TESIS DOCTORAL / PhD. THESIS

ANÁLISIS DE CICLO DE VIDA EN SISTEMAS DE CERTIFICACIÓN AMBIENTAL DE EDIFICIOS: ESTRATEGIAS PARA LA DESCARBONIZACIÓN EN EUROPA.

LIFE CYCLE ANALYSIS IN BUILDING RATING SYSTEMS: STRATEGIES FOR DECARBONIZATION IN EUROPE.

Autor:
Borja Izaola Ibáñez

Directores:
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Universidad del País Vasco
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Programa de doctorado/PhD. Program:
Ingeniería de proyectos

Universidad:
Universidad del País Vasco - Euskal Herriko Unibertsitatea (UPV/EHU)

Fecha:
Diciembre de 2023

Tesis por compendio de artículos
Thesis by compendium of contributions

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“The buildings and construction sector is not on track to achieve decarbonization by 2050”

United Nations Environment Programme, UNEP
At the Global Status Report for Buildings and Construction, on November 2022.

Imagen generada con IA basada en los impactos recogidos en esta tesis

AGRADECIMIENTOS

Deposito este compendio de investigaciones sobre los impactos de la edificación treinta y tres años después de pisar la universidad por primera vez. Pasé el mes de octubre de 1990 en la Escuela de Ingeniería de Bilbao, por la que he vuelto a pasar ahora, virtualmente, para el desarrollo de esta tesis. Entretanto, cada uno de los pasos, relaciones y aprendizajes, dejaron la marca de un lugar geográfico y edificado, que han ido definiendo quién era y quien soy: huellas, marcas, nombres.

Algunos, ahora, me llamarán Doctor. Será gracias a todo lo anterior, especialmente a quienes me trajeron al Mundo. Gracias Ama hacia el cielo. Gracias Aita hacia la tierra. Es gracias a quienes seguirán delante, especialmente a quienes dejo mi pequeño mundo. Gracias Kilian allí lejos. Gracias Jon, aquí cerca. Ha sido gracias a quienes están dentro, participando en lo cotidiano donde suceden las tesis, las antítesis y las síntesis, especialmente a mi conviviente. Gracias Almudena por alimentar la vida cada uno de estos días, por superar las crisis y por seguir amando.

Miles de gracias a miles de personas cuya relación me ha acompañado algún paso hasta aquí. De las muchas familiares, gracias a Leyre, y que te sirva. De los muchos amigos, gracias a Toni, de verdad. De las muchas compañeras de trabajo, gracias a Paula, y que la lectura siente bien. Millones de gracias al compa, amigo y hermano Ortzi, sin cuya dirección no habría dado ni los primeros pasos.

Gracias a la Vida, que me ha dado tanto. Espero poder dar a cambio. Gracias a la Tierra, que nos sigue sosteniendo. Espero que sostengamos al menos un terreno. Gracias a Dios, sí, sin saber, sin poder, sin tener. Confiante entusiasmado.

Urko Borja Agama. En Loreto, Xatafí, el 6 de Noviembre de 2023.

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Acrónimos

ADP	Abiotic Depletion Potential	Potencial de agotamiento abiótico
AP	Acidification Potential	Potencial de acidificación
BRS	Building Rating Systems	Certificación ambiental de edificios
BREEAM	Building Research Establishment Environmental Assessment Methodology	Metodología inglesa de evaluación ambiental de edificios
CE	Circular Economy	Economía circular
CASBEE	Comprehensive Assessment System for Built Environment Efficiency	Sistema de evaluación de la eficiencia ambiental de la construcción
CDW	Construction and Demolition Waste	Residuos de construcción y demolición
CLT	Cross-Laminated Timber	Madera contralaminada
DALY	Dissability Adjusted Life Years	Ajuste de años de vida perdidos por enfermedad o muerte prematura
DCB	Di-Chloro-Benzine	Diclorobenceno
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen	Consejo alemán de construcción sostenible
DGBC	Dutch Green Building Council	Consejo holandés de construcción sostenible
EC	Embodied Carbon	Carbono (CO_2) incorporado en los materiales
ED	Environmental Damage	Daño ambiental
EPBD	Energy Performance of Buildings Directive	Directiva europea sobre el comportamiento energético de los edificios
EPD	Environmental Product Declaration	Declaración ambiental de producto
EP	Eutrophization Potential	Potencial de eutrofización
ERESEE	Estrategia Española de Rehabilitación de Edificios a Largo Plazo	Long-Term Rehabilitation Strategy (LTRS)
FETP	Freshwater Ecotoxicity Potential	Potencial de ecotoxicidad del agua potable
GWP	Global Warming Potential	Potencial de calentamiento global
GBC	Green Building Council	Consejo de construcción sostenible
GBRT	Green Building Rating Tool	Herramienta de certificación de la sostenibilidad de edificios
GPP	Green Public Procurement	Contratación pública ecológica
GHG	Greenhouse Gas	Gases de Efecto Invernadero (GEI)
HH	Human Health	Salud humana
HQE	Haute Qualité Environnementale	Consejo francés de construcción sostenible
HPI	Home Performance Index	Consejo irlandés de construcción sostenible
HVAC	Heat-Ventilation-Air Conditioned	Climatización
IEA	International Energy Agency	Agencia internacional de la energía
IEQ	Indoor Environment Quality	Calidad ambiental interior
IPBES	Intergovernmental Panel on Biodiversity and Ecosystem Services	Plataforma intergubernamental sobre biodiversidad y servicios de los ecosistemas
IPCC	Intergovernmental Panel on Climate Change	Plataforma intergubernamental sobre cambio climático
JRC	Joint Research Centre	Centro de I+D de la comisión europea
LULUC	Land Use and Land Use Change	Usos y cambios de uso de la tierra
LEED	Leadership in Energy & Environmental Design	Metodología americana de evaluación ambiental de edificios
LCA	Life Cycle Assessment	Análisis de Ciclo de Vida (ACV)
LCC	Life Cycle Costs	Costes de ciclo de vida

