 from 57% to 67% due to the effects of decarbonisation in Spain (coal will no longer be consumed and the use of renewable energies will have increased considerably).

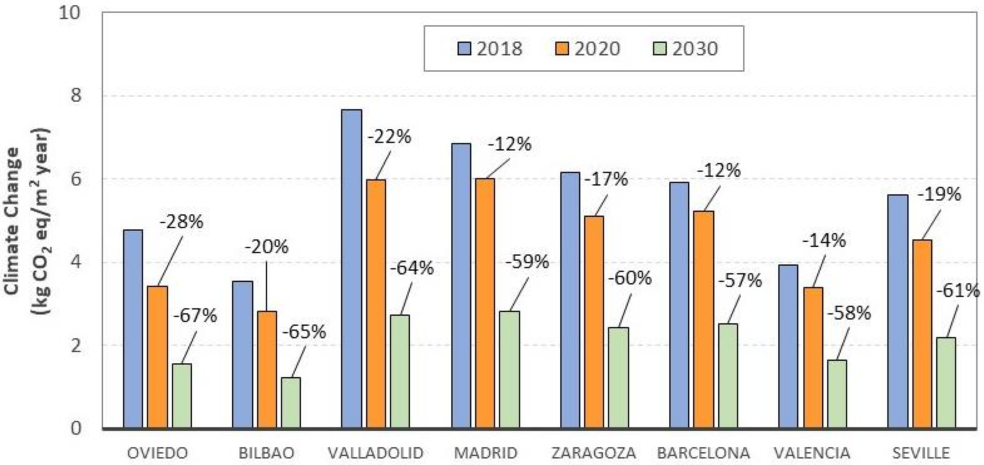

Figure 2.10. Damage category: Climate Change (values and percentage variation).

Finally, regarding the impact on Resources (Figure 2.11), the trend is similar to that of Climate Change, in the sense that the impact decreases at all locations in 2020 and 2030. In 2020, the largest reduction occurs in Oviedo (24%). This city also presented the largest reduction in the other damage categories. In 2030, the reductions range between 54% and 65%, with the maximum reductions also occurring in Oviedo.

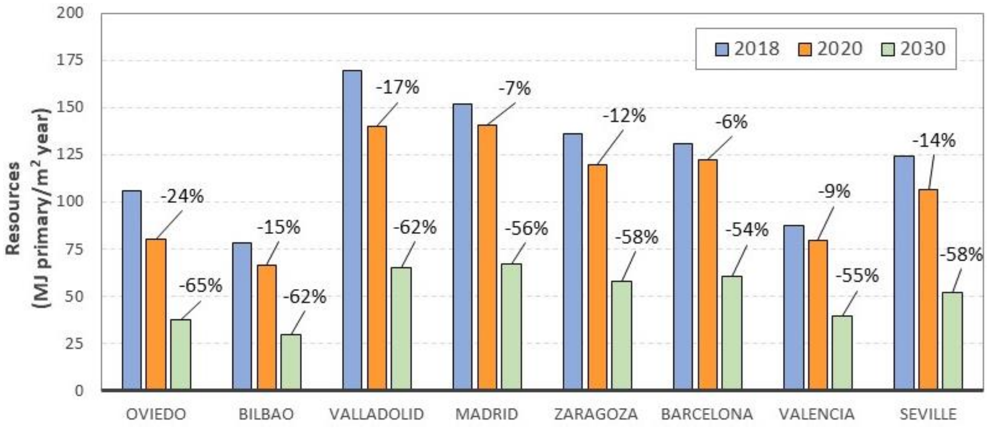

Figure 2.11. Damage category: (values and percentage variation).

The impact of buildings in future horizons is greatly dependent on electricity generation policies and the use of renewable energy at a district level or in each building, as well as on the specific climate and other factors. The great majority of studies on operational energy deal with future global warming impact (CO_2 emissions), though few address primary energy consumption, Karimpour et al. 2014 being an example. However, the aforementioned study does not include future horizon calculations.

Concerning CO_2 emissions in future horizons under the change of weather variables, Andric et al. 2016 reports that the annual CO_2 emissions from heating could decrease from 8% to 34% in 2050 (compared to 2010, depending on the weather scenario and heating system considered), the tendency being in line with the results of the present work. In contrast, the results obtained by Gercek et al. 2019 indicated a 37% rise in total annual CO_2 emissions when comparing recent values with those expected for 2050. In their study, the authors admit to a certain degree of uncertainty due to a lack of factors for Turkey, which convert the energy consumption to CO_2 emissions. In the present study, for Spain, the effect of changing the electricity generation mix in the future was obtained by using the National Integrated Energy and Climate Plan and performing an LCA calculation in SimaPro to assess the impacts.

2.4 Conclusions

The present study addresses the environmental impacts, using the LCA methodology, of the electricity consumption to supply the heating and cooling demands of a reference single-family house. Eight different locations for the house were studied to consider the climatic differences and future climate change. Electricity consumption from the national mix planned for the years 2020 and 2030 by Spain in its NIECP was used to meet heating and cooling demands.

Regarding the evolution of the environmental impact and damage due to electricity generation, it is observed that the damages on Human Health, Climate Change and Resources Consumption decrease in 2030 by 45%, 43% and 39%, respectively. This is mainly due to the elimination of coal as an energy source and the decrease in the use of nuclear power. However, there will foreseeably be a 70% increase in the damage to Ecosystem Quality, although this damage category will be less affected than the others. This variation can be attributed to the increase in the use of biomass and waste in electricity generation and, to a lesser extent, to an increased use of solar photovoltaic energy.

As for the evolution of the heating and cooling demands of the reference house, heating demand will foreseeably decrease by an average of 18% in 2030 in the cities with the highest demand, namely those with an oceanic and continental climate (Oviedo, Bilbao, Valladolid and Madrid). The demand for cooling is expected to increase in general, being greater at locations with a continental climate (Valladolid, Madrid and Zaragoza), with increases ranging between 22% and 45%. The total demand for heating and cooling in 2030 will generally decrease and will be higher at those locations with an oceanic and continental climate (21% to 15%).

The evolution of the damage categories due to heating and cooling when applying the Energy and Climate Plan and the variation in energy demand due to climate change are forecasted as follows: the damage to Human Health will decrease at all locations (from 59% to 68%), as will the damage to Climate Change (from 57% to 67%) and to Resources (from 54% to 65%), as the total demands for heating and cooling will decrease. Nevertheless, the damage to Ecosystem Quality will increase, because although energy requirements will decrease, the energy production scenario for 2030 will have a greater impact on this damage category. The expected increases will be between 5% and 28%, being higher in Spain's central, Mediterranean and southern areas.

A foreseeable future line of study would include a more in-depth calculation of the impacts for buildings under future climate and energy source scenarios, covering the stages of manufacturing, replacement, use, disposal and recycling from cradle to grave.

Chapter 3. Influence of Atlantic Microclimates in Northern Spain on the Environmental Performance of Lightweight Concrete Single-Family Houses

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Major parts of this Chapter have been published in the following article:

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3.1 Introduction

The reduction in energy consumption has mainly affected energy of use, also known as operational energy, which represents the highest percentage of the energy that the buildings will use throughout their life cycle (Sartori et al. 2007). In recent years, there has been a progressive evolution towards low-energy buildings, passive buildings and buildings with almost zero consumption. The decrease in energy of use has also led to a decrease in the ratio between this energy and the total energy to be used throughout building's lifespan. Consequently, the energy consumed in other stages of the life cycle, such as embodied energy, has gained importance. Karimpour et al. 2014 and Chastas et al. 2016 analysed cases to illustrate the embodied energy in the transition from conventional to nZEB, passive and low energy buildings, and realized that, despite the reduction in the total life cycle energy, the share of embodied energy takes an important role, mainly in nZEB and low-energy buildings. The need to understand the possibilities of reducing the embodied impacts has led to the "Annex 57" EBC (European Brain Council) project, a broad call for case studies launched with the aim of identifying design strategies to reduce the embodied energy and CO_2 emissions from buildings. Malmqvist et al. 2018 performed a systematic analysis of a collection of case studies in Annex 57, as well as of further scientific literature on this topic. Regarding passive houses, Stephan et al. 2013 studied the total life cycle energy demand of a typical Belgian single-family detached house, which comprises embodied, operational and transport energy, highlighting the importance of the manufacture of building materials, especially due to the large amount of insulation required to achieve high operational efficiencies.

Energies consumed in stages other than manufacturing and use, such as in maintenance, deconstruction and disposal or recycling, currently have a lower impact, as can be deduced from Morales et al. 2019 and Cuéllar-Franca et al. 2012. Therefore, manufacturing is the life cycle stage of the where interest is progressively gaining greater importance (Karimpour et al. 2014; Stephan et al. 2013).

Sustainability assessment has been performed for diverse climates, but most of these refer to cold climatic regions, as in Takano et al. 2015, where buildings with different typologies were studied. Concerning mild and warm climates, El-Hanandeh 2015 analysed six construction systems in Jordan, a country with a Mediterranean climate with great variation in temperatures and rainfall. The role played by the envelope materials in the tropical climate of Indonesia was presented by Utama et al. 2008. Energy demands in different climatic regions of China were discussed by Luo et al. 2017 for various insulation thicknesses. There are also examples for hot desert climates in Qatar (Elsarrag et al. 2012) and for the tropical Lebanese climate (Tibi et al. 2012).

As regards the materials used to manufacture building envelopes, there are numerous studies covering those most commonly used: brick masonry (Moschetti et al. 2015), laminated-timber (Premrov et al 2018a) and concrete (Robertson et al. 2012). Wooden constructions are the most widely studied, since timber is a frequently used material due to its near zero impact in the production of greenhouse gases and its relatively low conductivity (Premrov et al 2018a). However, there is a scarcity of data concerning buildings made of lightweight concrete, a material that admits a certain degree of recycling and has low conductivity (Napolano et al. 2016), being at the same time of great interest for its use in industrialized construction.

Previous studies have shown the importance of considering the embodied impacts of buildings for different materials and climates. However, particular case studies are required for housing typologies, especially for single-family houses. According to Eurostat 2017, in 2015 in the EU-28, more than 4 out of every 10 persons (42.0%) lived in flats, close to one quarter (24.1%) in semi-detached houses and one third (33.3%) in single-family houses. Therefore, single-family houses are important from the point of view of energy efficiency and environmental impacts.

As for the scenarios of sustainability and energy supply, recently it is necessary to apply decarbonisation policies, both in general and in the production of electricity, in order to reduce climate change. Recently, Spain presented to the European Union the Integrated Energy and Climate National Plan for Spain (Spanish Ministry of Ecological Transition 2019), which covers the objectives until 2030 and greatly increases electricity generation based on renewable sources. Therefore, in the near future an electricity-only scenario may become a highly appropriate option from a sustainability perspective, and that is the reason why it has been included as one of the scenarios to study in this work. On the other hand, in Spain, particularly in the north, the use of heat pumps is gaining increasing interest, due to their performance and also in order to comply with the mandatory Spanish standards contained in the "Spanish Technical Building Code" (Spanish Ministry of Housing 2006). According to this code, part of the demand for domestic sanitary water must be covered by renewable energy. In this respect, the heat pump is a very good alternative to solar hot water panels in those regions where solar insolation is quite low, such as in northern Spain. For this reason, a heat pump installation has been chosen as the second power supply scenario. Finally, to take into account fossil fuels, a third energy supply scenario based on natural gas has been added, since: (i) it is a relatively clean fuel (it does not contain sulphur); (ii) its use to satisfy heating and domestic water demands is widespread; and (iii) the performance of natural gas boilers has improved substantially in recent decades.

This work analyses sustainability aspects obtained from life cycle assessment of a single-family house that has been designed to be built industrially using lightweight concrete panels with expanded clay. Two sizes of houses are considered that adapt to the needs of the potential users of single-family housing in northern Spain. The thermal behaviour and embodied impacts of the houses as the insulation thickness increases is analysed for different locations in the Principality of Asturias, located on Spain's Atlantic coast. The set of considered locations presents a wide variety of climates, given that Asturias can be divided into sub-regions which, although geographically close, have very different weather conditions: the west and central coast, the central inland area and the mountains. The impacts on primary energy (embodied and use) and on greenhouse gas emissions (embodied and use) are analysed for various insulation thicknesses, taking into account that the two types of single-family houses have different shape factors and window-to-wall ratios. Regarding the impacts due to the energy used to cover the thermal demand, three supply scenarios are considered: (i) electricity only; (ii) heat pump plus electricity; and (iii) natural gas boiler. Finally, the influence on future impacts of the planned Spanish electricity mix in the 2030 horizon is analysed when using electricity only.

3.2 Materials and Methods

The information to calculate the life cycle assessment is provided in this section: thermal balance equations to calculate energy demand; geometric parameters (Design); materials, properties and inventory (Materials); climatic data (Climate); calculation of heating and cooling demands; and system boundaries. Figure 3.1 shows a flow chart to illustrate the development of the study: (i) thermal energy consumption, which includes the calculation of balances, heating and domestic hot water (DHW) demands; (ii) definition of the thermal energy supply in three scenarios (in this case: “only electric supply”, “with heat pump plus supplementary electric supply” and “natural gas boiler supply”); (iii) calculation of the building use impacts considering the Spanish passage factors (IDAE 2016); (iv) parallel calculation of the embodied impacts, in this case, primary energy (EP) and CO_2 equivalent emissions via Global Warming Potential (GWP); and (v) calculation of the use-to-total ratio of impacts for primary energy and CO_2 equivalent emissions.

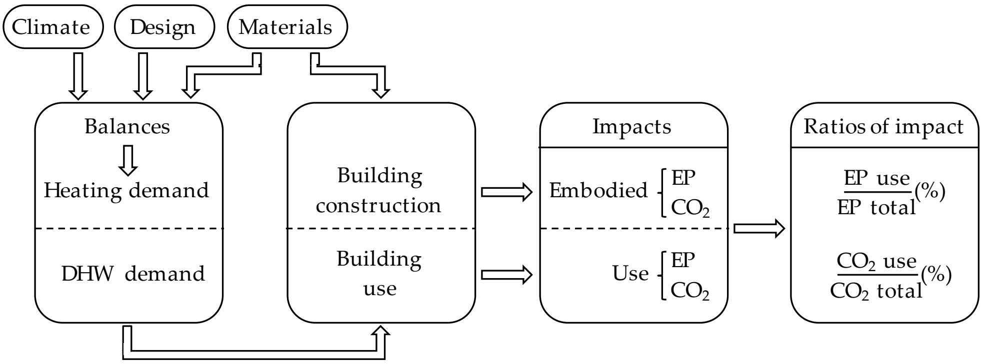


Figure 3.1. Flow chart of the application of the methodology.

3.2.1 Thermal Balances

Thermal balances are obtained using simplified expressions from EN (European Norm) and ISO (International Organization for Standardization) standards (ISO 13790:2008), which are used in [Premrov et al 2018a and in the Passive House Planning Package (PHPP) standard (PHPP v9 2015), which is the software used in the present study. The validity of the simulation model has been assessed in the literature. Recent papers discuss and compare the performance of buildings calculated under own country codes, using the widely employed software packages EnergyPlus and PHPP. An energy-efficient house built following Passive House design principles and equipped with extensive monitoring was compared to a reference house designed following the Romanian energy efficiency code in Dan et al. 2016.

Regarding the use of PHPP, the authors uphold the ability of this software to determine the energy performance of buildings according to European standards. Besides, four climatic regions of Portugal were also analysed in Figueiredo et al. 2016 using EnergyPlus software and the Portuguese code, concluding that it is essential to adapt and detail the technical and constructive solutions for different regions.

The energy balance in Eq. (3.1) considers heat inputs and outputs: transmission losses ($\boldsymbol{Q_t}$), ventilation losses ($\boldsymbol{Q_v}$), internal gains ($\boldsymbol{Q_i}$) and solar gains ($\boldsymbol{Q_s}$). This overall balance in the building is performed in order to obtain the heating ($\boldsymbol{Q_h}$) and cooling ($\boldsymbol{Q_c}$) demands from Eq. (3.2) and Eq. (3.3), respectively:

$$\boldsymbol{Q_t + Q_v + Q_i + Q_s = \Delta Q} \tag{3.1}$$

$$\boldsymbol{\Delta Q = Q_h} \tag{3.2}$$

$$\boldsymbol{\Delta Q = Q_c} \tag{3.3}$$

In the above equations, the building's thermal inertia and the performance of the building in the unsteady state should be taken into account. In the quasi-stationary method according to ISO 13790:2008, the heat gains are reduced by the utilization factor, η_G, which is introduced to calculate the heating demand in the following Eq. (3.4):

$$\boldsymbol{Q_h = Q_L - \eta_G Q_G} \tag{3.4}$$

where $\boldsymbol{Q_L}$ are the heat losses and $\boldsymbol{Q_G}$ are the heat gains, as expressed in Eq. (3.5) and Eq. (3.6), respectively:

$$\boldsymbol{Q_L = Q_t + Q_v} \tag{3.5}$$

$$\boldsymbol{Q_G = Q_s + Q_i} \tag{3.6}$$

The solar gains ($\boldsymbol{Q_s}$) for the annual calculation are proportional to the window-to-wall ratio gross area ($\boldsymbol{A_w}$) and the total solar insolation ($\boldsymbol{G_s}$) during the period considered (heating or cooling), according to Eq. (3.7):

$$\boldsymbol{Q_s = r\ g\ A_w\ G_s\ /A_{ref\_net}} \tag{3.7}$$

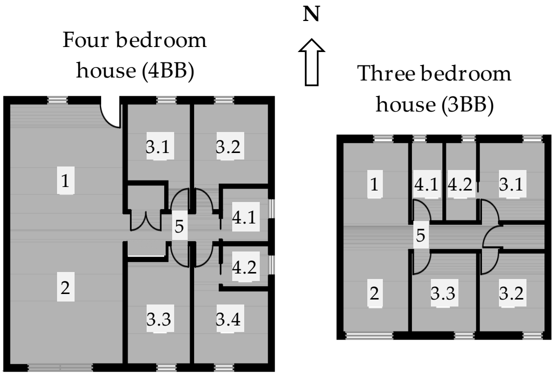
where r is the total shading reduction factor, g is the solar factor (energy transmitted through the glazing normal to the irradiated surface) and $\boldsymbol{A_{ref\_net}}$ is the usable floor area. The solar gains diminish the heat demand during the heating period, but increase the cooling demand in the summer period. Therefore, the solar factor should be carefully chosen according to the location to minimize the sum of the annual energy demand for the heating and cooling periods. More detailed expressions consider insolation according to the four orientations (N, S, E and W). However, as the transmittance of the windows is higher than the transmittance of the opaque elements, a high window-to-wall ratio also increases losses by transmission through the windows and hence the importance of an appropriate selection of the windows. The transmission losses are a function of the areas of the construction elements, as per Eq. (3.8):

$$\boldsymbol{Q_t = A\ U\ f_T\ G_t/A_{ref\_net}} \tag{3.8}$$

where $\boldsymbol{A}$ is the area of the element of the envelope (roof, floor, wall, window), $\boldsymbol{U}$ is the transmittance of the element, $\boldsymbol{f_T}$ is the temperature reduction factor and $\boldsymbol{G_t}$ is the sum of the differences in temperature (exterior air temperature and base temperature), which is calculated on an hourly basis, i.e., degree hours for the period (heating or cooling).

3.2.2 Geometric Parameters

The type of housing and the living spaces were defined based on the average income level of the potential users and the number of children per couple, as reported in González-Prieto et al. 2018. However, it is also very common for 5 occupants to live together in the house when considering a large family or when living with older relatives, so the study considers two sizes of single-family houses. The layout for both types of houses and the floor areas of the rooms is shown in Figure 3.2. The one on the left corresponds to a four-bedroom building (referred to as 4BB), while the one on the right is for a three-bedroom building (3BB); the houses include a living room/kitchen, corridor and a facilities room. The usable floor areas are 121.27 and 67 m^2, respectively. The houses are on one level, with a 20-degree pitched roof and slate finish.



		Usable area (m^2)	
	Rooms	4BB	3BB
1	Living room	19.2	15.0
2	Kitchen	34.2	10.0
3.1	Bedroom	12.3	10.0
3.2	"	12.2	10.0
3.3	"	12.5	10.0
3.4	"	10.1	-
4.1	Bathroom	4.6	4.5
4.2	"	3.5	4.5
5	Others	12.8	3.0
	Total	121.3	67.0

Figure 3.2. House layout: four-bedroom building (4BB) and three-bedroom building (3BB).

Table 3.1 shows parameters that define the thermal performance of the windows. The window-to-wall ratio (AWF) is defined in this work as the ratio of the gross area of the windows facing south to the total area of the south facade. The solar gains depend on the glazing fraction (AGF), which is the glazing-to-wall area ratio for the south oriented facade. The buildings have a rectangular floor plan, with windows only on the north and south facades. Two cases were studied: large windows facing south and small windows facing north (LW-SOUTH), and small windows facing south and large windows facing north (SW-SOUTH). The average glass fraction (GFavg) considers the ratio of the overall glazing areas to the total wall area of the building. Similarly, the average frame fraction (FFavg) considers the ratio of the overall framed areas to the total wall area of the building. The transmittances are: Uf for the frame, Ug for the glazing and Uw_avg for the average of all windows. The values for both buildings are quite similar, the windows being somewhat larger for the 4BB. The windows use argon-filled triple glazing with a solar factor g = 0.51. The window frames are made of aluminium, with thermal bridge breaking, absorptivity = 0.4 and infiltration class = 4.

Table 3.1. Characteristics of the windows of the buildings.

Characteristics of the windows	4BB		3BB	
	LW_South	SW_South	LW_South	SW_South
AWF	0.38	0.17	0.31	0.12
AGF	0.23	0.10	0.19	0.07
FFavg	0.40	-	0.43	-
GFavg	0.60	-	0.58	-
Uf (W/m^2 K)	0.83	-	0.83	-
Ug (W/m^2 K)	0.56	-	0.56	-
Uw_avg (W/m^2 K)	0.67	-	0.68	-

Table 3.2 contains the characteristics of the opaque components and the geometric values of the buildings: Aref_net is the usable area; Agross is the outer projection area; Atot is the total outer area of the envelope (i.e., the sum of areas of opaque elements in contact with the surrounding air: wall, roof and floor). The table also shows the shape factor, Fc, which is the ratio of Atot to the inner heated volume of the building, Vint. The shape factor and the window-to-wall ratio, AWF, are the two parameters that are most often taken into account when studying the performance of buildings. A compact shape (associated with a low shape factor) is desirable to minimize transmission losses. Concerning the influence of this factor, Albatici et al. 2011 found it more important in cold localities and less important in mild and warm climates. The aspect ratio (L/W), which is the ratio of the building's length to its width, is another parameter that is often considered to determine solar access to the building. In cold climates, the ideal L/W

value for a rectangular shape ranges from 1.3 to 1.5, as cited in Premrov et al 2018a. However, the influence of the L/W ratio for mild and warm climates is not so well defined (Takano et al. 2015; Premrov et al 2018b). Area ratios for the wall (Fwall) and the roof (Froof) help interpret transmission losses. The overall opaque transmittance of the building, Uop_avg, depends on the thickness of the insulation, and for the present study ranges from 0.14 to 0.33 W/m^2 K.

Table 3.2. Shape factor, other design ratios for the usable floor area and average thermal transmittance.

Characteristics of the opaque construction elements	4BB		3BB	
	6 cm XPS	20 cm XPS	6 cm XPS	20 cm XPS
Aref_net (m^2)	121.27	121.27	67.00	67.00
Aref_gross (m^2)	136.46	143.11	79.00	84.09
Atot (m^2)	425.39	448.25	271.37	289.65
Vint (m^3)	418.31	418.31	216.80	216.80
L/W	1.20	1.20	1.28	1.27
Fwall=Awall/Aref_net	1.13	1.21	1.54	1.66
Froof=Aroof/Aref_net	1.25	1.31	1.36	1.44
Aroof/(Awall+Aroof)	0.52	0.52	0.46	0.46
Fc=Atot/Vint	1.02	1.07	1.25	1.34
Uop_avg (W/m^2 K)	0.33	0.14	0.32	0.14

3.2.3 Materials and Properties

3.2.3.1 Construction Elements of the Building

Table 3.3 shows the life cycle inventory, with the areas of each constructive element, as well as the density, thickness and thermal conductivity of each layer of materials, all of which were obtained from the catalogue of construction elements (Construction Elements Catalogue 2010). The thickness of the expanded polystyrene (XPS) insulation installed on the building's exterior is studied parametrically for each location. When the thickness of the XPS insulation is increased, maintaining the rest of the building elements the same, the transmittance values decrease accordingly. PHPP requirements are met for a thickness of about 20 cm: 0.130 W/m^2 K for the floor and the external walls with internal lining, and 0.147 W/m² K for the roof.

Table 3.3. Characteristics of the construction elements of the houses without additional expanded polystyrene (XPS) insulation.

Construction element	Surface (m²) 4BB	Surface (m²) 3BB	Component	Thick. (cm)	Dens. (kg/m³)	Conduct. (W/m K)
External wall (inner cladded)	91.17	70.38	Gypsum plaster	0.013	800	0.250
			Mineral wool	0.047	40	0.035
			Lightweight concrete	0.14	1680	0.680
			Reinforcing steel	-	-	-
			XPS	-	32	0.034
			Coat of cement	0.018	1600	0.459
			Paint	-	-	-
External wall (non cladded)	19.45	10.34	Lightweight concrete	0.14	1680	0.680
			Reinforcing steel	-	-	-
			XPS	-	32	0.034
			Coat of cement	0.018	1600	0.459
			Paint	-	-	-
Floor slab	123.73	69.35	Solid parquet	0.02	770	0.130
			Conductive cement mortar	0.04	2000	2.00
			XPS with acoustic protection	0.04	23	0.034
			Lightweight concrete	0.14	1680	0.680
			Reinforcing steel	-	-	-
			XPS	-	32	0.034
			Polymer bitumen sealing	0.0078	1100	-
			Cement mortar	0.05	1600	1.050
			Concrete slab	0.2	2560	1.050
Roof	133.23	75.02	Lightweight concrete	0.14	1680	0.680
			Reinforcing steel	-	-	-
			XPS	-	32	0.034
			Polymer waterproofing	0.0078	1100	-
			Oriented strand board (OSB)	0.024	650	0.120
			Polymer bitumen sealing	0.0078	1100	-
			Slate	0.018	2800	2.200

Construction element	Surface (m²)		Component	Thick.	Dens.	Conduct.
	4BB	3BB		(cm)	(kg/m³)	(W/m K)
Horizontal partition	123.73	69.35	Plaster	0.013	800	0.250
			Mineral wool	0.04	40	0.035
			Paint	-	-	-
Vertical partition	76.74	61.61	Lightweight concrete	0.08	1680	0.680
			Reinforcing steel	-	-	-
			Paint	-	-	-
Window frames	7.54	5.11	Aluminium frame	-	-	-
Window glazing	11.15	6.93	Triple glazed panes	-	-	-
Interior doors	11.23	11.23	Hardwood timber	0.34	-	-
Exterior doors	1.89	1.89	Hardwood timber	0.44	-	-

3.2.3.2 Active Technical Systems

The characteristics of the active systems that are used by each of the three thermal energy supply scenarios are found in Table 3.4. The energy systems are decentralized and the houses are equipped with a heat recovery ventilation unit. They include heat pumps, gas boilers, water heating tanks and pipes, as well as hydronic radiant floors that will be used with heat pumps or boilers. In the electricity-only scenario, the electricity is used as an energy source for: space heating by electric radiators (about 50 W/m^2), DHW and LED lights (about 4 W/m^2).

The environmental behaviour depends on the embodied impacts (EP and GWP) of the materials that compose the active systems employed and therefore these impacts are included in the present study. Impact values for the active components were obtained from Ecoinvent v3.3 (2016) in SimaPro (aerothermal heat pump, gas boiler, hydronic floor, tank and ventilation unit) and Leskovar et al. 2019 (electric radiators, piping, electric cables and LED lights).

The active components that comprise each scenario are as follows: (i) the electricity-only scenario comprises electric radiators, a ventilation unit, pipes, electrical cables and LED lights; (ii) the heat pump plus electricity scenario comprises a heat pump, hydronic floor, ventilation unit, pipes, tank, electric cables and LED lights; and (iii) the natural gas boiler scenario comprises a boiler, hydronic floor, ventilation unit, pipes, tank, electric cables and LED lights.

Table 3.4. Data on the active components of buildings, including information on primary energy (EP), Global Warming Potential (GWP) and service life.

Active component	House	Character. (unit)	EP (KWh)	GWP (kg CO_2 eq)	Serv. life	Disposal
1- Electric radiators	4BB	-	9.20	2.27	20	Not considered
	3BB	-	9.20	2.27	20	
2- Aerothermal heat pump	4BB	7 (kW)	15.77	9.36	20	Not considered
	3BB	5 (KW)	20.39	12.10	20	
3- Gas boiler	4BB	12 (kW)	18.65	4.74	20	Not considered
	3BB	9 (KW)	25.33	6.43	20	
4- Hydronic floor installation	4BB	121.3 (m^2)	73.66	21.07	50	Not considered
	3BB	67.0 (m^2)	73.66	21.07	50	
5- Hot water tank	4BB	180 (l)	7.32	1.93	25	Not considered
	3BB	100 (l)	7.37	1.94	25	
6-Piping	4BB	-	3.20	0.79	50	Not considered
	3BB	-	3.20	0.79	50	
7- Ventilation unit	4BB	150 (m^3/h)	65.97	14.66	20	Not considered
	3BB	90 (m^3/h)	71.66	15.92	20	
8- Electric cables	4BB	-	5.00	0.74	50	Not considered
	3BB	-	5.00	0.74	50	
9- LED lights	4BB	-	17.70	0.97	12.5	Not considered
	3BB	-	17.70	0.97	12.5	

Values per m^2 of usable floor area

3.2.4 Climate Data

Asturias is located in the central region of Spain's Atlantic coast, where the climate is Atlantic with mild winters and cool summers. According to the Köppen–Geiger Classification (Peel et al. 2007), part of the territory is Cfb (oceanic) and part is Csb (Mediterranean). The annual thermal oscillation is generally slight and there is abundant rainfall because of the proximity of the ocean. However, the orography is very rugged due to the presence of the Cantabrian Mountains. This context of coast and mountains so close together produces strong variations in altitude between locations and results in a variety of microclimates. In general terms, four main climatic sub-regions can be established: the coastal strip, highly influenced by the sea, with a more continental climate in the west; the central inland strip, with an oceanic climate, although not as influenced by the sea as the coast; and the mountain strip in the Cantabrian Mountains. The locations whose climatic data were studied are numbered from 1 to 11 in the map of Figure 3.3.

The classification of the points into sub-regions, location names, geographical coordinates and altitudes can be seen in Table 3.5: Valdés, which is a typical tourist resort on the west coast; Gijón, also a tourist resort, which is located on the central coast and is the region's largest city; Oviedo, the administrative capital, which is the second largest city in terms of inhabitants; and Ibias, a representative location in the mountains that comprise several areas listed as Nature Parks, which was chosen for its high altitude and very different climatic conditions.

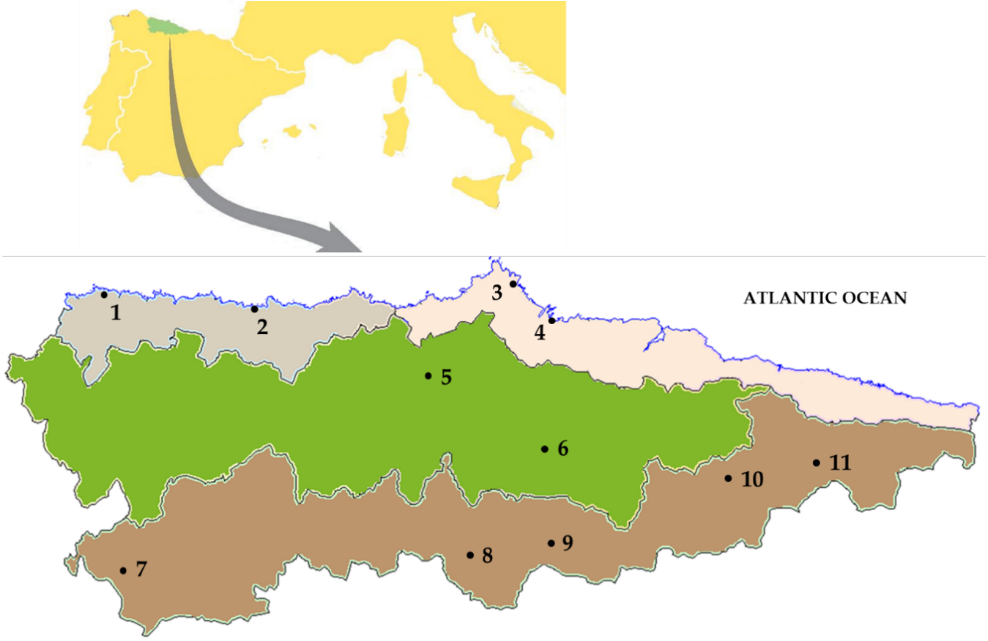


Figure 3.3. Chosen locations (from different climatic sub-regions of Asturias): west coast (top left); central coast (top right); central inland area (central strip); and nature parks (bottom).

Table 3.5. Coordinates and altitudes for the selected locations.

Sub-region	Location	Number	Coordinates [1]	Altitude (m)
West Coast	Caridad	1	43.558 N 6.826 W	70
	Valdés	2	43.472 N 6.390 W	216
Central Coast	Luanco	3	43.624 N 5.787 W	63
	Gijón	4	43.538 N 5.624 W	30
Central Inland	Oviedo	5	43.359 N 5.863 W	302
	Entrego	6	43.287 N 5.634 W	245
Nature Parks	Ibias	7	43.014 N 6.531 W	780
	Lena	8	43.076 N 5.492 W	370
	Aller	9	43.054 N 5.284 W	750
	Amieva	10	43.160 N 5.071 W	370
	Cabrales	11	43.311 N 4.853 W	458

(1) Coordinates are expressed in decimal degrees, in the same way as in Meteonorm v7.2 2017, the software used to obtain climate data.

Table 3.6 and Table 3.7 present climatic data for a representative location from each sub-region studied here. The data were obtained using the Meteonorm v7.2 2017 software.

Table 3.6 shows the following data for each period of thermal energy use (heating and cooling) and each sub-region: degree hours, solar insolation on the vertical planes (N, E, S and W) and global insolation on the horizontal plane. The degree hours are calculated as the sum over the period (heating or cooling) of temperature differences with respect to a reference temperature corresponding to each period (20°C for the heating period and 25°C for the cooling period). The heating period runs from the first day of October to the last day of May, and the rest is considered as the cooling period.

Table 3.7 presents monthly averaged data for outdoor air temperature (Tamb) and dew point (Tdew) for the representative location of each sub-region. These data were obtained for open field landscapes.

Table 3.6. Climate parameters of the representative location of each sub-region: degree hours, solar insolation for heating and cooling periods.

Climate parameters	(unit)	West Coast		Central Coast		Central Inland		Inland Nat. Parks	
		Heat. period	Cool. period	Heat. period	Cool. period	Heat. period	Cool. period	Heat. period	Cool. period
Degree hours (1)	(kWh/year)	47	-37	44	-45	57	-39	68	-34
Solar insolation N	(kWh/m^2 period)	159	226	159	261	181	229	181	238
Solar insolation E	(kWh/m^2 period)	352	478	357	567	417	488	432	584
Solar insolation S	(kWh/m^2 period)	582	510	576	622	687	513	708	600
Solar insolation W	(kWh/m^2 period)	352	460	356	552	407	466	423	568
Global insolation	(kWh/m^2 period)	570	794	584	953	664	805	685	963

(1) In the period

Table 3.7. Ambient and dew point temperatures (monthly average from hourly data).

Month	West Coast		Central Coast		Central Inland		Inland Nat. Parks	
	Heat. period	Cool. period	Heat. period	Cool. period	Heat. period	Cool. period	Heat. period	Cool. period
	Tamb (ºC)	Tdew (ºC)	Tamb (ºC)	Tdew (ºC)	Tamb (ºC)	Tdew (ºC)	Tamb (ºC)	Tdew (ºC)
January	9.4	4.8	11.1	5.3	9.2	4.4	4.2	1.2
February	9.6	4.8	11.1	5.3	9.4	4.6	6.0	1.2
March	11.2	6.4	12.4	6.8	11.1	6.1	8.9	2.6
April	11.8	7.6	13.0	7.8	11.8	7.3	10.8	3.8
May	14.3	10.3	15.4	10.5	14.4	10.4	14.8	6.5
June	17.2	13.3	18.3	13.5	17.7	13.7	20.1	9.6
July	18.6	14.5	19.7	14.8	18.9	14.7	21.0	10.1
August	19.2	15.2	20.4	15.3	19.5	15.3	21.0	10.3
September	17.6	13.5	18.9	13.7	17.7	13.8	17.9	8.8
October	15.3	10.9	16.6	11.3	15.3	11.1	12.8	7.9
November	11.5	7.3	13.2	7.7	11.2	7.1	7.5	4.0
December	9.6	5.0	11.4	5.6	9.2	4.6	4.5	1.3

3.2.5 Calculation of Heating and Cooling Demands

The software used to assess the energy performance of the houses was the Passive House Planning Package (PHPP v9 2015), in accordance with ISO 13790:2008.

The energy balances were analysed and the results compared for the four sub-regions of different microclimates. Subsequently, the effect of climatic variation was investigated, expanding the number of situations. Finally, to achieve the best sustainability conditions, the influence of the insulation thickness was studied for two possible orientations of the building: with the largest windows facing south (LW-SOUTH) and with the smallest windows facing south (SW- SOUTH). The results were obtained using a monthly steady-state computing method, implemented in PHPP. The set point temperature is 20°C for winter and 25°C for summer. The infiltration rate is 0.6 h^{-1} and the ventilation rate was calculated using PHPP software according to the number of occupants in the house: five people for 4BB and three people for 3BB. An air-to-air heat recovery unit with 82% efficiency was considered.

The domestic hot water energy needs include usable hot water and losses due to distribution and accumulation. The usable DHW is calculated considering 25 litres per person per day, which means 23.06 kWh/m^2 year for 4BB and 24.90 kWh/m^2 year for 3BB. The heat losses in the distribution and in the storage tanks are respectively: 4.29 and 1.47 kWh/m^2 year for 4BB and 5.17 and 1.88 kWh/m^2 year for 3BB. This calculation was performed considering the following heat loss coefficients: 0.11 W/m K per metre of length of a pipe with an interior diameter of 0.014 m and 0.45 W/m K per metre of height of a tank with an interior diameter of 0.220 m. These heat loss coefficients were calculated using an auxiliary calculation tool in PHPP, for an insulation of 0.034 W/m K, with a thickness of 30 mm for the pipes and 60 mm for the tank.

An electrical consumption of 2.7 kWh/m^2 year was added to the electrical energy needs for air conditioning and domestic hot water. This value, suggested in Leskovar et al. 2019, corresponds to the ventilation unit (including heat recovery equipment) and LED lights. As for the rest of the household appliances, their energy consumption was not considered strictly associated with the characteristics of the building, so it was excluded due to the difficulty in establishing accurate data and the variability of both its performance and the occupants' usage habits.

The service life, characteristics and software used to calculate the active systems are given in Section 3.2.3.2.

3.2.6 Life Cycle and System Boundaries

Concerns about environmental aspects have led to greater use of life cycle studies, with the impacts reflected in the environmental product declaration, UNE-EN 15804:2012+A1:2014, and the environmental performance of buildings, UNE-EN 15978:2012. The life cycle assessment in this study is carried out from cradle–to-grave and focuses on the calculation of the following impacts: primary energy (EP) and global warming potential (GWP, i.e., CO_2 equivalent emissions). The stages considered are: (i) manufacturing of components (A1 + A2 + A3), where A1 is the supply of raw materials, A2 is the transportation of raw materials and A3 is the manufacturing of the product; (ii) construction of the building, which consists of the transport of materials to the factory (A4) and the on-site erection of the building (A5); (iii) replacement (B5) of the active systems at the end of their service life, but not of the opaque elements of the building envelope, nor of the windows or coatings, since the durability of the chosen materials is greater than the lifespan of the building (50 years); and (iv) operational energy use (B6). To obtain the embodied primary energy and the CO_2 equivalent emissions, the CypeCad "Archimedes" database (CYPECAD MEP 2017), which implements ISO 14040:2006 and ISO 14044:2006 standards, was used for the materials of the passive elements of the buildings, which are those included in the inventory of materials in Table 3.3.

The envelope as a whole is a 14 cm skin of lightweight concrete panel with expanded clay and includes the exterior walls, roof and floor. It is cladded with mineral wool and plasterboard on the inside and with expanded polystyrene (XPS) of different thicknesses on the outside. The walls that divide the interior spaces are 8 cm thick and are also made of lightweight concrete panels. The panels are reinforced with steel mesh during their manufacture.

As no data were found in the "Archimedes" database or in other sources on the impacts corresponding to the manufacture of lightweight reinforced concrete panels, or of other concretes that had a composition sufficiently similar to them, impact data were obtained from the composition of the panels, as explained below.