LCIA	Life Cycle Impact Assessment	Evaluación ambiental de ciclo de vida
LCT	Life Cycle Thinking	Perspectiva (o enfoque) de ciclo de vida
MLP	Multi-Level Perspective	Perspectiva Multi Nivel
NFA	Net Floor Area	Superficie útil
NZCB	Nearly Zero-Carbon Buildings	Edificios de carbono casi nulo
NZEB	Nearly Zero-Energy Buildings	Edificios de energía casi nula
OC	Operational Carbon	Carbono (CO_2) operativo o emitido durante la fase de uso del edificio
PE	Primary Energy	Energía primaria
PED	Primary Energy Demand	Demanda de energía primaria
RE	Real Estate	Sector inmobiliario
SDG	Sustainable Development Goals	Objetivos de Desarrollo Sostenible (ODS)
SFH	Single Family Home	Vivienda unifamiliar
STT	Socio-Technical Transition	Transición socio-técnica
TEF	Total Energy Footprint	Huella Energética Total
UNEP	United Nations Environmental Program	Programa ambiental de las Naciones Unidas
VERDE	Valoración de Eficiencia de Referencia de Edificios	Herramienta española de certificación de la sostenibilidad de edificios
WLC	Whole Life Carbon	Carbono (CO_2) total emitido en la vida de un edificio
WCP	Water Consumption Potential	Potencial de Consumo de Agua

Listado de publicaciones

Artículo 1

Life Cycle Analysis Challenges through Building Rating Schemes within the European Framework
Autores: Borja Izaola, Ortzi Akizu-Gardoki y Xabat Oregi
Nombre de la revista científica y fecha de publicación:
MDPI, Sustainability, Abril de 2022
Impact factor: 3.9 Doi: https://doi.org/10.3390/su14095009

Artículo 2

Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building
Autores: Borja Izaola, Ortzi Akizu-Gardoki y Xabat Oregi
Nombre de la revista científica y fecha de publicación:
ELSEVIER, Sustainable Production and Consumption, Julio de 2023
Impact factor: 8.9 Doi: https://doi.org/10.1016/j.spc.2023.07.001

Artículo 3

Biodiversity burdens in Spanish conventional and low-impact single-family homes
Autores: Borja Izaola y Ortzi Akizu-Gardoki
Nombre de la revista científica y fecha de publicación:
ELSEVIER, Science of the Total Environment, Noviembre de 2023
Impact factor: 9.8 Doi: https://doi.org/10.1016/j.scitotenv.2023.168371

Otras publicaciones relevantes

Publicación 1:
Título de Libro: The Routledge Handbook of Embodied Carbon in the Built Environment.
Título del capítulo 10: The Levels process and the Life Levels project: Supporting the development of quality data.
Autor del capítulo: Borja Izaola. Editores del libro: Rahman Azari y Alice Moncaster. ISBN 9781032234878
Link: https://www.routledge.com/The-Routledge-Handbook-of-Embodied-Carbon-in-the-Built-Environment/Azari-Moncaster/p/book/9781032234861

Publicación 2:
Título del artículo: La descarbonización de la edificación en todo su ciclo de vida.
Autores: Dolores Huerta Carrascosa, Raquel Díez Abarca, Joaquim Arcas Abella, Lucía Martín de Aguilera Mielgo, Ander Bilbao Figuero, Borja Izaola.
Revista de Obras Públicas: Órgano profesional de los ingenieros de caminos, canales y puertos, ISSN 0034-8619, Nº. 3631, 2021, págs. 98-107
Link: https://www.revistadeobraspublicas.com/articulos/la-descarbonizacion-de-la-edificacion-en-todo-su-ciclo-de-vida/

Publicación 3:
Título del artículo: LIFE Level(s) mainstreaming sustainable buildings in Europe.
Autores: Borja Izaola y Benjamin Petrovic.
The Project Repository Journal Volume 11, págs 82-91. Octobre de 2021
Link: https://doi.org/10.54050/PRJ1117905

Publicación 4:
Título del artículo: Los retos para avanzar en la certificación.
Autor: Borja Izaola.
Revista Ecohabitar, ISSN 1697-9583, N.º 66, año 2020, págs 36-38.
Link: https://ecohabitar.org/los-retos-para-avanzar-en-la-certificacion/

Resumen gráfico

ANÁLISIS DE CICLO DE VIDA EN SISTEMAS DE CERTIFICACIÓN AMBIENTAL DE EDIFICIOS: ESTRATEGIAS PARA LA DESCARBONIZACIÓN EN EUROPA

Objetivo específico 1

Comparar certificaciones europeas de la sostenibilidad de edificios y sus respectivos umbrales.

ACV Referencias de demanda de energía y de potencial de calentamiento global de 5 certificaciones europeas con ACV

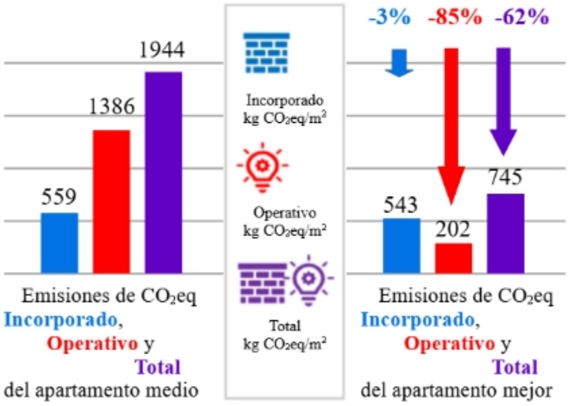
	Demanda de energía primaria $kWh/m^2{\cdot}a$	Potencial de calentamiento global $CO_2eq/m^2{\cdot}a$
	60*	20**
	29,22	40,49
	61,1	18,22
	27,5	25
	42	300
Promedio	**44,0**	**80,7**
Desviación	37%	152%

*Cumpliendo EPDB ** Cumpliendo RE2020

Objetivo específico 2

Proponer valores de referencia del CO_2eq incorporado y operativo de la vivienda colectiva española media y mejor.

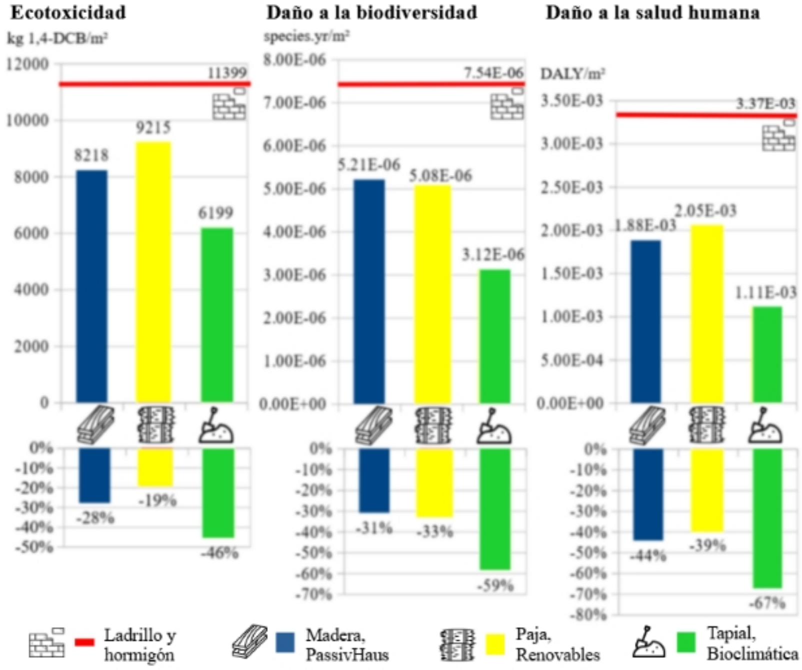
Apartamento medio en edificación residencial colectiva española entre 1981 y 2010: superficie útil, 73,1 m^2



Objetivo específico 3

Medir otros indicadores ambientales (ecotoxicidad, daño a la biodiversidad y a la salud) de viviendas unifamiliares.