The composition of lightweight expanded clay mortars was provided by the manufacturer Laterlite (Laterlite Company), while data on the reinforcing steel, for a square mesh of 10 x 10 cm with 4 mm diameter wire, were provided by the manufacturer GyM (GyM Company).

The composition considered for the panels was: 22.0% Portland cement; 25.0% expanded clay; 83% water; 1.95% and 2.2% reinforcing steel for panels 8 and 14 cm thick, respectively; 1.4% hydrated lime; 0.2% organic chemicals; and the rest, up to 100%, of silica sand. The impacts for the 8 and 14 cm thick panels were obtained from these compositions using SimaPro and the IMPACT 2002+ method software (PRè Consultants, Amersfoort, The Netherlands), as well as the Ecoinvent v. 3.2 database. The resulting total impacts, per m^2 of panel, for a panel lifespan of 50 years, were: 102.3 and 178.9 kWh/m^2 for EP and 47.3 and 82.7 kg CO_2 eq/m^2 for GWP, for 8 and 14 cm thick panels, respectively.

The overall impacts were calculated taking into account the total amount of each material present in the building, and are expressed per m^2 of usable floor area, which is the functional unit for all buildings.

All the products necessary to construct the building and their respective packaging are considered to be transported from the factory to the construction site by diesel trucks, with an average route of 80 km.

The calculation method and the service lives that were considered for the active systems are given in Section 2.3.2. The demolition and disposal stages were not considered in the present study, as they are of much less relative importance.

3.3 Results

3.3.1 Energy Use Assessment

3.3.1.1 Balances and Demands

The heating demand depends on the climatic data, construction elements and building design. Summer climatic severity is indicated by a number ranging from 1 (low severity) to 4 (high severity), according to the regulations in force in the Spanish Technical Building Code (Spanish Ministry of Housing 2006; Spanish Ministry of Housing 2009). Asturias is assigned a value of 1, which indicates that the cooling needs are very low, so the cooling demand is not included in the present study.

Table 3.6 presents climatic data obtained for the four representative locations. Both coastal locations have quite similar solar insolation during the heating period. However, insolation during the cooling period is higher on the central coast and consequently the degree hours are likewise greater there. The central inland location has a greater number degree hours per year during the heating period than the location on the central coast. Nevertheless, the number of degree hours per year during the cooling period is lower in the central inland area, because of the increasing distance from the coast. The location in the inland nature parks has more degree hours and days of heating and less cooling degree hours than the location in the central inland area. Therefore, the nature parks sub-region is expected to have higher heating needs than the central inland location and much higher needs than the coastal locations.

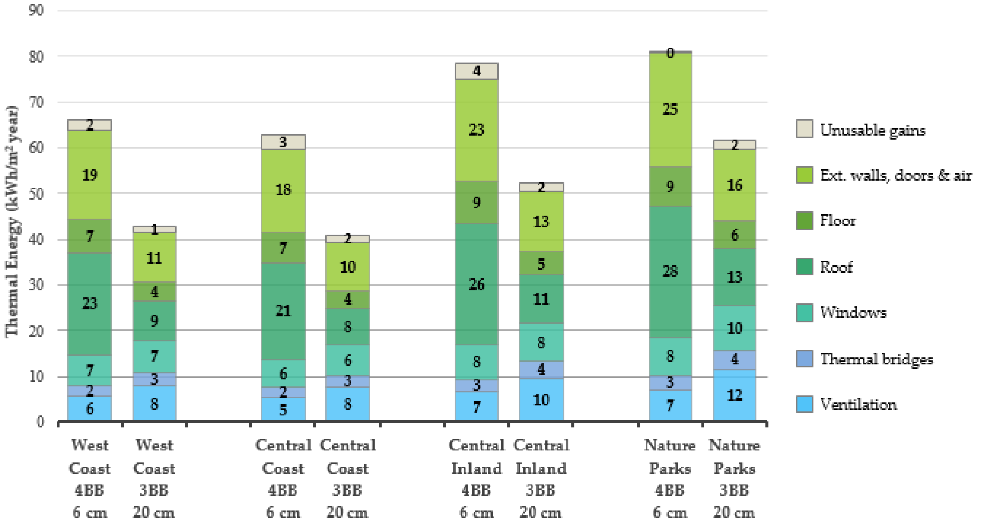
Temperatures in the central inland area are higher in the winter months than in the nature parks, while this trend is reversed in the summer months. The dew point is higher on the central coast than on the west coast, with a higher risk of condensation due to moisture. The dew point in the nature parks is much lower than at the other locations, so the risk of condensation due to moisture is lower there.

The energy balances for the representative locations are shown in Figure 3.4, for the case of the largest windows facing south (LW-SOUTH). The analysis was conducted at these locations for 4BB (to e_{XPS} = 6 cm) and 3BB (to e_{XPS} = 20 cm) in order to highlight the differences. These cases correspond to the extreme values of the Fc and Fwall parameters in Table 3.2: a shape factor (Fc) of 1.02 (4BB, 6 cm) and 1.34 (3BB, 20 cm) and an area ratio (Fwall) of 1.13 (4BB, 6 cm) and 1.66 (3BB, 20 cm). Total gains and losses vary for each sub-region, with the greatest differences among sub-regions being for 3BB (due to its higher Fc). Location in the nature parks increase 29% for 4BB and 50% for 3BB with respect to the central coast.

Heat losses are represented in Figure 3.4 (a). The most significant are transmission losses. External wall losses are very important, along with roof losses. Roof losses are the greatest for the 4BB building, because it has less insulation. For the 3BB building, which has more insulation, these losses are less important, although losses for the walls are greater than for the roof. Relative losses through the floor are not very great in either type of building, being somewhat higher in the nature parks. Transmission losses through windows vary little with the type of building, except in the case of the nature parks, and, like other transmission losses, they become greater when shifting from the coast to the inland nature parks. The percentages of transmission losses with respect to total losses are higher for 4BB, which has less insulation, ranging from 87% on the central coast to 91% in the nature parks. Changes are minor for 3BB and range from 77% on the central coast to 78% in the nature parks. Therefore, as the insulation increases, the percentage of transmission losses decreases and the differences between locations are smaller. Ventilation losses are essentially due to the increase in the number of occupants from 3 to 5 and the amount of air that enters due to infiltration, which increases with the size of the house, as it depends on its interior volume. However, when the calculation refers to the usable area, the 3BB presents higher values. When the location of the house changes from the central coast to the nature parks, the losses increase 36% for 4BB and 57% for 3BB due to the change in climate between these locations.

The heat gains are presented in Figure 3.4 (b). The most important are the solar gains, which for 4BB represent values comparable to the heating demands of the building, even with the thinnest insulation, except for the case of the nature parks, where the solar gains provide slightly more than half of the energy to be supplied for heating.

(a) DISTRIBUTION OF LOSSES (kWh/m² year)



(b) DISTRIBUTION OF GAINS (kWh/m² year)

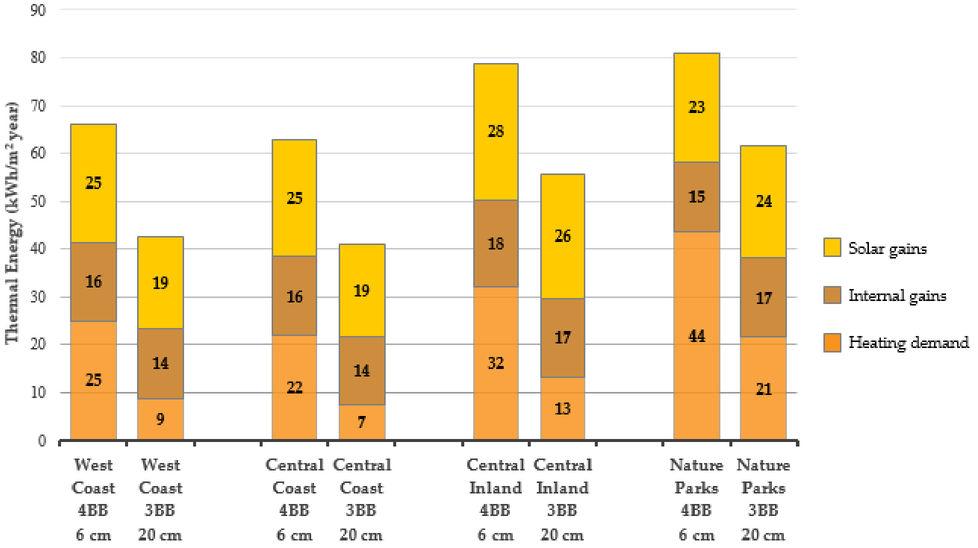


Figure 3.4. Thermal balances for the four locations, for the case of the largest windows facing south (LW-SOUTH), for 4BB (e_{XPS} = 6 cm) and 3BB (e_{XPS} = 20 cm): (**a**) Losses; (**b**) Gains.

For 3BB, the solar gains are much higher than the heating requirements, except for the case of the nature parks, where both magnitudes are similar, although the solar gains are somewhat higher. As for internal gains, these are similar for 4BB and 3BB and vary somewhat with climate and insulation. The calculated trends in heating demands considering the effects of the shape factor (Fc) and the area ratio (Fwall) are in agreement with Premrov et al 2018a, Premrov et al 2018b and Takano et al. 2015, who studied the variation of these factors for different types of buildings and climates.

Table 3.8 presents the heating and domestic hot water (DHW) demands for the eleven locations in the different sub-regions. At all the locations, the heating demand for the same insulation thickness is higher for 3BB, which has higher Fc values. It has also been shown in all eleven cases that the heating demand depends inversely on the shape factor, as noted in Premrov et al 2018a, Premrov et al 2018b and Takano et al. 2015.

Table 3.8. Heating and domestic hot water demand for the locations and insulation thickness.

Sub-region	**Location**	**4BB**					**3BB**				
		Heating demand					**Heating demand**				
		6 cm XPS	**12 cm XPS**	**20 cm XPS**	**30 cm XPS**	**DHW**	**6 cm XPS**	**12 cm XPS**	**20 cm XPS**	**30 cm XPS**	**DHW**
West Coast	Caridad	21	8	3	1	29	29	14	7	3	32
	Valdés	24	10	4	2	29	33	17	9	4	32
Central Coast	Luanco	21	9	4	2	29	28	14	7	4	32
	Gijón	21	9	4	1	29	29	14	7	4	32
Central Inland	Oviedo	31	15	7	4	29	42	23	13	8	32
	Entrego	29	13	6	3	29	39	21	12	7	32
Inland Nature Parks	Ibias	42	26	17	12	29	56	33	21	15	32
	Lena	31	17	9	5	29	41	22	13	7	32
	Aller	41	24	15	10	29	54	32	20	13	32
	Amieva	31	17	10	6	29	42	23	13	8	32
	Cabrales	32	18	10	6	29	43	24	14	8	32

Values in kWh/m^2 year

Concerning conformity with PHPP standards, for 12 cm thick or more insulation, demand is less than or equal to 15 kWh/m^2 year for 4BB in three of the sub-regions: west coast, central coast and central inland. However, in these three sub-regions, 3BB has a higher demand and at least 20 cm of insulation thickness would be required to reduce demand to 15 kWh/m^2 year or less. A special case is that of the nature parks, which have the highest thermal demands and require 30 cm of insulation. However, using such thick insulation in these locations increases the chance of overheating, so changes in the size and location of windows are likely to be required.

The calculation of domestic hot water includes the water consumption associated with the number of occupants of the house, plus the heat losses in the distribution of the water circuit and the water tank. It can be seen that this demand is very important for both houses and becomes relatively more important with increasing insulation. This was also highlighted in a technical note in Hassell 2016, which argues that, in UK households and in passive housing standards, DHW demand becomes more important as insulation increases. In passive house standards, DHW almost doubles heating needs, so it is very important to address this concept in passive houses. Therefore, in order to reduce the energy consumption for DHW, it would be necessary to additionally use other complementary renewable energy systems (e.g., photovoltaic or thermal solar panels).

3.3.1.2 Electricity Consumption

Three scenarios are considered to meet heating and DHW demands: (i) “Electricity only”, in which the total thermal demand is supplied only by electricity; (ii) “Heat pump + electricity”, in which the thermal demand is supplied by a heat pump, which heats the water up to 45°C (for low temperature heating), plus the electricity to power an element that heats the water from 45°C to 60°C necessary to store DHW; and (iii) “Natural gas boiler”.

The study includes the electricity-only scenario because, although it is not very common in single-family homes, it may become a very appropriate option in the future, seeing as the decarbonisation policies of European countries contemplate generating electricity with a significant amount of use of renewable energy for the 2030 and 2050 horizons.

Figure 3.5 and Figure 3.6 show the variation in the consumption of electrical energy with respect to the thickness of the insulation, respectively considering electricity only and heat pump plus electricity. Figure 3.5 corresponds to the case where the south-facing windows are the large ones and Figure 3.6 represents the case where south-facing windows are the small ones.

The same heat pump was considered for 4BB and 3BB, employing a seasonal coefficient of performance of 4. The curves representing the behaviour of 3BB are above those corresponding to 4BB, which means that 4BB has a better use of energy (due to its lower F_C value), regardless of the insulation thickness. The comparison between locations indicates that the lowest values are obtained for the central coast, followed by the west coast (both have very close values, the difference being slightly greater for 3BB). The difference in consumption is slightly greater for the central inland location and increases considerably in the location of the nature parks, which is further from the coast and at a higher altitude. As the thickness increases, all locations show very similar behaviour. Although consumption is influenced by DHW demand, DHW values practically do not vary with location and are essentially a function of the occupancy (higher for 4BB than for 3BB).

The heat pump significantly reduces the consumption of electrical energy, as it uses renewable energy. In fact, comparison of the two graphs shows that consumption is divided by a factor of at least two, being almost three for the lowest insulation thickness. The heat pump reduces the environmental impacts caused by electricity consumption during the stage of use of the buildings in the same proportion.

The effect of variation in the size of the south-facing windows can be appreciated by comparing Figure 3.5 and Figure 3.6. This effect is quite relevant on the consumption of electrical energy, although its magnitude depends on the insulation thickness. Considering, for example, the location on the central coast, when shifting from small south-facing windows (SW-SOUTH) to large south-facing windows (LW-SOUTH), the consumption for 4BB (e_{XPS} = 6 cm) decreases 18.59% when using electricity only and 11.99% when using a heat pump plus electricity; while the consumption for 3BB (e_{XPS} = 30 cm) increases 23.81% when using electricity only and 12.42% when using a heat pump plus electricity.

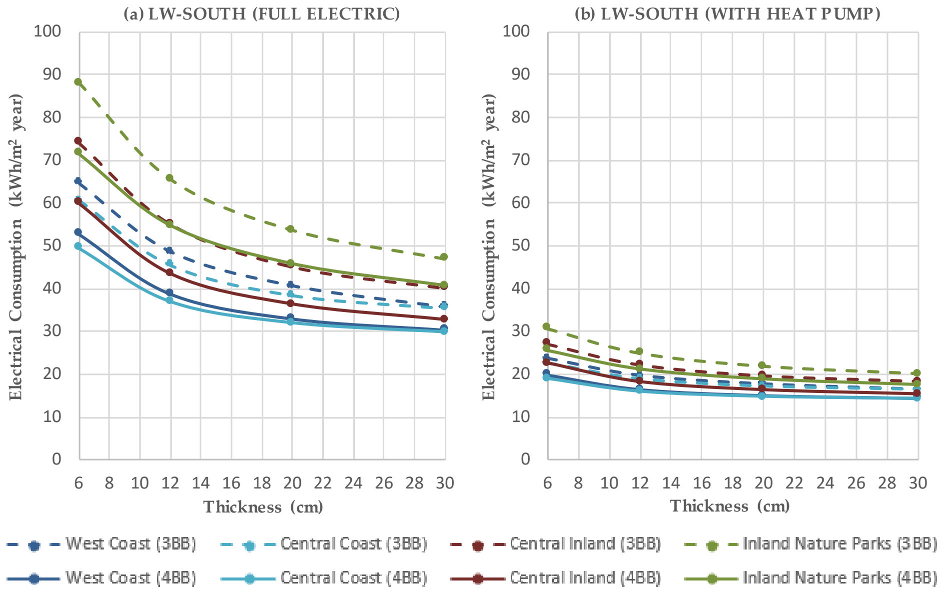


Figure 3.5. Electrical consumption according the insulation thickness for the four locations with LW-SOUTH for 4BB and for 3BB: (**a**) Electricity only; (**b**) Heat pump plus electricity.

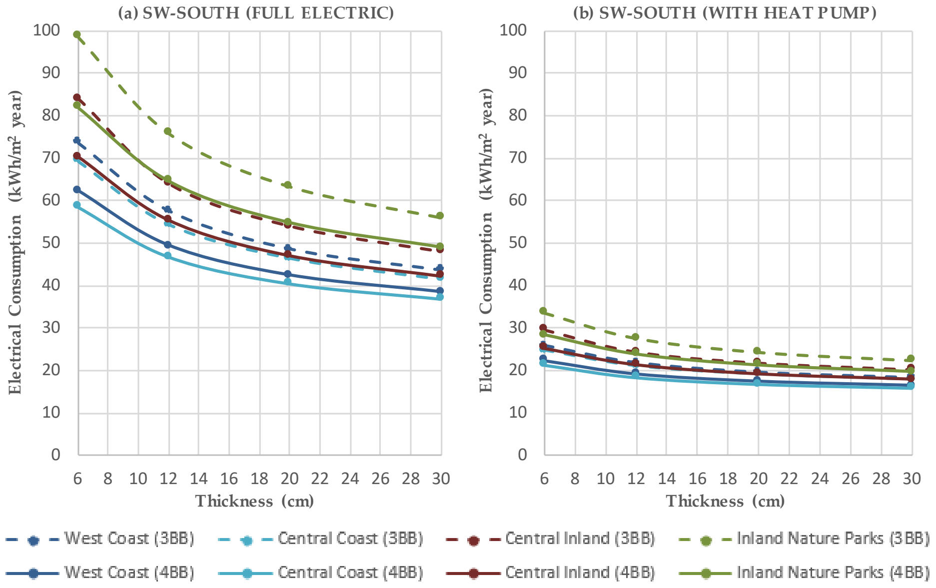


Figure 3.6. Electrical consumption according the insulation thickness for the four locations with SW-SOUTH for 4BB and for 3BB: (**a**) Electricity only; (**b**) Heat pump plus electricity.

3.3.1.3 Natural Gas Consumption

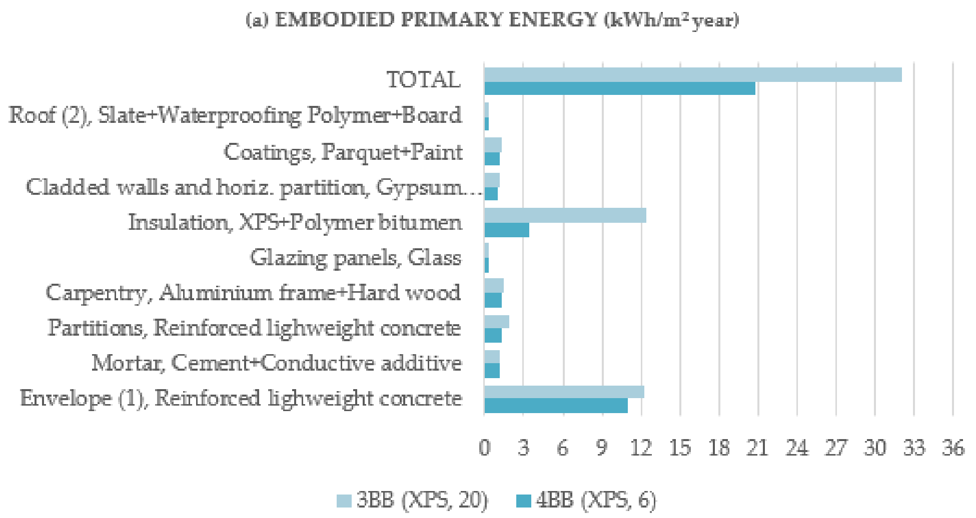
The behaviour for the scenario with a natural gas boiler is similar to that obtained for the electricity-only scenario, but the amount consumed in the case of gas increases because the thermal performance coefficient considered for the condensation boiler is 0.92 (in terms of the gross calorific value), which is less than 1 (the performance for the electricity only scenario).

3.3.2 Buildings Impacts

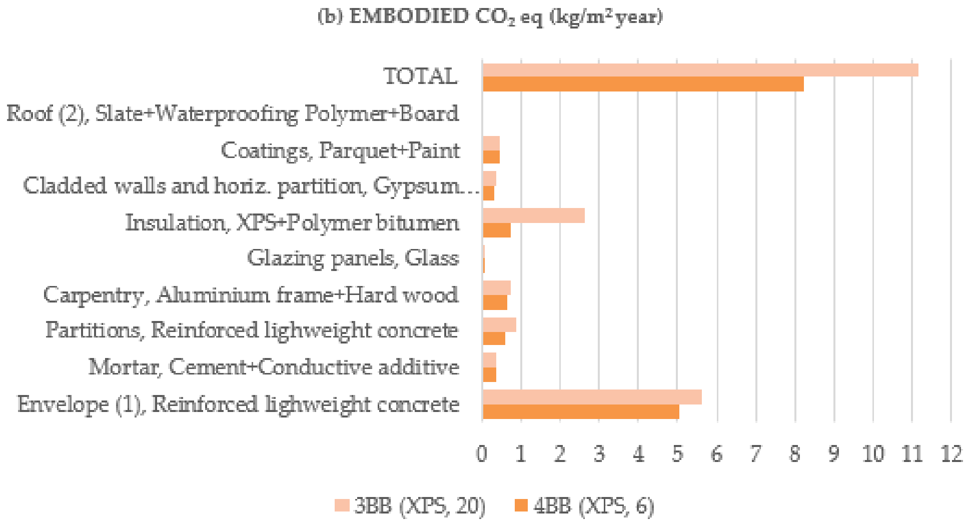
3.3.2.1 Construction of Buildings

Figure 3.7 shows the results of the embodied energy and CO_2 equivalent emissions taking into account the stages of manufacturing, transportation and construction of the building components. The impacts also take into account the inventory of materials in Table 3.3, along with the areas and thicknesses of those employed. The total values of the impacts of the components refer to the usable area of each building, as stated in Section 3.2.6. The label "Total" indicates the global impact of the building. The components of the construction elements are grouped into the categories indicated in the figure to highlight their impacts, rather than those of the construction elements.

The categories considered and the percentages for 4BB of EP and GWP are respectively: the envelope (reinforced lightweight concrete in exterior walls, roof and floor slab), 53 and 61%; mortar, 5 and 4%; vertical partitions of reinforced lightweight concrete, 6 and 7%; external walls (cladded on the inside) and horizontal partition of the attic; insulation (XPS) and polymer membranes, 16 and 9%; glazing panels, 1 and 1%; carpentry, 6 and 8%; coatings, 6 and 5%; and the roof (except XPS insulation and reinforced lightweight concrete), 1 and lower than 1%. The components that contribute the most are: the panels of the envelope, which are lightweight concrete (14 cm thick); the interior partitions, which are also lightweight concrete (8 cm thick); the sum of the insulation (XPS), the claddings and the horizontal partition, which includes glass wool; and the sum of carpentry and glazing.



(a) EMBODIED PRIMARY ENERGY (kWh/m² year)



(b) EMBODIED CO₂ eq (kg/m² year)

(1) Reinforced ligthweight concrete panels of the building envelope: walls, roof and floor slab.

(2) Roof without insulation and structural panels of reinforced lightweight concrete.

Figure 3.7. Impacts of the construction elements, by components, per m^2 of usable floor area for 4BB (e_{XPS} = 6 cm) and 3BB (e_{XPS} = 20 cm): (**a**) Embodied energy; (**b**) Equivalent of CO$_2$ emissions throughout the manufacturing, transport and construction stages.

Table 3.9 shows the embodied impacts for primary energy and CO$_2$ equivalent emissions according to the type of house and insulation thickness (e_{XPS} = 6 to 30 cm) for the building components. The impacts for the three stages were added: manufacturing of components (A1 + A2 + A3), transport (A4) and construction (A5). As with active systems, disposal was not considered. Insulation was shown to be one of the building components that generates the greatest impacts, which increase with the thickness used: for 4BB, a change in thickness from 6 to 30 cm increases EP by 64.43% and GWP by 34.59%; for 3BB, the increases are 63.39% for EP and 33.87% for GWP.

Table 3.9. Embodied cradle-to-grave impacts of the building components: primary energy and CO$_2$ equivalent emissions for 4BB and 3BB with various insulation thicknesses.

Thickness (cm)	4BB		3BB	
	Energy	**CO$_2$ eq**	**Energy**	**CO$_2$ eq**
	kWh/m^2 year	**kg/m^2 year**	**kg/m^2 year**	**kg/m^2 year**
6	20.75	8.24	23.41	9.33
12	24.10	8.95	27.12	10.12
20	28.55	9.90	32.07	11.17
30	34.12	11.09	38.25	12.49

Table 3.10 presents the embodied impacts for primary energy and CO$_2$ equivalent emissions according to the active system used. The impacts for the three stages were added: manufacturing of components (A1 + A2 + A3), transport (A4) and construction (A5). For both types of building, the impacts of the heat pump and gas boiler scenarios are greater than those of the scenario with electricity only, which is consistent with the greater complexity and quantity of materials used (heat supply equipment plus hydronic soil). It can be seen that: (i) the increase in embedded impacts due to active systems is slightly higher for the 3BB building; and (ii) the increases are greater in GWP than in EP. The increase in GWP ranges from 62.42% (3BB building with natural gas boiler) to 82.22% (4BB building with heat pump). The increase in EP ranges from 35.47% (4BB building with heat pump) to 42.53% (3BB building with natural gas boiler).

Table 3.10. Embodied cradle-to-grave impacts of the active technical systems: primary energy and CO_2 equivalent emissions for 4BB and 3BB.

Active systems scenario	**4BB**		**3BB**	
	Energy	**CO_2 eq**	**Energy**	**CO_2 eq**
	kWh/m^2 year	**kg/m^2 year**	**kWh/m^2 year**	**kg/m^2 year**
Electricity only	6.09	1.12	6.43	1.20
Heat pump + electricity	8.25	2.05	8.87	2.29
Natural gas boiler	8.42	1.77	9.17	1.95

3.3.2.2 Embodied and Use Impacts

Figure 3.8 and Figure 3.9 show the impacts EP and GWP due to the operational and embodied life cycle stages considering the scenarios of electricity only and heat pump plus electricity, respectively. Values were obtained using passage factors from final energy (energy consumption) to primary energy and from final energy to CO_2 equivalent emissions. These factors were calculated in González-Prieto et al. 2020 according to the Spanish electricity mix in 2018 and applying SimaPro software. The factors used are: 2.133 KWh EP/kWh consumed and 0.347 kg CO_2 eq/kWh consumed. Previous factors available for 2016 in IDAE 2016 are: 2.403 KWh EP/kWh consumed and 0.357 kg CO_2 eq/kWh consumed.

In Figure 3.8, which corresponds to the electricity-only scenario, it can be seen that the impacts of use vary greatly with location and thickness of insulation. Total impacts for EP vary from a minimum of 108 kWh/m^2 year for 4BB on the central coast, to a maximum of 224 kWh/m^2 year for 3BB in the inland nature parks. On the other hand, total impacts for GWP vary from a minimum of 23 kg CO_2 eq/m^2 year for 4BB on the central coast to a maximum of 42 kg CO_2 eq/m^2 year for 3BB in the inland nature parks. As shown in the graph, the EP impact of the use stage of buildings is always greater than that of their construction stages (including thermal systems), which represent embedded impacts. Likewise, the GWP impact due to the use stage is greater than that of the embodied impact, except for high thicknesses, where the use impact curves intersect with the embodied impact curves. For the central coast, the intersection corresponds approximately to e_{XPS} = 25 cm for 4BB and e_{XPS} = 26 cm for 3BB. For locations with higher demand, such as the central inland area, the intersection corresponds to e_{XPS}

= 30 cm for 4BB, and no intersection occurs for the location in the nature parks.

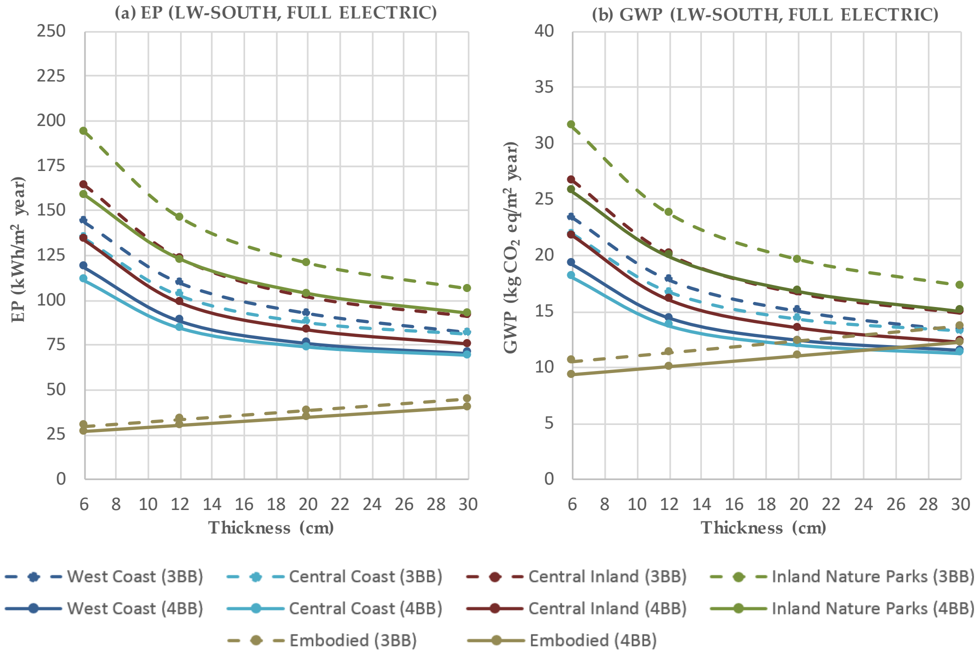


Figure 3.8. Embodied and use impacts of primary energy and CO_2 equivalent emissions for the electricity-only scenario, depending on insulation thickness, for the four locations, with LW-SOUTH both for 4BB and 3BB.

Figure 3.9, which represents the impacts of the heat pump plus electricity scenario, shows that the variation in use impacts with location and thickness is much lower than in the other two power system scenarios. Total EP impacts range from 72 kWh/m^2 year (4BB on the central coast) to 86 kWh/m^2 year (3BB in the inland nature parks). In terms of total GWP impacts, they range from 14 kg CO_2 eq/m^2 year (4BB on the central coast) to 22 kg CO_2 eq/m^2 year (3BB in the inland nature parks). The EP impact curves of the use stage and those of the construction stages of buildings (including thermal systems) intersect significantly in the analysed range of thicknesses. On the central coast, the intersection corresponds to about 18 cm for 4BB and about 20 cm for 3BB. For places with higher demand, the intersection occurs for a thickness of about 22 cm in the central inland area and about 30 cm in the inland nature parks. The impact of the GWP of the use stage is less than the embodied impact and there is no intersection of the curves, except for 4BB in the inland natural parks when the thickness is low.

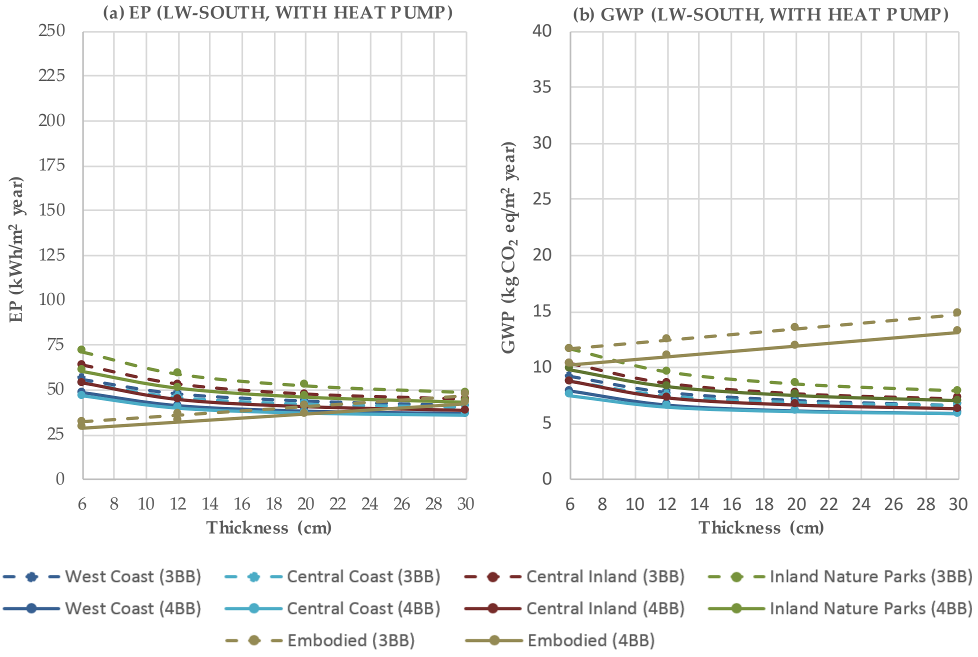


Figure 3.9. Embodied and use impacts of primary energy and CO_2 equivalent emissions for the heat pump plus electricity scenario, depending on insulation thickness, for the four locations, with LW-SOUTH both for 4BB and 3BB.

Figure 3.10 shows the impacts due to the operational energy considering the scenario of thermal demand covered with natural gas. Values were obtained using conversion factors from final energy (energy consumption) to primary energy and from final energy to CO_2 equivalent emissions, from the Spanish Institute for the Diversification and the Energy Savings (IDAE 2016). The latest factors available for natural gas correspond to 2016 and are: 1.195 KWh EP/kWh consumed and 0.252 kg CO_2 eq/kWh consumed. The behaviour is intermediate between the two previous scenarios. Total impacts for EP range from 78 kWh/m^2 year (4BB on the central coast) to 135 kWh/m^2 year (3BB in the inland nature parks), while total impacts for GWP vary from 20 kg CO_2 eq/m^2 year (4BB on the central coast) to 28 kg CO_2 eq/m^2 year (3BB in the inland nature parks). In this scenario, both in the case of EP and that of GWP, the embodied impact curves intersect those of the use impact, except in the case of EP in the interior nature parks. EP curves intersect when the insulation thickness is around 26 cm. GWP curves intersect for a thickness of about 10 cm in coastal areas and about 20 cm in inland natural parks.

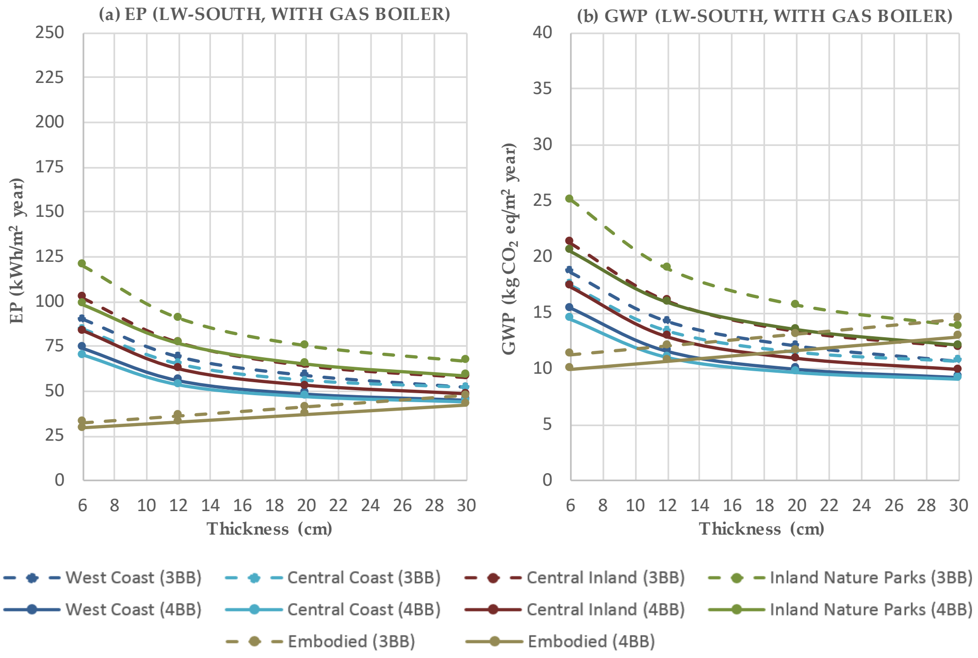


Figure 3.10. Embodied and use impacts of primary energy and CO_2 equivalent emissions for the natural gas boiler scenario, depending on insulation thickness, for the four locations, with LW-SOUTH both for 4BB and 3BB.

Figure 3.11 plots the electricity-only scenario for the 2030 horizon if the Spain's decarbonisation plan in Spanish Ministry of Ecological Transition 2019 is implemented. The coefficients of passage were obtained from González-Prieto et al. 2020, applying the SimaPro software for the electricity mix proposed for 2030, the forecast coefficients being 1.007 KWh EP/kWh consumed and 0.149 kg CO_2 eq/kWh consumed. In relation to the coefficients of passage for natural gas, these are kept constant. This scenario notably improves the impacts that are currently obtained with the 2016 passage factors, the behaviour being close to that of the heat pump at present, although with somewhat greater impacts on primary energy. EP impacts are similar to those of the natural gas boiler scenario. However, the positive effect of this system lies in the GWP impact value, which is close to that of the heat pump and is much lower than that obtained for the natural gas boiler scenario.

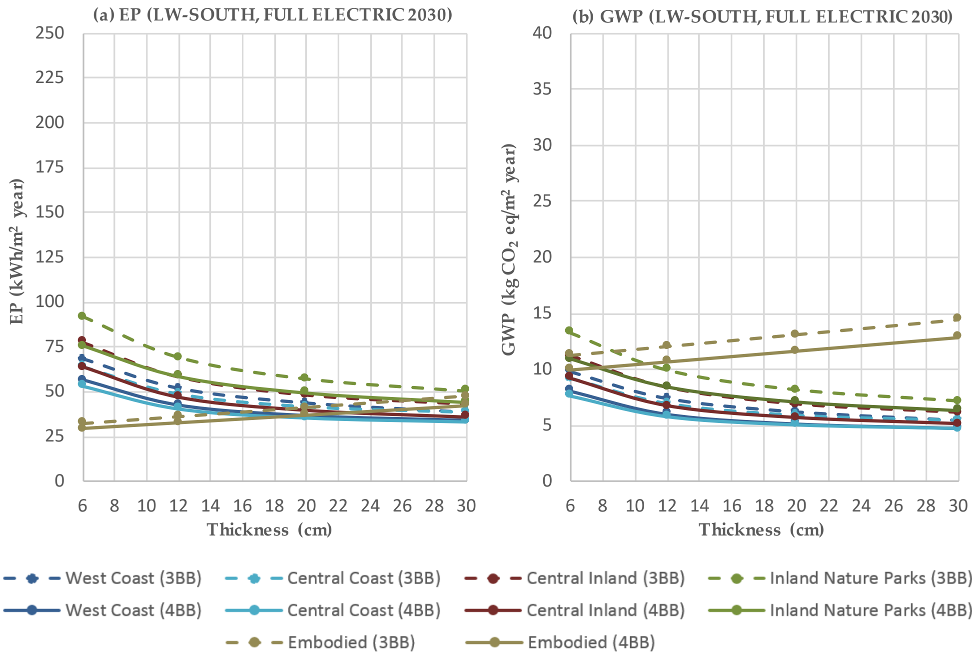


Figure 3.11. Embodied and use impacts of primary energy and CO_2 equivalent emissions for the electricity-only scenario in Spain's 2030 horizon (Spanish Ministry of Ecological Transition 2019; González-Prieto et al. 2020), depending on insulation thickness, for the four locations, with LW-SOUTH both for 4BB and 3BB.

3.3.3 Ratios of Impacts

The ratios of impacts are calculated by dividing the impacts of use by the total impacts (embodied in building materials and active systems plus use) from data plotted of primary energy and CO_2 equivalent emissions in Figure 3.8 to Figure 3.11.

Two criteria, applied to each energy supply scenario, are followed for the discussion of the results: (i) calculation of the average values considering all the thicknesses, sub-regions and buildings; and (ii) analysis of the maximum and minimum values considering each mode of energy supply. The results are shown in Table 3.11.

Table 3.11. Criteria for comparing the impacts for different energy supply scenarios.

Criteria	Impact	Scenario			
		Electricity only (2018) (1)	Heat pump + electricity (2018) (1)	Natural gas boiler (2016) (2)	Electricity only (2030) (1)
Average	EP	74.2	55.4	63.0	59.4
	GWP	59.3	38.0	52.5	40.4
Max (3BB, 6 cm)	EP	86.7	68.9	78.7	76.0
	GWP	75.0	50.0	69.0	57.2
Min (4BB, 30 cm)	EP	63.3	46.0	51.1	47.0
	GWP	48.0	30.9	41.4	30.5

(1) González-Prieto et al. 2020

(2) IDAE 2016

The average impact ratios for EP vary from 55.4% for heat pump plus electricity to 74.2% for electricity only, for the electricity mix in 2018. The EP value for the electricity-only scenario in 2030 is low: 59.4%, indicating that the effects of decarbonisation may lead to considering electricity as an environmentally-friendly scenario. As for the GWP average impact ratios, these decrease from 59.3% to 38.0% for the electricity-only and heat pump plus electricity scenarios in 2018, respectively. It is well known that the implementation of the Spanish decarbonisation plan may make the electricity-only scenario more environmentally friendly than the use of a natural gas boiler by 2030.