Vivienda unifamiliar española media en zona climática D3: Superficie construida, 180 m^2; parcela, 800 m^2



1. Resumen de la tesis

1. RESUMEN

Esta tesis parte del análisis del estado de cinco sistemas de certificación de la sostenibilidad de edificios con respecto a su grado de cumplimiento con el Marco europeo Level(s). Los sistemas de certificación, en tanto que voluntarios, aportan mejores prácticas y proponen valores de referencia, aunque con limitada capacidad de tracción del sector de la construcción (Díaz López et al., 2019). Por otro lado, aunque los marcos de información de huella ambiental, estándares y declaraciones ambientales de producto, y la inclusión del sector en grandes objetivos climáticos como el Acuerdo de París o los Objetivos de Desarrollo Sostenible marcan horizontes de reducción de emisiones, en la atmósfera en 2023 hay 254,71 Bn tCO_2-eq más que en 2015 (UNEP, 2022). Level(s) es el primer sistema de reporte que está basado en la perspectiva de ciclo de vida y que estandariza una metodología de aplicación de la huella de carbono de edificios. Esta tesis cuantifica la capacidad que tienen materiales y técnicas constructivas diferentes a la convencional, pero igualmente disponibles en el mercado, y habituales en las certificaciones, de reducir las emisiones de carbono y otros impactos de la edificación, contribuyendo así con la sostenibilidad del sector.

La metodología principal utilizada en esta tesis es el Análisis de Ciclo de Vida (ACV). Se ha aplicado ACV en edificios residenciales, con alcance de la cuna a la tumba. Se han comparando edificios convencionales con edificios de las mismas prestaciones, con soluciones constructivas factibles de menor impacto, y se han obtenido valores reducidos de emisiones por vivienda en edificio residencial colectivo y unifamiliar. Partiendo de un valor de referencia de 1944 kg $CO_2eq{\cdot}m^{-2}$ en la vivienda media de edificios residenciales colectivos convencionales en España, se han incorporado medidas menos contaminantes, como marcos y suelos de madera, y aislamiento de corcho, que permiten proponer un valor límite de 745 kg $CO_2eq{\cdot}m^{-2}$, es decir, una reducción del 63% respecto al valor de referencia, todo ello para un ciclo de vida de 50 años.

Para alcanzar los objetivos de esta tesis, la investigación consta de tres partes. En la primera se evalúa en qué medida los cinco sistemas Europeos más extendidos de certificación de sostenibilidad (NF Habitat HQE, VERDE, DGNB, BREEAM y HPI) han integrado el enfoque del ciclo de vida durante su proceso de evaluación (Izaola et al, 2022), utilizando cuatro metodologías de análisis: evaluación

cuantitativa, perspectiva multinivel, análisis del mapeo de vacíos y entrevistas a personas expertas. Esto permite identificar valores de referencia de emisiones de CO_2 de 44 kg $CO_2eq \cdot m^{-2} \cdot a^{-1}$ en estos sistemas, y concluir que parece posible una transición del sector hacia objetivos de descarbonización. Aunque a nivel europeo el Marco Level(s) está impulsando la transición, aunando criterios y facilitado mejores prácticas, a nivel ejecutivo por edificio es necesario armonizar datos para que el ACV de resultados agregables.

En la segunda parte se calcula el potencial de calentamiento global por m^2 construido en un edificio representativo del parque residencial colectivo español (Izaola et al, 2023) y se establecen escenarios de mejora, desglosados en impactos incorporados en los materiales durante la extracción, fabricación, construcción y su fin de vida, e impactos operativos durante la fase de uso del edificio. En esta fase del doctorado se identifican las emisiones equivalentes de carbono a lo largo de un ciclo de vida de 50 años de un apartamento con una superficie útil neta de 73,1 m^2. Se ha obtenido que este apartamento medio tiene un potencial de calentamiento global de 1.944 $kgCO_2$-eq/m^2, un 30,8% (559 $kgCO_2$-eq/m^2) incorporado en los materiales, y el 69,2% restante operativo en su fase de uso. La investigación demuestra que es posible disminuir el carbono incorporado a 543 kg CO_2-eq/m^2 (-3%) usando marcos de ventana y suelos de madera, y aislamiento de corcho; y operativo de 202 kg CO_2-eq/m^2 (- 85%) cuando se aplican los estándares del Edificio de Energía casi Nula (European Commission, 2021b). Es decir se puede llegar a reducir los impactos de un apartamento medio en un 62% con técnicas constructivas actuales, sobre todo en la fase de uso del edificio.