The maximum values of the proportions of impacts correspond to 3BB with 6 cm thick insulation in the nature parks, the case in which EP varies from 69.9% (heat pump plus electricity, in 2018) to 86.7% (electricity only, in 2018) and in which GWP varies from 50.0% to 75.0% in line with the same energy scenarios as EP. The minimum values of the impact ratios correspond to 4BB with 30 cm thick insulation on the central coast, the best scenario being the heat pump plus electricity in 2018, which has EP = 46.0% and GPW = 30.9%, followed by the electricity-only scenario in 2030, which has EP = 47.0% and GPW = 30.5%. Concerning the effects of the microclimate, 4BB presents higher percentages of improvement in impact ratios than 3BB with increasing insulation thickness, the percentage improvement being greater for the heat pump plus electricity scenario.

These findings demonstrate that the electricity-only scenario can be very suitable versus the gas boiler. However, the impacts of the electricity-only scenario will always be greater than those of the heat pump scenario, since if the electricity mix is improved, the improvement will also have a favourable effect on the heat pump impacts. On the other hand, the energy obtained from the air must also be taken into account. One of the aspects in which the heat pump could be disadvantageous compared to the electricity-only scenario, would be damage to the ozone layer, which is a very important impact to consider.

3.4 Discussion

In the calculation of use demands, the importance of the demand for DHW was highlighted for the studied buildings, which have a high level of insulation. The demand for DHW is twice that of the demand for heating, a fact that has also been highlighted in Hassell 2016 for other buildings with a high level of insulation. The heating demands calculated in this work for sub-regional Atlantic climates depend inversely on the shape factor, as observed for other buildings and climates in Premrov et al 2018a, Premrov et al 2018b and Takano et al. 2015.

From the present study, it was found that the embodied primary energy depends on the insulation level and the shape factor, with values ranging from 26.8 kWh/m^2 year (4BB, $e_{XPS} = 6$ cm) to 47.4 kWh/m^2 year (3BB, to $e_{XPS} = 30$ cm). Data in the literature show dependence on lifespan, usable floor area and construction materials. Lifespan ranges from 40 to 100 years in previous works, as reported in the review by Karimpour et al. 2014. Mithraratne et al. 2004 studied an individual house in New Zealand with 90 m^2 of usable floor area, a 100-year lifespan and built in concrete, obtaining an embodied primary energy of 13 kWh/m^2 per year, a result that is not so far from that calculated in the current study, bearing in mind that the latter corresponds to a 50-year lifespan. Ramesh et al. 2012 carried out a life cycle energy analysis in different climatic zones of India for a residential building with 85.5 m^2 of usable floor area, a 75-year lifespan and built using aerated concrete for the envelope. They obtained a value of 27 kWh/m^2 year of embodied primary energy and an operational energy of 167 kWh/m^2 year.

In general, it is observed that, although the values of embodied energy may be more in agreement, this is not the case of those of energy use. This result is reasonable, seeing as the technologies for obtaining and manufacturing materials have similar efficiencies everywhere. However, energy use is highly dependent on the climate and the technology used for its supply. In addition to this, it depends on the country's energy mix, which has a major influence on the results. As for CO_2 equivalent emissions, this is an impact related to the system used for energy supply, which is strongly linked to the country's mix in the case of electricity.

The average data (for all locations and thicknesses studied) obtained for primary energy and CO_2 equivalent emissions are in keeping with data reported in the literature for mild climates. Data normalized in kWh/m^2 year of embodied and operational energy were summarized from a literature review in Karimpour et al. 2014 for several buildings with a usable net area from 50 to 130 m^2 and in a variety of climates and construction technologies. The ratio of embodied to total was found to be around 25% for primary energy and 35% for CO_2 eq emission in mild climates. The primary energy in Karimpour et al. 2014 falls within the range of the results obtained in the current study, in which the embodied energy varies on average from 25.80% to 44.60% of the total energy, as the energy use varies on average from 74.20% to 55.40% of the total energy, depending in both cases on the energy scenario (the extreme values corresponding to the electricity-only and heat pump plus electricity). Similarly, average CO_2 equivalent emissions range from 25.03% to 69.13%, when expressed as embodied-to-total ratio, and from 74.97% to 30.87%, when expressed as use-to-total ratio.

Moschetti et al. 2015 analysed the sustainability of buildings with different typologies and climates in Italy. In their paper, the lifespan was considered to be 50 years and the aspects of sustainability that were studied include total primary energy and climate change. Several energy supply systems were also analysed, including one with a natural gas boiler and another with electrical energy from the energy mix in Italy. Although various types of buildings were studied and the energy demands were established for insulation thicknesses lower than those of the present study, both the methodology and the global trends show similarities. The values of the total primary energy found in [18] range from 69 to 121 kWh/m^2 year, the stage of energy of use representing 75% on average, while the values obtained in the present study range from 51.1 kWh/m^2 year (Spanish energy mix) to 88.7 kWh/m^2 year (gas boiler). The differences in values are related to the different types of buildings and the different levels of insulation used. Regarding the impact of climate change, the average value in Moschetti et al. 2015 is 34.2 kg CO_2 eq/m^2 year, while in the present study the values range from 41.4 kg CO_2 eq/m^2 year (Spanish energy mix) to 75.0 kg CO_2 eq/m^2 year (gas boiler). As in the present study, in Moschetti et al. 2015 it was found that the GWP values are greatly defined by the energy supply system.

For their part, Leskovar et al. 2019 carried out a study comparing several typologies of wooden buildings (cross-laminated timber) with similar construction characteristics, a high degree of insulation and different form factors. The buildings were located in a Dfb climate-classified region of Central Europe, with cold winters and hot summers. The active systems consisted of an air conditioning unit, the system for heating the domestic hot water not being clearly specified. The environmental study was carried out for a lifespan of the building of 50 and 100 years. Regarding the analysed impacts, non-renewable primary energy and global warming were evaluated, in addition to the potential for acidification. Although the materials are very different from those used in the present study, the overall trends regarding the effects of the form factor are similar when comparing the two buildings in this study (67.0 m^2 for 3BB and 121.3 m^2 for 4BB) with the two buildings in Leskovar et al. 2019 that have the closest size to them (42.3 and 84.5 m^2), the thermal behaviour and effect of impacts being better when the form factors are smaller (the case of the larger building). The total global warming potential for these buildings in Leskovar et al. 2019 is 23 and 29 kg CO_2 eq/m^2 year, respectively, the GWP impact of use representing 73% in both cases. These values are lower than those calculated in the present study due to the use of laminated wood in the structure of buildings in Leskovar et al. 2019, instead of lightweight concrete panels.

3.5 Conclusions

The relative importance of embodied and use impacts of buildings is increasingly changing because of the application of energy efficiency and environmental directives. In this work, these impacts are investigated for single-family houses with lightweight concrete envelopes in sub-regions of northern Spain presenting different Atlantic microclimates. The effects of varying the insulation thickness, compactness, size of the windows and three scenarios of thermal energy supply (electricity only, heat pump plus electricity and gas boiler) are calculated.

The use of electricity only has impacts on primary energy and on climate change that almost triple those calculated for heat pumps and there is greater variation with the microclimate.

For the heat pump and for the gas boiler, the embodied impact can exceed the impacts of use, hence the interest in achieving insulation with less environmental impact and in using insulation thicknesses according to the climate.

The current Spanish electric energy mix does not have sufficient supply of renewable energy to compete in terms of environmental impacts with the use of the heat pump and natural gas. However, although the heat pump will continue to be a very sustainable system in the long term, natural gas may no longer have the environmental advantages it currently has if environmental policies planned for Spain are implemented by the 2030 horizon.

As future work, aimed at improving the life cycle analysis, it would be convenient to carry out a broader-reaching study that considers the variation in lifespan and the recycling of lightweight concrete. This would help in future decisions to select the most appropriate material for each microclimatic sub-region.

Chapter 4. Environmental Life-Cycle Assessment of a Nineteenth-Century Building Retrofitting in Electricity Decarbonisation Scenarios

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

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

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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, 2010/31/EU; Directive, 2012/27/EU; Directive 2018/844/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 28,702, Italy with 27,269, UK with 25,472 and Spain with 20,823 (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 1990s 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.

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Chapter 5. Use of Economic Indicators for Environmental Assessment of an Office Building Refurbishment

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Chapter 6. General Conclusions and Future Work

6.1 General Conclusions

The studies carried out show the importance of the combined effects of the decarbonisation plan and climate change, based on the environmental impacts caused by the electricity required to meet thermal demands. The combined effects for Spanish climates and single-family homes lead to a forecast of damage reduction in Human Health (59–68%), Climate Change (57–67%) and Resources (54–65%). However, the damage to the Ecosystem Quality will increase (5-28%), as a result of the greater impact in this category of damage of the energy production scenario for 2030, even despite the lower thermal requirements expected in homes for that year.

Atlantic microclimates in northern Spain can vary the requirements for adequate insulation and, consequently, the operational energy use. However, even for houses with a good level of insulation, the use-to-total impact ratios vary significantly: from 46% to 87% for primary energy and from 31% to 75% for global warming potential, depending on the shape factor of the house, the microclimate and the heat supply scenario. By applying future environmental policies, electricity can become a more environmentally friendly option than natural gas.

The life cycle assessment (LCA) prior to the retrofit of an office building classified as of cultural interest, reveals the possibility of being respectful with the environment even for the current energy mix if active systems are implemented in the building itself. For the 2018 Spanish electricity mix, the results of this work highlight the possibility of reducing the global warming potential (GWP) from 59 to 25% and the cumulative energy demand (CED) from 69 to 31%, by combining the previous measures.

For the scenario in which energy demands are fully covered by the electricity mix, impacts in 2030 will decrease by 40% for GWP and 15% for CED, compared to 2018. These reductions will further increase, up to 54% and 61%, respectively, if photovoltaic panels are implemented in combination with a heat pump.

The use of economic indicators for environmental assessment has been shown in this work to be a very useful tool for selecting the best intervention when choosing the active systems and construction elements of the envelope of buildings. Two studies have been made of the refurbishment of an office building, with multiple scenarios each. The indicators (payback, net present value and return on investment) allow, when used together, to have a global vision of the best option (for retrofitting, in this case), even when so many cases are considered, each one taking into account not only the economic investment, but six environmental impacts (in the few antecedents in the literature, one or two indicators are usually studied, with one or two impacts, applied to a small number of cases). For the analysed office building, the most recommended intervention would be the installation consisting of photovoltaic panels and a heat pump, without improving the envelope.

6.2 Future Work

The life cycle processes related to the exploitation of waste through the reuse or manufacture of new products that can be reincorporated in buildings or used for other purposes is still little analysed. This is also due to a scarcity of data on the treatment processes, as well as the low rate of generation of deconstruction materials. Therefore, it is proposed as a possible future work, the incorporation to the studies of stage D of the life cycle, according to its definition in UNE-EN 15978:2012: Supplementary information - Benefits and loads beyond the system boundary, which includes the sub-stages of re-use, recovery and recycling potential.

Another possible line of work would be to extend the life cycle study to a neighbourhood in Gijón (Asturias), including the deconstruction and rehabilitation of buildings, and in such a way that, as a whole, a nearly zero-energy neighbourhood is obtained. Regarding own energy systems, it is proposed to install solar panels at the neighbourhood level on the current roofs, as well as the inclusion of centralized heat pumps with heating and DHW supply for the entire neighbourhood.

Urban centres with high building compactness and envelopes with a high capacity to absorb and reflect heat, without elements of climate regulation in the urban environment, must be reconsidered in the future. The rise in temperature on the planet will increase the heat island effect more and more, so that comfort in the city will be relevant and will lead to the need for thermal comfort design projects at the neighbourhood level. More and more elements will be introduced to reduce warming: strategic shading, green areas or systems that improve evaporative cooling, artificial water reservoirs, etc. All these aspects should also be the subject of future research.

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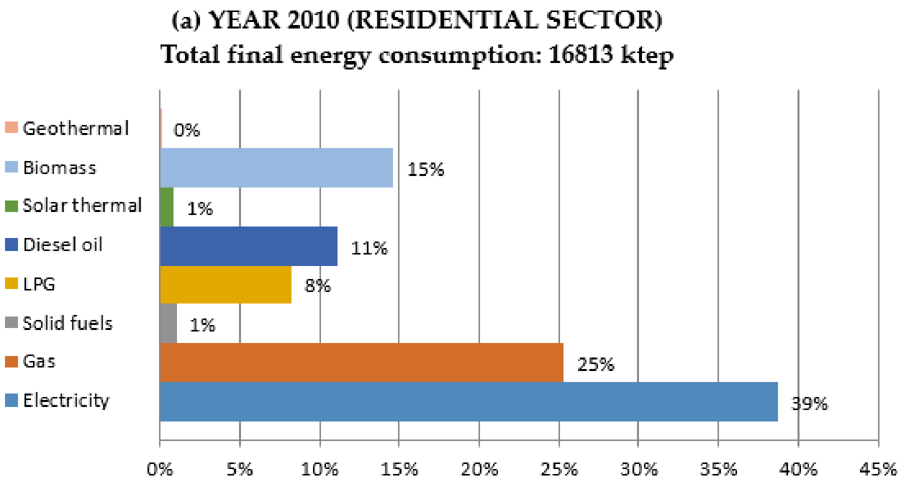
Appendices

Appendix A. Supplementary Materials for Chapter 1

A.1. Consumption for Uses and Energies in the Residential sector

Consumption for the residential sector (2010-2018), by uses and energy sources, expressed in energy units, in IDAE 2018a:



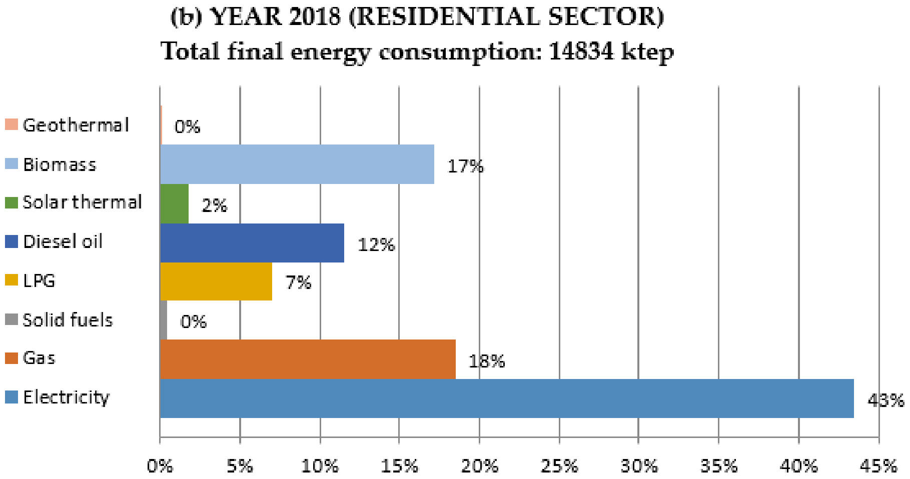


Figure A.1. Total final energy consumption in the residential sector, including heating, cooling, DHW, kitchen, lighting and appliances. Years: (**a**) 2010; (**b**) 2018. In IDAE 2018a (own elaboration).

A.2. Details of Consumption in the Services Sector

Energy consumption (2018), by branches of the services sector and energy sources, expressed in energy units, in IDAE 2018a:

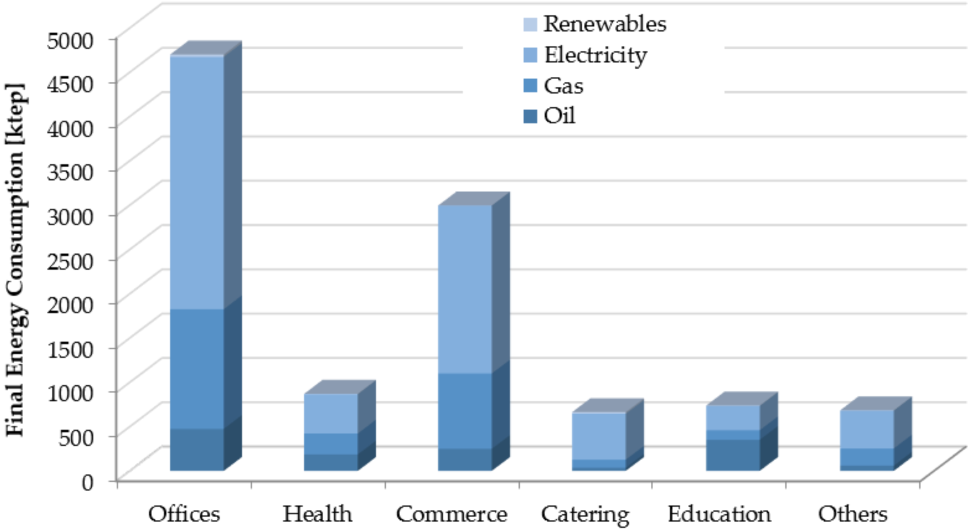
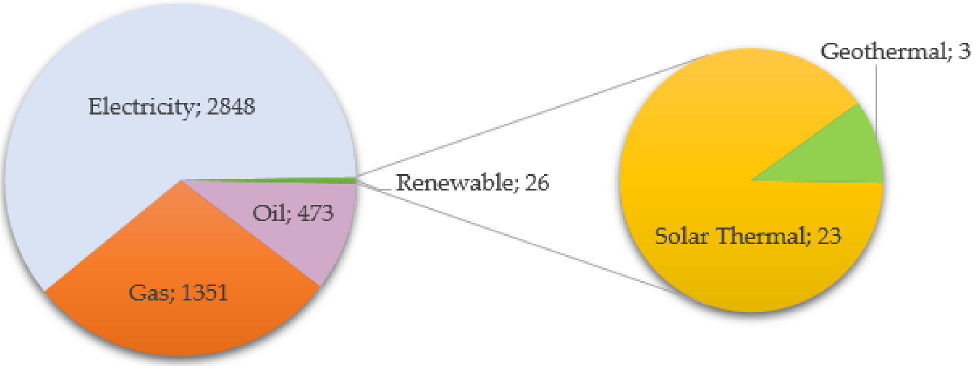


Figure A.2. Final energy consumption (2018), by branches of the services sector and energy sources, in IDAE 2018a (own elaboration).



(Energy units: ktep)

(Public and private offices are included; sources do not include biomass or biogas, because there is no disaggregated data for this subsector)

Figure A.3. Final energy consumption (2018), by energy sources in the offices subsector, in IDAE 2018a (own elaboration).

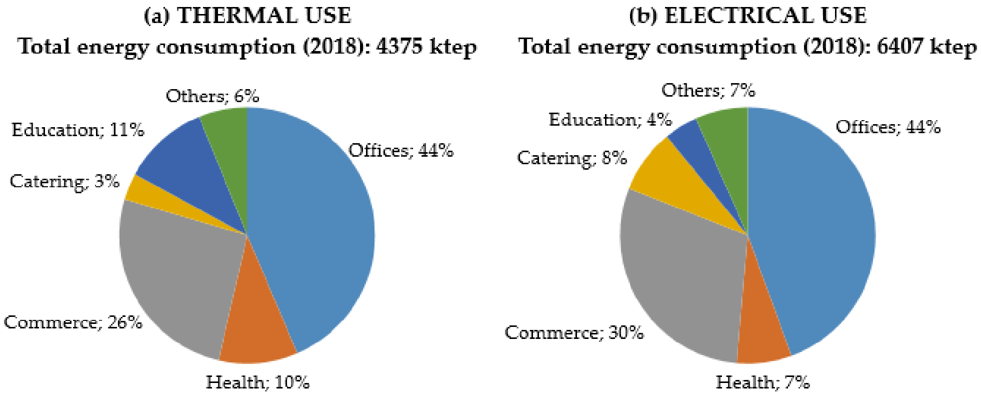


Figure A.4. Final energy consumption (2018), by branches of the services sector, for: (**a**) thermal use; (**b**) electrical use. In IDAE 2018a (own elaboration).

Appendix B. Supplementary Materials for Chapter 2

B.1. Processes Contribution to Impact Categories of 2018, 2020 and 2030 Electricity Generation Scenario

The abbreviations and acronyms included in the following tables are in concordance with the terms used in Ecoinvent v3.3(2016):

AU	Australia
BR	Brazil
CA-QC	Canada, Quebec
CH	Switzerland
CN	China
DE	Germany
ES	Spain
GLO	Global (represents activities which are considered to be an average valid for all countries in the world)
ID	Indonesia
IN	India
RAS	Asia
RFC	Reliability First Corporation
RLA	Latin America and the Caribbean
RoW	Rest-of-the-World
SE	Sweden
SERC	The SERC region lies within the Eastern Interconnection, and includes the states of Missouri, Alabama, Tennessee, North Carolina, South Carolina, Georgia, Mississippi, Iowa, Illinois, Kentucky, Virginia, Oklahoma, Arkansas, Louisiana, Texas and Florida
US	United States
ZA	South Africa

These geographic locations are reported using internationally accepted shortcuts

Table B.1. Processes contribution to Respiratory Inorganics (kg PM2.5 eq) impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14; Cut-off: 0.5%).

Process	**2018**	**2020**	**2030**
Electricity, high voltage {IN} electricity production, lignite	3.22×10^6	3.40×10^6	4.88×10^6
Electricity, high voltage {ES} electricity production, hard coal	5.41×10^7	4.89×10^7	4.68×10^6
Electricity, high voltage {ES} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	1.21×10^6	1.85×10^6	4.66×10^6
Electricity, high voltage {ES} electricity production, oil	3.81×10^6	5.80×10^6	3.20×10^6
Electricity, high voltage {ID} electricity production, lignite	9.90×10^5	1.07×10^6	1.82×10^6
Electricity, high voltage {ES} electricity production, lignite	1.93×10^7	1.74×10^7	1.67×10^6
Natural gas, high pressure {RoW} natural gas production	1.50×10^6	1.41×10^6	1.34×10^6
Digester sludge {GLO} treatment of digester sludge, municipal incineration	3.08×10^5	4.70×10^5	1.18×10^6
Electricity, high voltage {RFC} electricity production, lignite	7.78×10^5	8.38×10^5	1.12×10^6
Electricity, high voltage {ZA} electricity production, hard coal	1.12×10^6	1.05×10^6	1.02×10^6
Electricity, high voltage {SERC} electricity production, lignite	6.83×10^5	7.37×10^5	9.91×10^5
Electricity, high voltage {ES} electricity production, natural gas, combined cycle power plant	7.73×10^5	7.63×10^5	8.56×10^5
Diesel, burned in diesel-electric generating set, 10MW {GLO} diesel, burned in diesel-electric generating set, 10MW	8.26×10^5	9.27×10^5	6.99×10^5
Diesel, burned in building machine {GLO} processing	6.10×10^5	6.05×10^5	6.55×10^5
Electricity, high voltage, for internal use in coal mining {RoW} electricity production, hard coal, at coal mine power plant	4.31×10^5	3.53×10^5	6.08×10^5
Blasting {RoW} processing	8.62×10^5	8.07×10^5	5.92×10^5

Process	2018	2020	2030
Electricity, for reuse in municipal waste incineration only {ES} treatment of municipal solid waste, incineration	5.75×10^5	5.92×10^5	5.91×10^5
Copper concentrate {RAS} copper mine operation	3.94×10^5	4.27×10^5	5.80×10^5
Natural gas, high pressure {US} natural gas production	4.89×10^5	4.69×10^5	4.82×10^5
Coke {RoW} coking	7.38×10^5	2.95×10^5	4.60×10^5

Table B.2. Processes contribution to Non-Carcinogens (kg C_2H_3Cl eq) impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14; Cut-off: 1%).

Process	2018	2020	2030
Wood ash mixture, pure {Europe without Switzerland} treatment of wood ash mixture, pure, landfarming	1.26×10^8	1.93×10^8	4.83×10^8
Digester sludge {GLO} treatment of digester sludge, municipal incineration	4.32×10^7	6.59×10^7	1.66×10^8
Copper {RAS} production, primary	1.09×10^8	1.18×10^8	1.61×10^8
Copper {RoW} production, primary	1.00×10^8	1.09×10^8	1.47×10^8
Copper {RLA} production, primary	9.16×10^7	9.92×10^7	1.35×10^8
Electricity, high voltage {ES} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	2.21×10^7	3.39×10^7	8.52×10^7
Natural gas, unprocessed, at extraction {GLO} production	5.80×10^7	5.43×10^7	5.18×10^7
Redmud from bauxite digestion {RoW} treatment of, residual material landfill	1.55×10^7	1.97×10^7	4.96×10^7
Sugarcane {BR} production	3.76×10^7	3.94×10^7	4.61×10^7
Sinter, iron {GLO} production	7.51×10^7	2.90×10^7	4.30×10^7
Natural gas, high pressure {US} market for	4.31×10^7	4.13×10^7	4.25×10^7
Uranium tailing, non-radioactive emission {GLO} treatment of	4.63×10^7	5.07×10^7	2.52×10^7
Copper {AU} production, primary	1.57×10^7	1.70×10^7	2.31×10^7
Lead smelter slag {GLO} treatment of, residual material landfill	1.33×10^7	1.47×10^7	2.30×10^7
Dust, unalloyed electric arc furnace steel {RoW} treatment of, residual material landfill	1.06×10^7	1.21×10^7	2.10×10^7
Natural gas, high pressure {US} natural gas production	1.80×10^7	1.72×10^7	1.77×10^7

Table B.3. Processes contribution to Carcinogens (kg C_2H_3Cl eq) impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14; Cut-off: 0.5%).

Process	2018	2020	2030
Natural gas, high pressure {RoW} natural gas production	9.62×10^8	9.01×10^8	8.60×10^8
Natural gas, high pressure {US} natural gas production	3.14×10^8	3.01×10^8	3.09×10^8
Coke {RoW} coking	7.78×10^7	3.11×10^7	4.85×10^7
Steel, low-alloyed {RoW} steel production, electric, low-alloyed	2.42×10^7	2.74×10^7	4.54×10^7
Electricity, high voltage {ES} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	7.78×10^6	1.19×10^7	3.00×10^7
Digester sludge {GLO} treatment of digester sludge, municipal incineration	4.65×10^6	7.09×10^6	1.78×10^7
Steel, low-alloyed {RER} steel production, electric, low-alloyed	8.80×10^6	9.97×10^6	1.65×10^7
Copper {RAS} production, primary	1.07×10^7	1.16×10^7	1.58×10^7
Wood ash mixture, pure {Europe without Switzerland} treatment of wood ash mixture, pure, landfarming	4.01×10^6	6.13×10^6	1.54×10^7
Copper {RoW} production, primary	9.84×10^6	1.07×10^7	1.45×10^7
Copper {RLA} production, primary	9.00×10^6	9.75×10^6	1.32×10^7
Water discharge from petroleum/natural gas extraction, onshore {GLO} treatment of	9.85×10^6	1.34×10^7	9.91×10^6
Sinter, iron {GLO} production	1.69×10^7	6.52×10^6	9.68×10^6
Natural gas, high pressure {US}	8.45×10^6	8.10×10^6	8.33×10^6
Electricity, high voltage {ES} treatment of coal gas, in power plant	4.90×10^7	4.49×10^5	1.11×10^6

Table B.4. Processes contribution to Terrestrial Ecotoxicity (kg TEG soil) impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14; Cut-off: 0.5%).

Process	2018	2020	2030
Wood ash mixture, pure {Europe without Switzerland} treatment of wood ash mixture, pure, landfarming	4.00×10^{11}	6.11×10^{11}	1.53×10^{12}
Distribution network, electricity, low voltage {RoW} construction	6.45×10^{11}	7.03×10^{11}	9.39×10^{11}
Transmission network, electricity, medium voltage {RoW} construction	2.36×10^{11}	2.37×10^{11}	2.38×10^{11}
Blasting {RoW} processing	3.01×10^{11}	2.82×10^{11}	2.07×10^{11}
Drilling waste {CH} treatment of, landfarming	1.21×10^{11}	1.36×10^{11}	1.13×10^{11}
Blasting {RER} processing	1.49×10^{11}	1.39×10^{11}	1.02×10^{11}
Electricity, high voltage {ES} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	2.36×10^{10}	3.61×10^{10}	9.10×10^{10}
Transmission network, electricity, medium voltage {CH} construction	8.32×10^{10}	8.33×10^{10}	8.39×10^{10}
Copper {RAS} production, primary	5.27×10^{10}	5.71×10^{10}	7.74×10^{10}
Copper {RoW} production, primary	4.83×10^{10}	5.23×10^{10}	7.10×10^{10}
Copper {RLA} production, primary	4.42×10^{10}	4.79×10^{10}	6.50×10^{10}
Uranium tailing, non-radioactive emission {GLO} treatment of	9.73×10^{10}	1.06×10^{11}	5.30×10^{10}
Ferrochromium, high-carbon, 68% Cr {GLO} production	1.64×10^{10}	1.89×10^{10}	3.00×10^{10}

Table B.5. Processes contribution to Land occupation (m^{2}org.arable) impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14; Cut-off: 0.5%).

Process	2018	2020	2030
Photovoltaic mounting system, for 570kWp open ground module {GLO} production	2.99×10^8	4.95×10^8	1.93×10^9
Wood chips, wet, measured as dry mass {SE} hardwood forestry, birch, sustainable forest management	3.09×10^8	4.69×10^8	1.17×10^9
Wood chips, wet, measured as dry mass {SE} softwood forestry, pine, sustainable forest management	2.35×10^8	3.57×10^8	8.90×10^8
Wood chips, wet, measured as dry mass {SE} softwood forestry, spruce, sustainable forest management	2.28×10^8	3.47×10^8	8.64×10^8
Wood chips, wet, measured as dry mass {DE} hardwood forestry, beech, sustainable forest management	1.70×10^8	2.58×10^8	6.43×10^8
Wood chips, wet, measured as dry mass {DE} softwood forestry, spruce, sustainable forest management	8.36×10^7	1.27×10^8	3.16×10^8
Wood chips, wet, measured as dry mass {DE} softwood forestry, pine, sustainable forest management	5.83×10^7	8.86×10^7	2.21×10^8
Wood chips, wet, measured as dry mass {DE} hardwood forestry, oak, sustainable forest management	3.23×10^7	4.91×10^7	1.22×10^8
Road {RoW} road construction	2.85×10^7	3.33×10^7	5.75×10^7
Alfalfa-grass silage {RoW} alfalfa/grass silage production	1.37×10^7	2.08×10^7	5.18×10^7
Soybean {US} production	1.23×10^7	1.83×10^7	4.48×10^7
Wind power plant, 800kW, fixed parts {GLO} construction	1.75×10^7	2.14×10^7	4.06×10^7
Transmission network, electricity, high voltage {CA-QC} transmission network construction, electricity, high voltage	2.87×10^7	2.94×10^7	3.16×10^7
Hard coal {RoW} mine operation	2.01×10^8	1.81×10^8	2.35×10^7
Biogas {RoW} treatment of biowaste by anaerobic digestion	5.99×10^6	9.13×10^6	2.29×10^7
Hard coal {CN} mine operation	1.43×10^7	1.17×10^7	2.01×10^7

Process	2018	2020	2030
Wood chips, wet, measured as dry mass {RoW} hardwood forestry, birch, sustainable forest management	1.54×10^7	1.62×10^7	1.97×10^7
Soybean {BR} production	4.98×10^6	7.38×10^6	1.80×10^7
Sulfidic tailing, off-site {GLO} treatment of	1.14×10^7	1.24×10^7	1.74×10^7

Table B.6. Processes contribution to Terrestrial Acidification/nutrification (kg SO_2 eq) impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14; Cut-off: 0.85%).

Process	2018	2020	2030
Electricity, high voltage {ES} heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	4.83×10^7	7.40×10^7	1.86×10^8
Electricity, high voltage {ES} electricity production, oil	1.19×10^8	1.82×10^8	1.00×10^8
Electricity, high voltage {ES} electricity production, hard coal	9.71×10^8	8.76×10^8	8.39×10^7
Digester sludge {GLO} treatment of digester sludge, municipal incineration	1.08×10^7	1.65×10^7	4.14×10^7
Electricity, high voltage {ES} electricity production, natural gas, combined cycle power plant	2.87×10^7	2.83×10^7	3.18×10^7
Blasting {RoW} processing	4.25×10^7	3.98×10^7	2.92×10^7
Electricity, high voltage {ZA} electricity production, hard coal	2.81×10^7	2.65×10^7	2.57×10^7
Natural gas, high pressure {RoW} natural gas production	1.93×10^7	1.80×10^7	1.72×10^7
Diesel, burned in building machine {GLO} processing	1.52×10^7	1.51×10^7	1.64×10^7
Electricity, high voltage {ES} heat and power co-generation, natural gas, conventional power plant, 100MW electrical	2.89×10^7	2.49×10^7	1.59×10^7
Diesel, burned in diesel-electric generating set, 10MW {GLO} diesel, burned in diesel-electric generating set, 10MW	1.80×10^7	2.02×10^7	1.52×10^7
Blasting {RER} processing	2.10×10^7	1.97×10^7	1.44×10^7
Electricity, for reuse in municipal waste incineration only {ES} treatment of municipal solid waste, incineration	1.35×10^7	1.39×10^7	1.39×10^7
Electricity, high voltage {ES} heat and power co-generation, oil	1.56×10^7	2.37×10^7	1.31×10^7
Transport, freight, sea, transoceanic ship {GLO} processing	2.27×10^7	1.73×10^7	1.12×10^7
Electricity, high voltage {ES} electricity production, lignite	3.64×10^7	3.28×10^7	3.14×10^6
Hard coal {RoW} mine operation	2.10×10^7	1.88×10^7	2.44×10^6

Table B.7. Processes contribution to Global Warming (kg CO_2 eq) impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14; Cut-off: 0.8%).

Process	**2018**	**2020**	**2030**
Electricity, high voltage {ES} electricity production, natural gas, combined cycle power plant	1.09×10^{10}	1.08×10^{10}	1.21×10^{10}
Electricity, high voltage {ES} heat and power co-generation, natural gas, conventional power plant, 100MW electrical	7.67×10^{9}	6.62×10^{9}	4.21×10^{9}
Electricity, high voltage {ES} electricity production, oil	4.20×10^{9}	6.39×10^{9}	3.52×10^{9}
Electricity, high voltage {ES} electricity production, hard coal	3.43×10^{10}	3.10×10^{10}	2.97×10^{9}
Electricity, high voltage {ES} heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	3.62×10^{9}	3.12×10^{9}	1.99×10^{9}
Natural gas, burned in gas motor, for storage {RoW} processing	1.35×10^{9}	1.25×10^{9}	1.15×10^{9}
Electricity, high voltage {ZA} electricity production, hard coal	1.01×10^{9}	9.46×10^{8}	9.17×10^{8}
Electricity, high voltage {ES} electricity production, natural gas, conventional power plant	5.86×10^{8}	5.78×10^{8}	6.49×10^{8}
Electricity, high voltage {ES} heat and power co-generation, oil	5.48×10^{8}	8.35×10^{8}	4.60×10^{8}
Hard coal {RoW} mine operation	3.90×10^{9}	3.51×10^{9}	4.55×10^{8}
Electricity, high voltage {ES} electricity production, lignite	2.09×10^{9}	1.89×10^{9}	1.81×10^{8}
Electricity, high voltage {ES} electricity production, natural gas, combined cycle power plant	1.09×10^{10}	1.08×10^{10}	1.21×10^{10}
Electricity, high voltage {ES} heat and power co-generation, natural gas, conventional power plant, 100MW electrical	7.67×10^{9}	6.62×10^{9}	4.21×10^{9}
Electricity, high voltage {ES} electricity production, oil	4.20×10^{9}	6.39×10^{9}	3.52×10^{9}

Table B.8. Processes contribution to Non-renewable energy (MJ primary) impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14; Cut-off: 1%).

Process	**2018**	**2020**	**2030**
Natural gas, high pressure {DZ} natural gas production	2.30×10^{11}	2.13×10^{11}	1.92×10^{11}
Uranium, in yellowcake {GLO} uranium production, in yellowcake, in-situ leaching	2.94×10^{11}	3.22×10^{11}	1.60×10^{11}
Uranium ore, as U {RNA} uranium mine operation, underground	1.72×10^{11}	1.88×10^{11}	9.36×10^{10}
Uranium ore, as U {RoW} uranium mine operation, underground	1.62×10^{11}	1.78×10^{11}	8.83×10^{10}
Natural gas, high pressure {NO} petroleum and gas production, off-shore	9.26×10^{10}	8.60×10^{10}	7.82×10^{10}
Hard coal {RoW} mine operation	3.78×10^{11}	3.40×10^{11}	4.40×10^{10}
Natural gas, high pressure {RoW} natural gas production	4.77×10^{10}	4.47×10^{10}	4.26×10^{10}
Natural gas, high pressure {RU} natural gas production	4.55×10^{10}	4.30×10^{10}	4.24×10^{10}
Natural gas, unprocessed, at extraction {GLO} production	4.21×10^{10}	3.94×10^{10}	3.76×10^{10}
Uranium ore, as U {RoW} uranium mine operation, open cast	6.41×10^{10}	7.01×10^{10}	3.49×10^{10}
Petroleum {RoW} petroleum and gas production, on-shore	3.42×10^{10}	4.67×10^{10}	3.45×10^{10}
Petroleum {RME} production, onshore	3.38×10^{10}	4.62×10^{10}	3.41×10^{10}
Hard coal {CN} mine operation	2.27×10^{10}	1.86×10^{10}	3.20×10^{10}
Uranium ore, as U {RNA} uranium mine operation, open cast	4.47×10^{10}	4.89×10^{10}	2.43×10^{10}
Natural gas, high pressure {RoW} petroleum and gas production, on-shore	1.87×10^{10}	1.75×10^{10}	1.67×10^{10}
Petroleum {RU} production, onshore	1.47×10^{10}	2.02×10^{10}	1.49×10^{10}

B.2. Substances Contribution to Impact Categories of 2018, 2020 and 2030 Electricity Generation Scenario

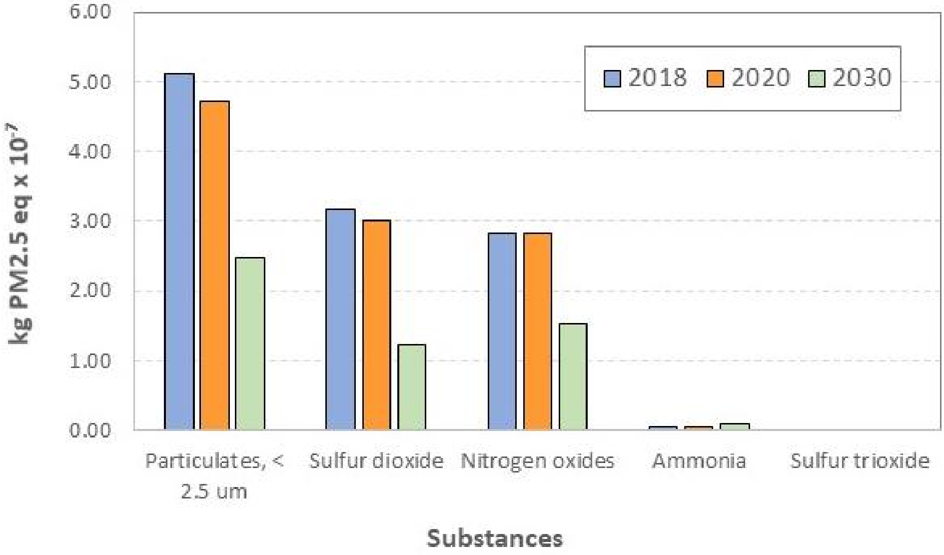


Figure B.1. Substances contribution to Respiratory Inorganics impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14).

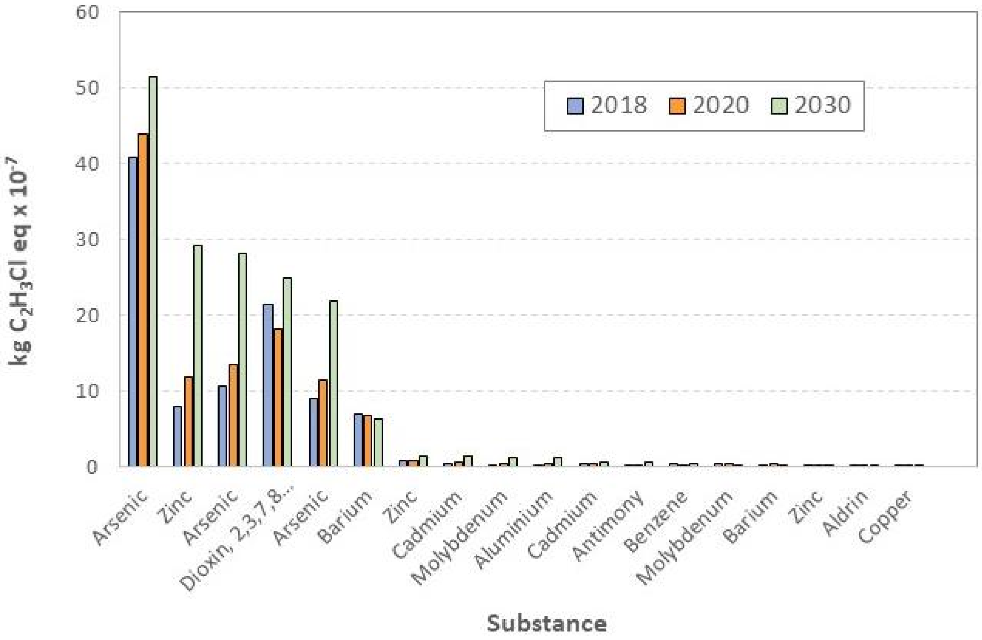


Figure B.2. Substances contribution to Non-Carcinogens impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14).