En la tercera fase del doctorado, se analiza además del potencial de calentamiento global, la pérdida de biodiversidad causada por la edificación de viviendas unifamiliares (Izaola & Akizu-Gardoki, 2023). Se han cuantificado los efectos sobre la biodiversidad y sobre la salud humana, así como la ecotoxicidad de una vivienda unifamiliar española media de 180 m^2 de superficie construida. La vivienda unifamiliar convencional de ladrillo y hormigón impacta con 7,54E-6 species.yr$\cdot m^{-2}$ de pérdida de biodiversidad, con 3,37 E-3 DALY$\cdot m^{-2}$ de daño a la salud humana y con 11.399 kg 1,4 DCB$\cdot m^{-2}$ de ecotoxicidad. Para reducir los impactos, se han modelado soluciones alternativas de viviendas de las mismas o mejores prestaciones, construidas con madera estructural, balas de paja, y tierra apisonada, las cuales tienen el potencial de reducir en un 31%, 33% y 59% la pérdida de biodiversidad, respectivamente, con respecto a la convencional. Asimismo, la casa de tierra reduce con mejores valores los impactos ambientales, en un −81% el potencial de calentamiento global, en un −67% el daño a la salud humana y en un −46% la ecotoxicidad, en gran parte debido a producir más energía renovable local que la que consume.

Este doctorado concluye que, con las actuales técnicas constructivas, es factible reducir el potencial de calentamiento global entre un 62% y un 81%, así como un 59% los impactos en la biodiversidad por la edificación y uso de viviendas. Asimismo, se vislumbra un límite de emisiones de efecto invernadero (de media 80,7 kg CO_2-eq/m^2) en edificios de bajo impacto ambiental que definen los cinco estándares más usados en Europa, pero con una desviación típica aún elevada de 152%.

Thesis Abstract

This thesis is based on the state of the art of five building rating systems regarding their compliance with the European Level(s) Framework. Certification systems, as voluntary, provide best practices and propose reference values, although with limited driving capacity of the construction sector (Díaz López et al., 2019). On the other hand, although the environmental footprint information frameworks, standards and environmental product declarations, and the inclusion of the sector in major climate objectives such as the Paris Agreement or the Sustainable Development Goals mark emission reduction targets, there are in the atmosphere 254.71 Bn tCO_2-eq more in 2023 than in 2015 (UNEP, 2022). Level(s) is the first reporting system that is based on the life cycle perspective and that standardizes a methodology for applying the carbon footprint of buildings. This thesis quantifies the capacity of materials and construction techniques that are different from conventional ones, but also available on the market, and common in rating systems, to reduce carbon emissions and other impacts of building, thus contributing to the sustainability of the sector.

The main methodology used in this thesis is Life Cycle Analysis (LCA). LCA has been applied in residential buildings, on a cradle to grave scope. Conventional buildings have been compared with buildings with equal performance, with feasible construction solutions of lower impact. Reduced values of emissions per home in multifamily and single-family residential buildings have been obtained. Starting from a reference value of 1944 kg $CO_2eq \cdot m^{-2}$ in the average home of conventional collective residential buildings in Spain, less polluting measures have been implemented, such as wooden windowframes and floors, and cork insulation, which allow us to propose a limit value of 745 kg $CO_2eq \cdot m^{-2}$, that is, a reduction of 63% compared to the reference value, all for a 50 year life cycle.

To achieve the objectives of the Thesis, this research includes three parts. The first one assesses the extent to which the five most widespread European building rating systems (NF Habitat HQE, VERDE, DGNB, BREEAM and HPI) have integrated the life cycle approach during their evaluation process (Izaola et al, 2022), using four analysis methodologies: quantitative evaluation, multilevel perspective, gap mapping analysis and interviews with experts. This makes it possible to identify reference values of CO_2eq emissions of 44 kg $CO_2eq \cdot m^{-2} \cdot a^{-1}$ in these systems, and to conclude that a transition of the sector towards decarbonization objectives seems possible. Although at European level the Level(s) Framework is driving this transition, unifying criteria and facilitating best practices,

at an executive level per building it is necessary to harmonize data so that LCA provides aggregated results.

The second part calculates the global warming potential per built m^2 of a representative building of the Spanish multifamily housing stock (Izaola et al, 2023) and establishes improvement scenarios, broken down into impacts incorporated in the materials during extraction, manufacturing, construction and its end of life, and operational impacts during the use phase of the building. In this part of the PhD, the equivalent carbon emissions over a 50-year life cycle of an apartment with a net useful area of 73.1 m^2 are identified. It has been found that this average apartment has a global warming potential of 1,944 $kgCO_2$-eq/m^2, 30.8% (559 $kgCO_2$-eq/m^2) incorporated in the materials, and the remaining 69.2% operational in its use phase. Research shows that it is possible to reduce embodied carbon to 543 kg CO_2-eq/m^2 (-3%) using wooden window frames and floors, and cork insulation; and operational of 202 kg CO_2-eq/m^2 (-85%) when Nearly Zero Energy Building standards are applied. In other words, the impacts of an average apartment can be reduced by 62% with current construction techniques, especially in the use phase of the building.

Thirdly, in addition to the global warming potential, the loss of biodiversity caused by the construction of single-family homes is analyzed (Izaola & Akizu-Gardoki, 2023). The damages on biodiversity and on human health have been quantified, as well as the ecotoxicity of an average Spanish single-family home with a built area of 180 m^2. The conventional brick and concrete single-family home impacts biodiversity loss with 7.54E-6 species.yr m^{-2}, causes 3.37 E-3 DALY m^{-2} of damage to human health and impacts ecotoxicity with 11,399 kg 1 .4 DCB·m^{-2}. To reduce impacts, alternative housing solutions with the same or better performance have been modeled, built with structural wood, straw bales, and rammed earth, which have the potential to reduce by 31%, 33% and 59% the loss of biodiversity, respectively, with regard to the conventional house. Likewise, the earth house reduces environmental impacts with better values, by −81% the global warming potential, by −67% the damage to human health and by −46% the ecotoxicity indicator, largely due to generating more local renewable energy than it consumes.

This PhD concludes that, with current construction techniques, it is feasible to reduce the global warming potential between 62% and 81%, as well as the impacts on biodiversity due to the construction and use of homes, by 59%. Likewise, a limit value of greenhouse emissions is seen (on average 80.7 kg CO_2-eq/m^2) in buildings with low environmental impact, defined by the five most used standards in Europe, but still with a high standard deviation of 152%.

2. Introducción y antecedentes

2. INTRODUCCIÓN

La contribución del sector de la construcción a las emisiones mundiales de gases de efecto invernadero que provocan el calentamiento global fue del 37% en 2021 (UNEP, 2022). El sector de la construcción a escala mundial consume el 45% de las materias primas, el 36% de la energía primaria y el 50% del agua dulce (Kaja & Goyal, 2023). Según la Organización Mundial de la Salud, mueren a nivel global prematuramente 3,2 millones de personas al año por respirar aire contaminado en el interior de los hogares (WHO, 2023). En Europa genera el 30% de los residuos (European Commission, 2020). Se estima que 988 millones de aves mueren al año en EE. UU. por colisión con edificios (Loss et al., 2012). La contaminación lumínica y acústica de las ciudades provoca graves daños en los ecosistemas. Respirar partículas en suspensión PM2,5 (resultantes de la calefacción, movilidad y consumo urbano) provoca la muerte prematura de 10,2 millones de personas al año (Vohra et al., 2021).

Los primeros sistemas de certificación de la sostenibilidad de edificios recogían una lista de acciones a realizar durante el proceso constructivo. Después se incorporaron referencias de valores admisibles provenientes de diversas instituciones del mundo de la salud, la toxicología o las ciencias ambientales, ponderando los resultados según criterios variables. Actualmente se exige un análisis de prestaciones y un sistema de interpretación más integrado que la mera ponderación respecto a referencias externas descontextualizadas del objeto analizado (WGBC, 2020a). El Análisis de Ciclo de Vida (ACV) aparece como herramienta capaz de calcular los impactos ambientales para posteriormente realizar comparaciones e interpretar las conexiones entre diferentes categorías de impacto ambiental, y analizar los impactos de diferentes ámbitos de actuación. En el caso del sector de la construcción lo hace desde el material o el producto de construcción hasta el edificio completo o el entorno urbano y territorial en que se inserta. Los límites del sistema que se pueden modelar en ACV cuentan con la totalidad de los materiales, procesos de extracción, transporte y erección del edificio, recursos utilizados para su funcionamiento durante la etapa de uso de una o varias generaciones de usuarios, así como los residuos generados en esta etapa y en una etapa final en la que se puede derribar o revalorizar el edificio o sus partes (AENOR, 2021), (CEN/TC350, 2022). El ACV denomina aspectos embebidos a los incorporados en los materiales durante la construcción, sustitución y fin de vida. Denomina aspectos operativos a los relacionados con el consumo de energía y agua durante la fase de uso u operativa (CEN, 2011). En el ámbito europeo todo esto queda recogido exhaustivamente en la norma EN15978 (*CEN TC 350 - Building level standards*, s. f., 2011).