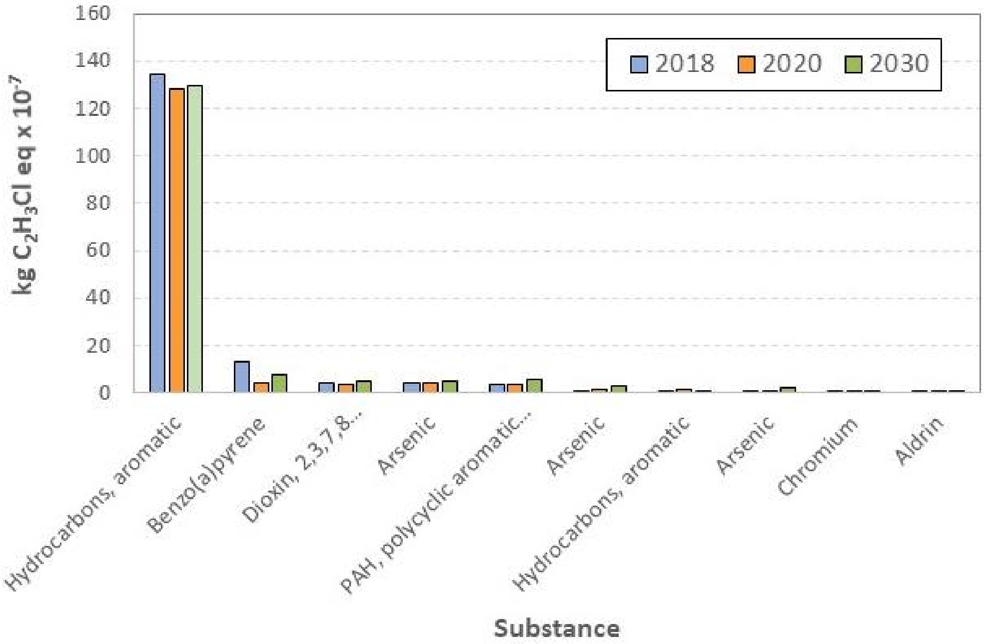


Figure B.3. Substances contribution to Carcinogens impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14).

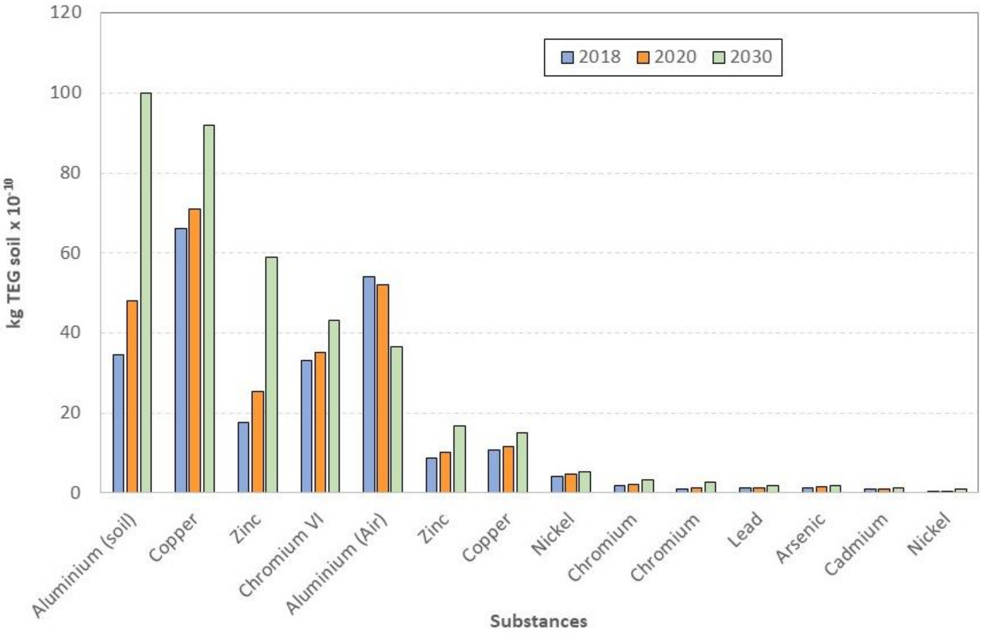


Figure B.4. Substances contribution to Terrestrial ecotoxicity impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14).

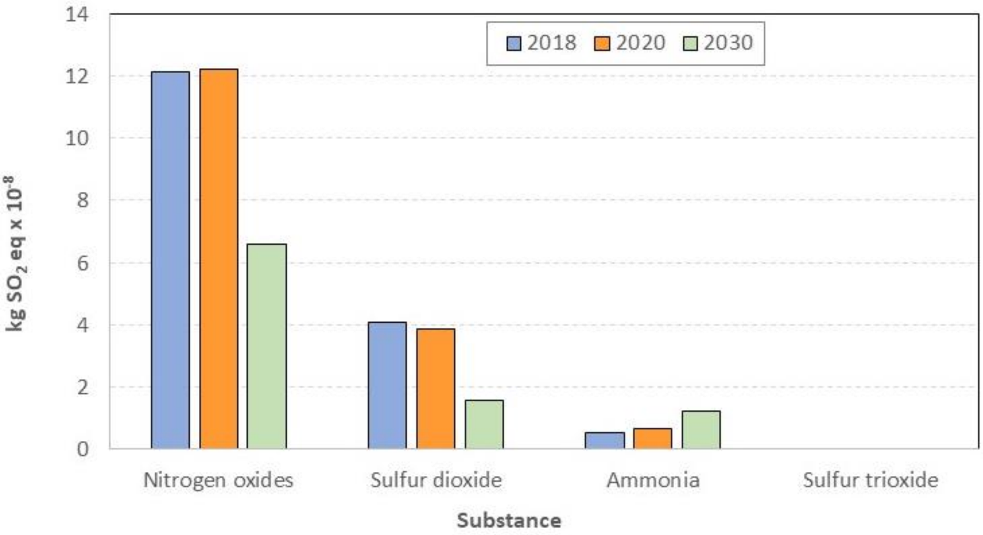


Figure B.5. Substances contribution to Acidification/nutrification impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14).

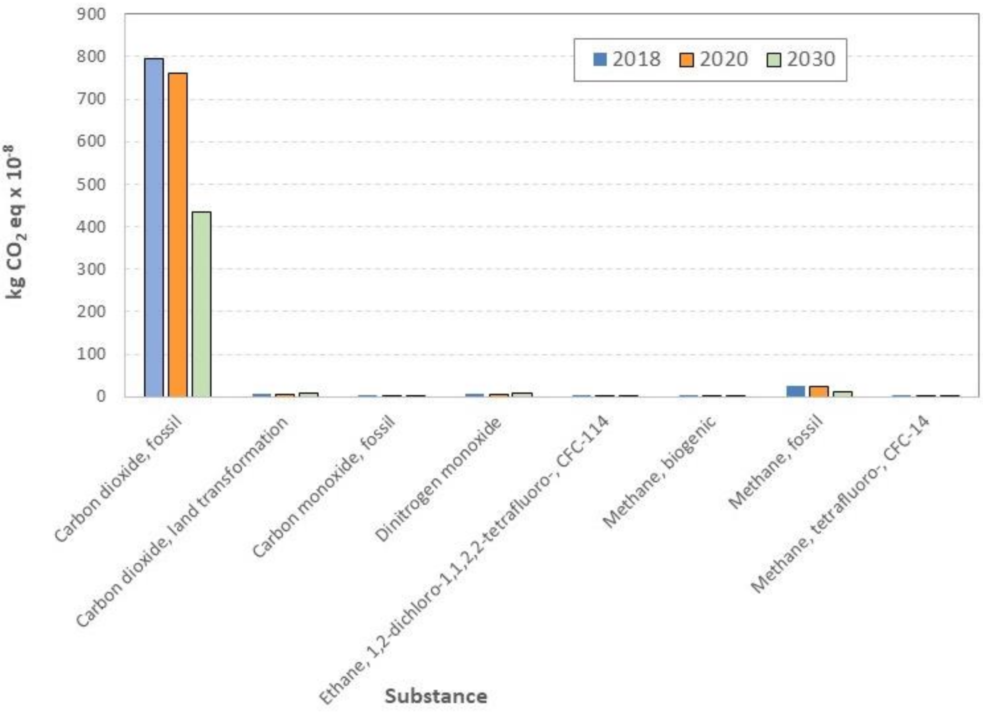


Figure B.6. Substances contribution to Global warming impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14).

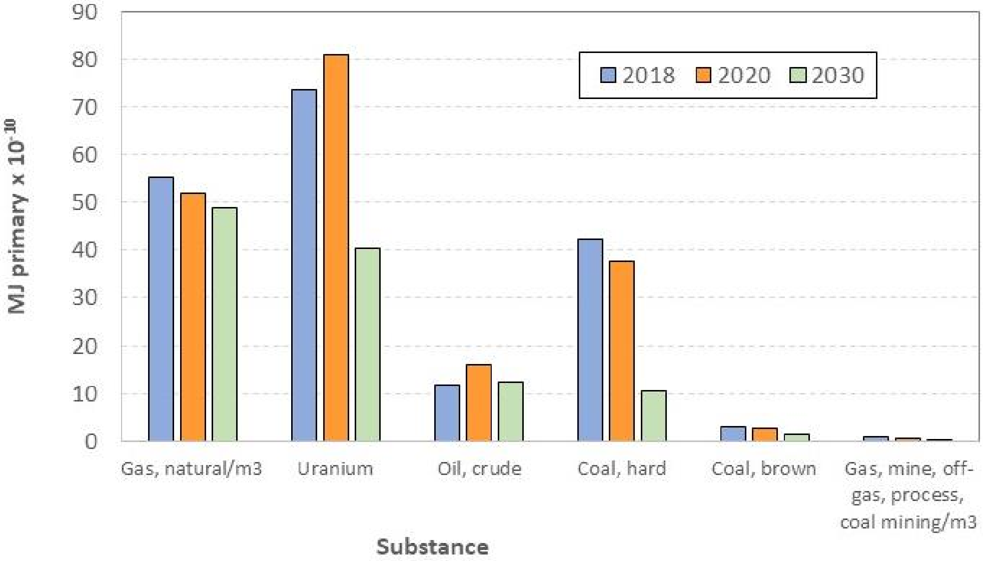


Figure B.7. Substances contribution to Non-renewable energy impact category of 2018, 2020 and 2030 electricity generation scenario (Method IMPACT 2002+ V2.14).

Appendix C. Supplementary Materials for Chapter 3

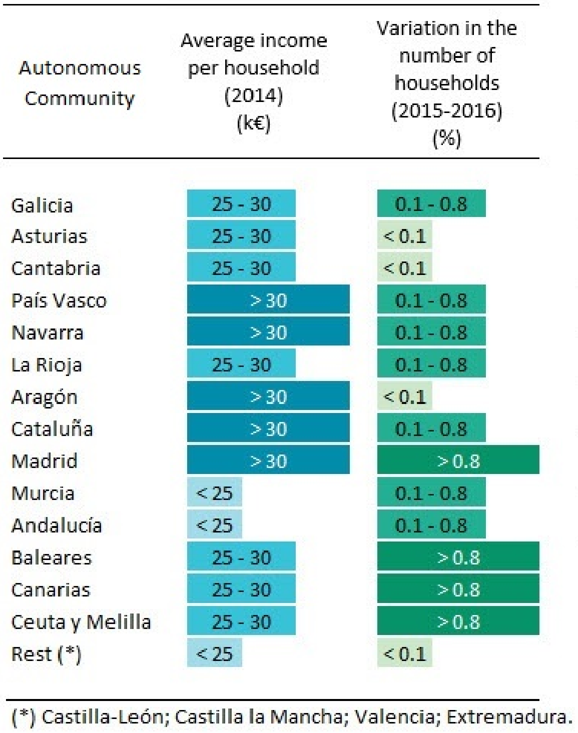
C.1. Socio-Economic Aspects: Needs of The Buyer of Housing

Figure C.1 and Figure C.2 represent data from the book INE 2017, which have been selected to illustrate the needs of the buyer of housing in the case of Spain.

In Figure C.1, in the horizontal bar graph with a range of blues, the average annual rent is represented by Autonomous Communities (a first-level political and administrative division in Spain), since such a rent is an indicator of the capacity to invest in housing. The graph of horizontal bars with a range of greens shows the annual percentage change in the number of households: growth or decrease due to migration effects or the family reunification inherent in the economic recession. The graph of vertical bars, with the same ranges of colours (blues for one variable and greens for the other), represents how these data affect the whole of the Spanish state (taking into account the percentage of territory that each Autonomous Community represents) and allows appreciate that the average income is less than € 25,000 in 66.7% of the territory (Murcia, Andalusia and the rest), which is between € 25,000 and € 30,000 in 12.4% of the territory (Galicia, Asturias, Cantabria, La Rioja, Balearic Islands, Canary Islands, Ceuta and Melilla) and that is greater than € 30,000 in 20.8% of the territory (Basque Country, Navarre, Aragon, Catalonia and Madrid).

The annual variation in the number of households is very small in the Autonomous Communities of Asturias, Cantabria, Aragon and the rest, being Madrid the Autonomous Community where it grows the most. In 59.7% of the Spanish territory the variation is very small and only in Madrid, which represents 4% of the territory, varies more than 0.8%.

In Asturias, where the studied housing is located, the average rent is between € 25,000 and € 30,000 and the annual variation in the number of homes takes a very small value.



Autonomous Community	Average income per household (2014) (k€)	Variation in the number of households (2015-2016) (%)
Galicia	25 - 30	0.1 - 0.8
Asturias	25 - 30	< 0.1
Cantabria	25 - 30	< 0.1
País Vasco	> 30	0.1 - 0.8
Navarra	> 30	0.1 - 0.8
La Rioja	25 - 30	0.1 - 0.8
Aragón	> 30	< 0.1
Cataluña	> 30	0.1 - 0.8
Madrid	> 30	> 0.8
Murcia	< 25	0.1 - 0.8
Andalucía	< 25	0.1 - 0.8
Baleares	25 - 30	> 0.8
Canarias	25 - 30	> 0.8
Ceuta y Melilla	25 - 30	> 0.8
Rest (*)	< 25	< 0.1

(*) Castilla-León; Castilla la Mancha; Valencia; Extremadura.

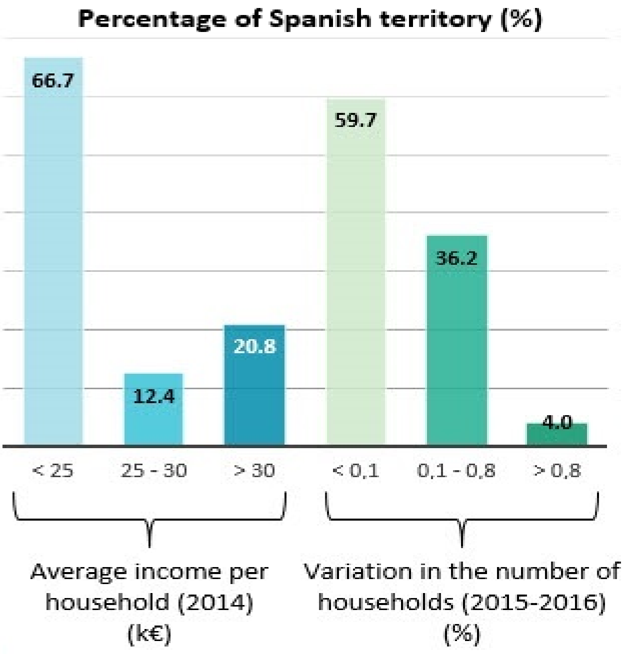


Figure C.1. Average income per household (2014) and variation in the number of households (2015-2016) in INE 2017 (own elaboration).

In Figure C.2, the graph of vertical bars represents the purchase of housing in 2015 and 2016, being noteworthy that there is a decrease in transactions of new homes, an increase in used homes and that is the free housing the one that experiences the greatest growth. The total number of transactions increased by approximately 16% in 2016. The pie chart reports the housing tenure regime in 2016 and shows that 49% of the homes were already paid, while 29% still had outstanding payments and 17% corresponded to homes for rent.

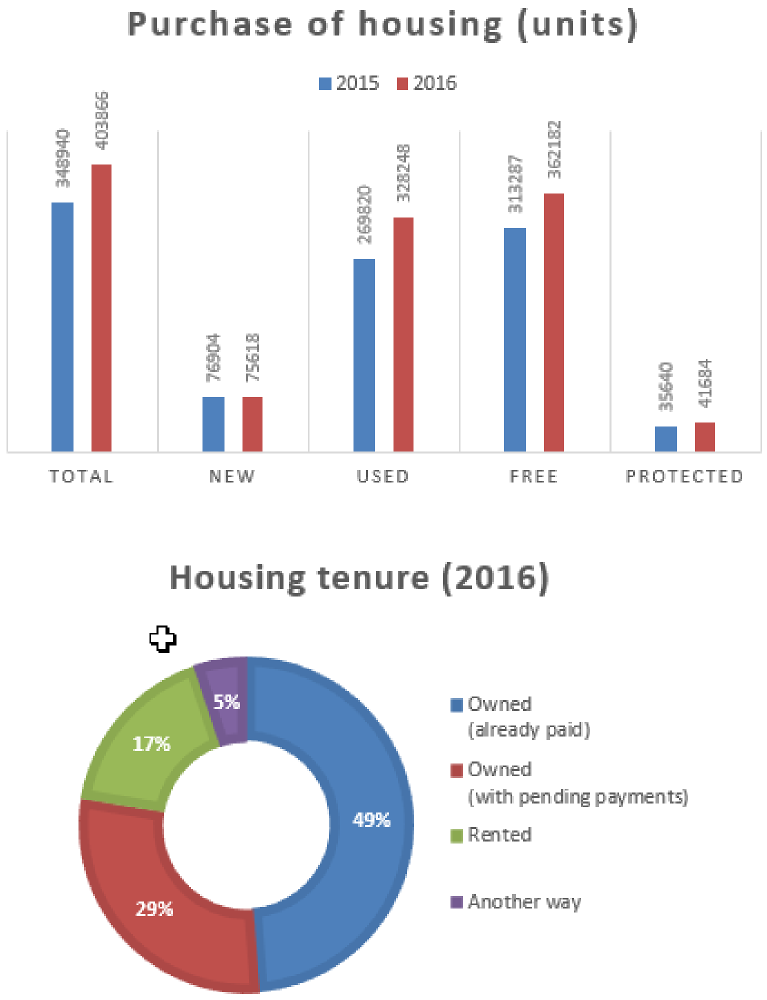


Figure C.2. Purchase of housing (2015-2016) and housing tenure (2016) in INE 2017 (own elaboration).

Figure C.3 represents the types of households in 2015 and 2016 taking into account the form of cohabitation.

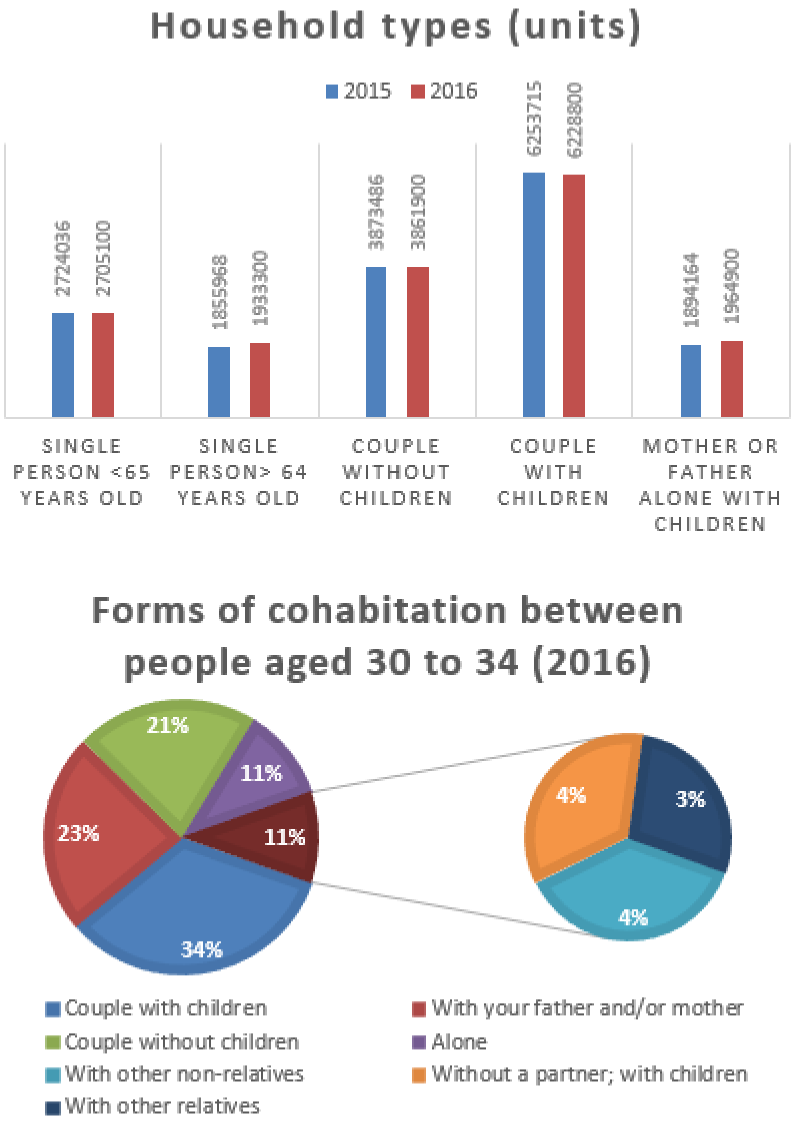


Figure C.3. Household types and forms of cohabitation between people aged 30 to 34 (2016) in INE 2017 (own elaboration).

It is observed that there was hardly any variation between 2015 and 2016 in the number of households assigned to each form of cohabitation. The vertical bar chart takes into account all ages of the population, while the pie chart refers only to people aged 30 to 34 years. In the population as a whole, 28% of people live alone (12% of people over 64 and 16% of those under that age), 60% live in a couple (37% with children and 23% without children) and 12% are single fathers or mothers with children. With regard to people between 30 and 34 years old, 11% live alone, 55% live with a partner (34% are couples with children and 21% are couples without children), 23% live with their parents, 7% live with other relatives or non-relatives and 4% live without a partner and with children. From these data it seems that living together with or without children is associated with people between 30 and 34 years of age and that having or not having children is also related to that age group. The number of children per couple in Spain has been around 1.3 for several years. Therefore, considering the cohabitation as a couple within the whole population and pondering those couples with and without children, the average number of people living in a couple results 2.8. Consequently, the number of people that will be considered in the case study will be 3.

C.2. Impact of Sub-Regional Climates on the Design of a Single Family House

This study was carried out for the house with three-bedrooms (3BB). There was used the Passive House Planning Package (PHPP v9 2015) for different microclimates in Asturias: coast and mountain very close together. The aims are to determine the effect of site, landscape and soil on the performance of a modular single family house for each microclimate and also to determine the effects on the house of the insulation thickness, building orientation and size of the windows, all of which condition comfort and heating demand considerably.

Conditions at the locations

Table C.1 presents the conditions at the locations in four of the studied sub-regions, along with the name of the location, its acronyms and its geographical coordinates, as well as its landscape and soil types.

Table C.1. Site, landscape and soil at the locations.

Sub-region	Acronym	Location	Coordinates	Height (m)	Landscape	Soil
west coast	CAR	La Caridad_open	43.558 N 6.826 W	70	open field	natural
	VO	Valdés_open	43.472 N 6.390 W	216	open field	natural
	VV	Valdés_valley	43.472 N 6.390 W	216	valley	natural
	VC	Valdés_city	43.472 N 6.390 W	216	city	artificial
	VVS	Valdés_valley_south	43.472 N 6.390 W	216	valley south	natural
central coast	LUA	Luanco_open	43.624 N 5.787 W	63	open field	natural
	GO	Gijón_open	43.538 N 5.624 W	30	open field	natural
	GC	Gijón_city	43.538 N 5.624 W	30	city	artificial
	GS	Gijón_sea	43.538 N 5.624 W	30	sea	natural
central inland	OSO	Oviedo_suburbs_open	43.359 N 5.863 W	332	suburbs, open f.	natural
	OCO	Oviedo_centre_open	43.359 N 5.863 W	332	open field	natural
	OCC	Oviedo_ centre_city	43.359 N 5.863 W	332	city	artificial
	EO	El Entrego_open	43.287 N 5.634 W	245	open field	natural
	EC	El Entrego_city	43.287 N 5.634 W	245	city	artificial
inland nature parks	IBI	Ibias_open	43.014 N 6.531 W	780	open field	natural
	LEN	Lena_open	43.076 N 5.492 W	370	open field	natural
	ALL	Aller_open	43.054 N 5.284 W	750	open field	natural
	AMI	Amieva_open	43.160 N 5.071 W	370	open field	natural
	CAB	Cabrales_open	43.311 N 4.853 W	458	open field	natural

The type of landscape considers where the building is situated: in an open field, a valley or a valley facing south, in a city or close to the sea. The type of soil is classified as natural (green areas) or artificial (paved), to take into account the different values of soil reflectivity and absorptivity. In each of the first three sub-regions, although sites of different coordinates are studied, some locations may share the same coordinates with only the landscape or the soil varying. In the last of the four sub-regions, all the study cases have different coordinates. When a site (certain coordinates) is associated with a single case study, its acronym comprises up of three letters that recall the name of that site (e.g. "LUA" for Luanco). In the remaining cases, the first letter of the acronym stands for the physical place ("V" for Valdés, "G" for Gijón, "O" for Oviedo, etc.) and the remaining letters indicate the type of landscape ("C" for city, "O" for open field, "S" for by the sea, "V" for valley and "VS" for valley facing south), except for Oviedo, where the last letters

“SO” stand for suburbs in an open field, “CO” for town centre in an open field landscape and “CC” for town centre in a city landscape. In the central inland sub-region, besides Oviedo, there is a small country town, El Entrego, which has two associated locations: open field and city. Finally, the locations with to the inland nature parks always correspond to a pre-alpine open field landscape.

The following data are used to evaluate the thermal load that is required in each location: heating and cooling periods, degree hours per year, solar irradiation levels, temperature oscillation in summer and monthly average data on ambient temperature and dew point.

A total of 19 cases are studied: those locations corresponding to combinations of site, landscape and soil listed in Table C.1 and associated with the 11 sites presented. The analysis is carried out sub-region by sub-region: (a) west coast; (b) central coast; (c) central inland; and (d) inland nature parks.

In addition to the effect of the location (site, landscape and soil), a study of the influence of the increase in XPS insulation thickness at each location is presented so as to select the most suitable value in each sub-region that would allow the building to be classified as a passive house. In parallel, possible overheating depending on the thickness of the insulation is also checked. The effect of the orientation of the house at each location is also studied, considering two situations: large windows facing south and large windows facing north. In the former case, the percentages of the façades occupied by the openings are: 32% in the south-facing façade and 13% in the north-facing façade. This distribution of openings allows solar gains to be exploited. However, significant overheating can arise depending on the thickness of the insulation that is installed. In the latter case, the openings occupy 13% of the south-facing façade and 32% of the north-facing façade; hence, for high insulation thicknesses, overheating can be avoided or its frequency decreased.

Figure C.4 and Figure C.5 correspond to the large windows facing south and large windows facing north, respectively. Both figures show the demand and frequency of overheating results for the different locations in the four studied regions and the XPS insulation thicknesses considered.

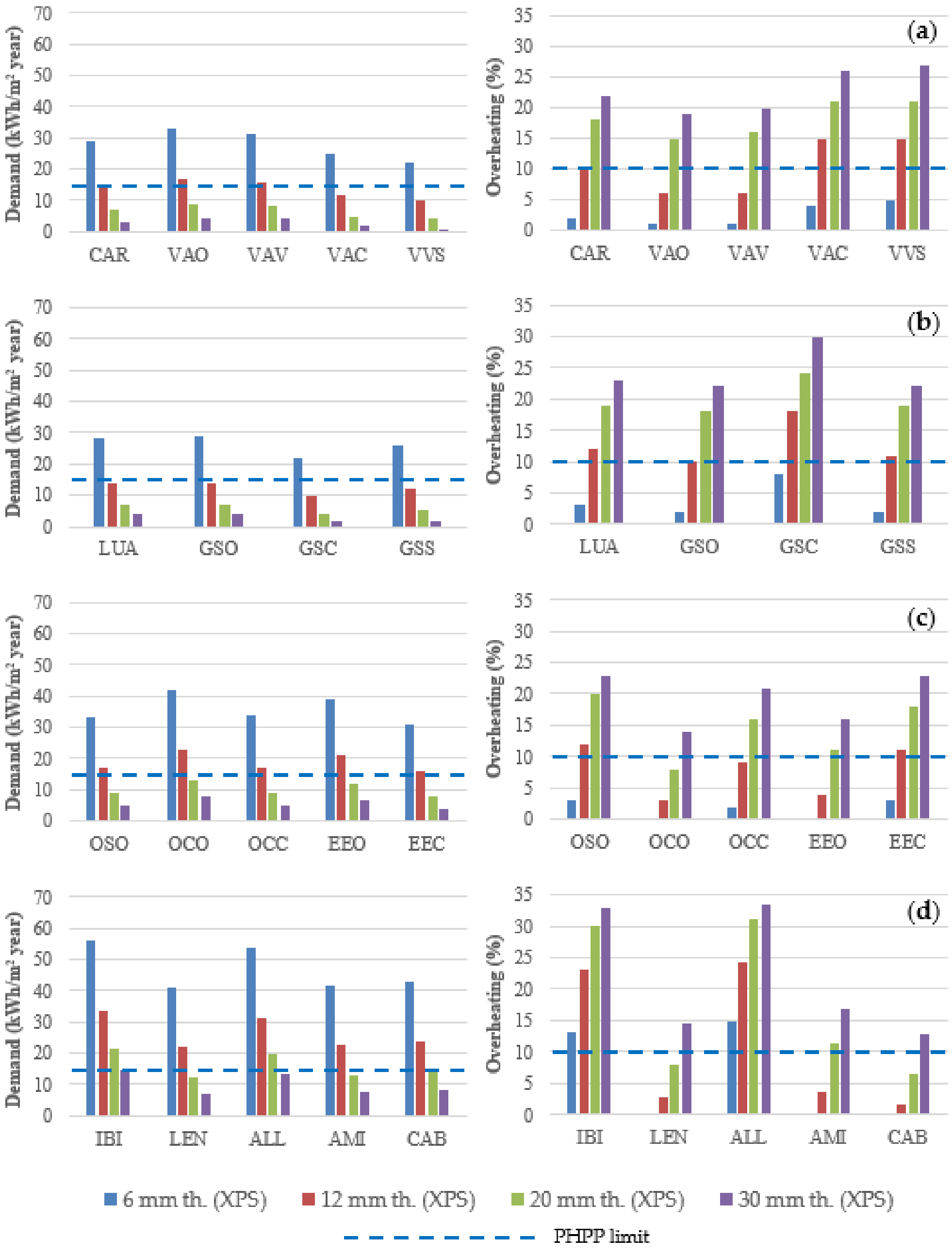


Figure C.4. Demand (left column) and overheating (right column) for different insulation thicknesses, in the case of large windows facing south, for several locations from different climatic sub-regions: (**a**) west coast (top charts); (**b**) central coast (medium top charts); (**c**) central inland (medium bottom charts); and (**d**) inland nature parks (bottom charts).

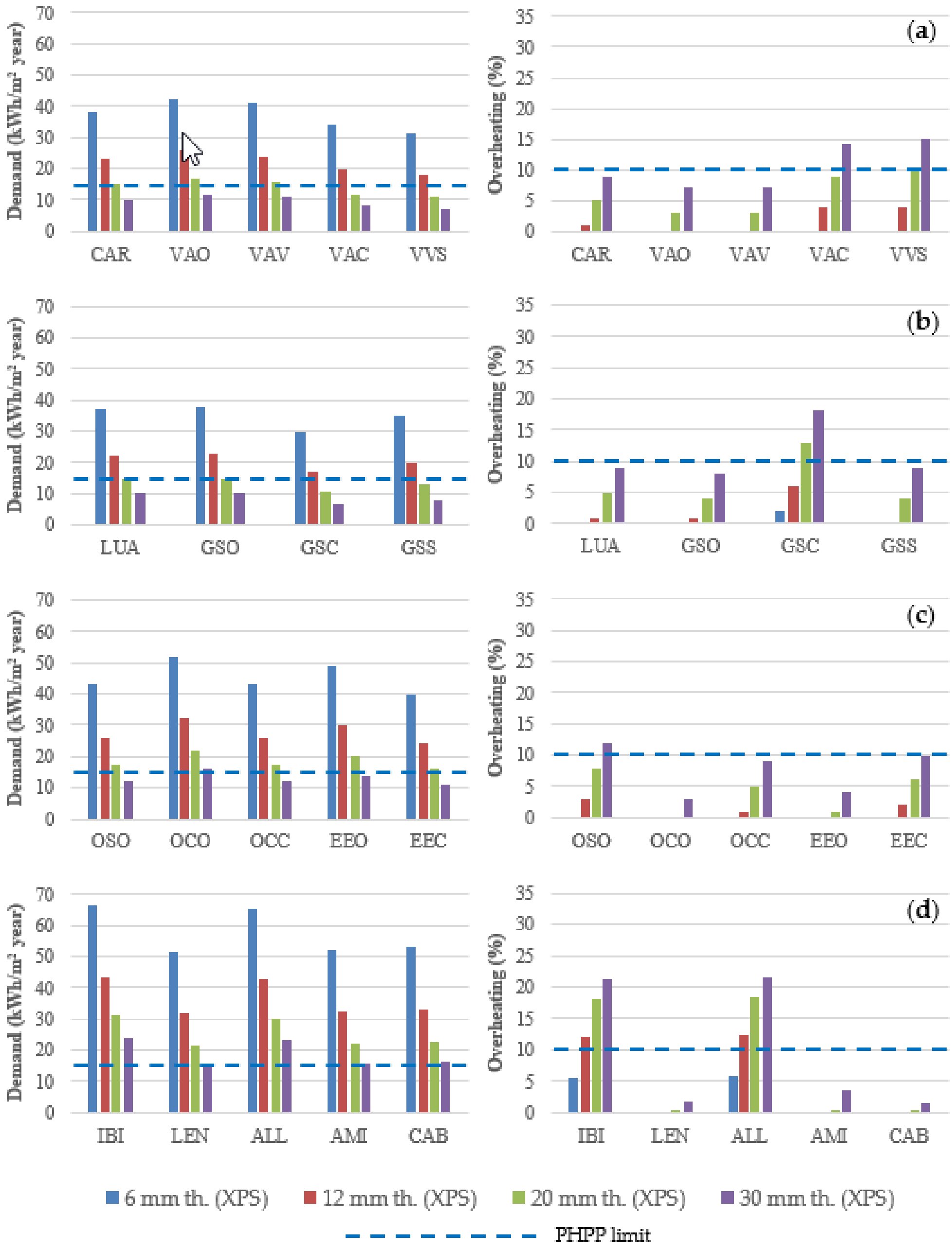


Figure C.5. Demand (left column) and overheating (right column) for different insulation thicknesses, in the case of large windows facing north, for several locations from different climatic sub-regions: (**a**) west coast (top charts); (**b**) central coast (medium top charts); (**c**) central inland (medium bottom charts); and (**d**) inland nature parks (bottom charts).

Large windows facing south

For all the analysed thicknesses, the demands of the locations on the west coast (except for the case of Valdés valley to the south, VVS) are greater than those on the central coast. The locations in the central inland region have greater demand than the coastal locations, this demand growing considerably for the mountainous areas (inland nature parks).

In the two coastal sub-regions (west and central), an XPS insulation thickness of 12 cm entails a demand below 15 kWh/(m^2 year) at all locations, except for Valdés open field (VO) and Valdés valley (VV); although in these cases, the demand is also practically that required for a passive house. Overheating is observed for this thickness of 12 cm, except for Gijón open field (GO), Valdés open field (VO) and Valdés valley (VV). To reduce this effect, the openings could be downsized by making the large south-facing windows smaller. Observing the case of large north-facing openings, in Figure C.5, it can be seen that there is no overheating at any coastal location for an insulation thickness of 12 cm.

Comparing the effects of landscape and soil type in the two coastal sub-regions for an insulation thickness of 12 cm, as far as the different locations in Gijón and Valdés are concerned, there is a drop in demand with respect to the demand for each open field location (GO and VO). This is the case at city locations, GC and VC (6.7% for Gijón and 12.5% for Valdés), valley locations in Valdés (1.3% VV and 12.5% VVS), and one location by the sea, GS (6.7% for Gijón). The landscape is a factor influencing overheating, as the following locations exceed the 10% limit: Gijón city, GC (44%), Gijón by the sea, GS (9%), Valdés city, VC (33%) and Valdés valley to the south, VVS (33%).

In the central inland sub-region, the demands are greater than in the coastal sub-regions, and insulation thicknesses between 12 and 20 cm are generally needed to meet the passive house standard. For 20 cm of insulation, the demand requirement for a passive house would be met at all of the five locations studied here. Nevertheless, to avoid major overheating, the thickness should be less than 20 cm in Oviedo suburbs open field OSO (50%), Oviedo city centre OCC (37.5%), El Entrego open field EO (9%) and El Entrego city EC (44%). If a thickness of 20 cm were to be established for these sub-regions, in addition to solar shading for the windows, it would be necessary to reduce the size of the south-facing openings at those locations presenting significant overheating. The landscape and type of soil are found to have a significant effect on both demand and overheating.

A greater insulation thickness is required in the inland nature parks (30 cm in Ibias, IBI, and Aller, ALL), although very substantial overheating also increases at all locations, leading to all of them exceeding the permitted maximum, especially in Ibias and Aller, which exceed the limit. Bearing these findings in mind, the size of the south-facing windows should be reduced. Analysing this option in Figure C.5, it can be seen that overheating no longer occurs in three of the five locations. However, for the values of the total size of openings used, there is still significant overheating at the two highest mountain locations: Ibias (780 m) and Aller (750 m), which at least duplicate the permitted maximum value.

Large windows facing north

West coast: The insulation thickness that would allow the building to be classified as a passive house increases to values close to 20 cm. However, Valdés valley to the south (VVS) nearly reaches the permitted limit of frequency of overheating when this thickness is employed.

Central coast: The required insulation thickness is also around 20 cm, but overheating appears at the Gijón city location (GC), where the maximum frequency is exceeded (23.1%).

Central inland: The necessary insulation thickness increases up to 30 cm, without overheating, except in Oviedo suburbs open field (OSO), where there is slight overheating (16.7%), though below the permitted limit.

Inland nature parks: Except for Lena (LEN), Amieva (AMI) and Cabrales (CAB), which would be at the limit of demand for a passive house, it is necessary to increase the insulation above 30 cm. However, in Ibias and Aller, as stated when discussing Figure C.5, classification as a passive house is still not obtained when using 30 cm of insulation, as substantial overheating is appreciated, thereby requiring a reduction in the size of the south-facing openings below 13%, as already stated.

Conclusions

Four climatic sub-regions (west and central coast, central inland and inland nature parks) were analysed to determine the influence of the size of the windows, both for the case of large windows facing north and large windows facing south. It was found that the optimal thicknesses obtained for the different cases have to be reconsidered to avoid overheating.

For large windows facing south on the coast, the XPS insulation thickness should be around 12 cm. However, it is recommended to decrease the size of the windows in some cases: "city" (artificial soil), "valley facing south" and "by the sea". Landscape effects are also very important: on the coast, the heating demand could differ by 12.5% and considerably influence the condition of overheating, more than 50%. For the central inland sub-region, the thickness of the XPS insulation should be around 20 cm. However, landscape and soil can cause overheating, making it advisable to study the sizes of the windows depending on their orientation. Finally, the inland nature parks require around a thickness of 30 cm XPS insulation, which can cause major problems of overheating, requiring a very complete design that includes the recommendation that the size of the south-facing openings should be below 13%.

For large windows facing north, insulation thicknesses increase quite considerably: from 12 to 20 cm on the coast (west and central). In the central inland region, the XPS insulation thickness does not increase as much, being around 20 cm for both orientations of the windows. In the inland nature parks, the thickness would be 30 cm for both orientations. However, substantial overheating occurs in the case of large openings facing south.

The general conclusion is that the study of the size of the openings for each location and their orientation is very important: large openings facing south allow a reduction in insulation thickness, but overheating can increase significantly depending on the location.

Appendix D. Supplementary Materials for Chapter 4

Appendix E. Supplementary Materials for Chapter 5

University of Oviedo

DOCTORAL THESIS
2021