La Comisión Europea incluye el ACV a través de su Marco de Reporte de la sostenibilidad de los edificios, Level(s) (European Commission, 2019b), que no califica ni certifica pero sí obliga a su empleo para acceder a subvenciones como la de los fondos para la Rehabilitación Sostenible (Taxonomy, 2020). El Marco Level(s) se basa en el enfoque de ciclo de vida e intenta mitigar el cambio climático reportando la huella de carbono y la huella energética, pero no incorpora aspectos relacionados con la biodiversidad ni con el entorno construido. Level(s) se ha convertido en la referencia para validar la sostenibilidad de los edificios, en línea con la reglamentación europea, las políticas globales y los sistemas de certificación de la sostenibilidad de edificios (Figura 1). En la Directiva Europea de Eficiencia Energética de Edificios (EPBD) se señala que el 75% de las viviendas europeas no son sostenibles desde el punto de vista energético, considerando sostenibles los que consumen menos de 60 kWh/m^2 y año en la zona climática mediterránea (Fernbas, 2019). A escala mundial, la Agencia Internacional de la Energía comunica que si las tecnologías de secuestro de carbono (aún en TRL 4) no llegan a tiempo (año 2050) ni escala (reducción del 58%), habremos superado el umbral de calentamiento global de +1,5ºC (IEA, 2023).

La Comisión Europea ha realizado una consulta pública (European Commission, 2023) en 2023 para recabar datos sobre el desarrollo de una nueva hoja de ruta para reducir las emisiones de carbono durante la vida de los edificios. En España en 2021 (GBCe, 2022) se acordó una hoja de ruta con 230 entidades del sector. En la hoja de ruta española se explica cómo la industria nacional de la construcción debe pasar de emitir 48 Mt CO_2-eq anuales actuales, a cero en el año 2050. Se propone rehabilitar energéticamente 9 millones de viviendas en este período para bajar su calificación de la media actual de Clase E (42 $kWh/m^2 \cdot$año), a Clase B (15 $kWh/m^2 \cdot$año), así como recuperar 1,9 millones de viviendas secundarias o vacías, como vivienda principal para aprovechar su materialidad. Se propone la desaparición de la combustión fósil para calefacción y agua caliente sanitaria para el 2030. En esta hoja de ruta se recomienda también promover el uso de materiales de origen biológico como madera, corcho y fibras, así como materiales locales de muy baja transformación, como piedra natural y tierra. Por último, se recomienda medir y cuantificar la huella de carbono de los edificios mediante el ACV, pero no se sugiere ninguna cifra (GBCe, 2022).

Certificaciones y Level(s)		Marco Europeo	Marco Global
BREEAM	1991		
	…		
	1997		Protocolo de Kyoto
	…		
LEED	2002	EPBD, 1ª Directiva 2002/91/EC	
	…		
	2007	Estrategia Europea 20/20/20	
	2008	Paquete Europeo de Energía y Cambio Climático 2008-2020	
	2009	RED, 1ª Directiva 2009/28/EC	
VERDE, DGNB, NF- HQE	2010	EPBD, 2ª Directiva 2010/31/EU	
	…		
HPI	2012	EED, Directiva 2012/27/EU EPBD, 3ª Directiva 2012/244/EC	
	…		
	2014	Marco Europeo de Clima y Energía 40/32/32,5	
Inicio de Level(s) dentro de las políticas de economía circular	2015		ODS, Agenda 2030 COP 21, Acuerdo de París
	2016	Agenda Urbana EU Recomendación 2016/1318 NZEB	
Testeo de Level(s) en 130 edificios de 21 países	2017		
	2018	EPBD, 4ª Directiva 2018/844/EC Regulación 2018/1999 sobre gobernanza energética RED, 2ª Directiva 2018/2001 Hoja de Ruta para la Descarbonización 2050 Plan de Acción sobre Financiación Sostenible	IPCC Informe sobre calentamiento global de +1,5°
Análisis del testeo y modificaciones	2019	Recomendación 2019/786 Building Renovation	
Lanzamiento de Level(s), Adopción en Taxonomy	2020	Plan de Acción sobre Economía Circular, Pacto Verde Europeo, Taxonomy, Marco de Financiación Sostenible	
Academia Level(s)	2021	New European Bauhaus	Informe conjunto IPCC e IPBES
Criterios de GPP según Level(s)	2022		
	2023	Hojas de Ruta nacionales para la descarbonización en el ciclo de vida del edificio, Pasaporte del Edificio	

BREEAM, LEED, VERDE, DGNB, NF-HQE, HPI: Sistemas de certificación de la sostenibilidad de edificios de Gran Bretaña, EE.UU., España, Alemania, Francia e Irlanda, respectivamente.
GPP: Green Public Procurement

EPBD: Energy Performance of buildings Directive
20/20/20 (y 40/32/32,5): % de Reducción de Gases de Efecto Invernadero/de generación de Renovables/de Eficiencia energética
RED: Renewable Energy Directive
EED: Energy Efficiency Directive
NZEB: Nearly Zero Energy Buildings

ODS: Objetivos de Desarrollo Sostenible
COP: Conference of Parties
IPCC: Intergovernmental Panel on Climate Change
IPBES: Intergovernmental Panel on Biodiversity and Ecosystem Services

Figura 1. Mapa de iniciativas relacionadas con el Marco Level(s) (realizado por el autor).

En el análisis de la situación climática nacional se estima que el sector de transporte emite el 27% de las emisiones nacionales, la industria el 20,8%, la agricultura el 14%, el suelo residencial, comercial e institucional el 9,2%, y el resto de sectores el 28,9% (PNIEC, 2021). En el sector y la regulación nacionales se han desarrollado las ventajas de cambiar ventanas (reducir consumo energético en un 24% o invertir en fotovoltaica (reducir energía primaria en un 11%) (IDAE, 2011). Y se recomiendan como primera medida para reducir los impactos del sector multiplicar por 10 la tasa de rehabilitación de edificios para reducir un 32% su consumo energético (MITMA, 2020).

Al mismo tiempo, el cambio climático no solo se manifiesta en el entorno político sino en la población: el 93% de la población española considera que el cambio climático es una problemática real (Ideara & MITERD, 2021). A pesar de los Objetivos de Desarrollo Sostenible o del Acuerdo de París, la concentración de gases de efecto invernadero (GEI) subió un 2,3% de 2019 a 2020, un 2,4% de 2020 a 2021 y un 1,8% de 2021 a 2022. A fecha 26 de noviembre de 2023, la atmósfera tiene 420,59 ppm de CO_2, 1.922,26 ppb de CH_4, 336,66 ppb de N_2O y 11,42 ppt de SF_6 (US Department of Commerce, 2023) y se estima que en 2023 subirá entre un 2,1 y un 2,3% por encima de 2022. No solo en lo atmosférico percibimos nuevos riesgos; en lo doméstico, el 8% de los hogares no pueden pagar su calefacción (INE, 2023). El 89% de las personas encuestadas afirma que existe la necesidad de «subvencionar la mejora del aislamiento en las viviendas» (Ideara & MITERD, 2021).

A pesar de existir una necesidad de reducir los impactos de Gases de Efecto Invernadero (GEI), España no cuenta con un valor de referencia de las emisiones de GEI incorporadas en los materiales del edificio en la normativa vigente. Por otro lado, las emisiones relacionadas con el consumo energético durante el uso del edificio (carbono operativo), se han ido restringiendo un 67% con la exigencia de aislamiento desde el Código Técnico de 1979 (CT 79) y, especialmente, con las medidas de eficiencia e inclusión de renovables desde el Código Técnico de la Edificación de 2006 (CTE 2006), aunque no haya una referencia hasta la citada Directiva de Eficiencia Energética de Edificios, EPBD (Fernbas, 2019). Incluso, el límite de demanda energética (clase E) de la EPBD de 60 $kWh \cdot m^{-2} \cdot y^{-1}$ para los edificios que la propia EPDB denomina “de energía casi nula” admite unas emisiones de 42 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$ (2.100 kg CO_2-eq$\cdot m^{-2} \cdot$en un ciclo de 50 años). En la Figura 2 se comparan umbrales de emisiones admisibles por las normativas de edificación residencial de varios países. En el caso de Suiza, los datos son de 2009 (Heeren et al., 2009) y permiten observar la reducción en los otros países, que se corresponde con datos de 2021 en línea con los resultados de la Tesis (Zimmermann et al., 2021), (Suomen Ympäristöministeriö, 2021), (Décret n° 2021-1004, 2021), (DGNB, 2021) y (UK Parliament Post, 2021) respectivamente.

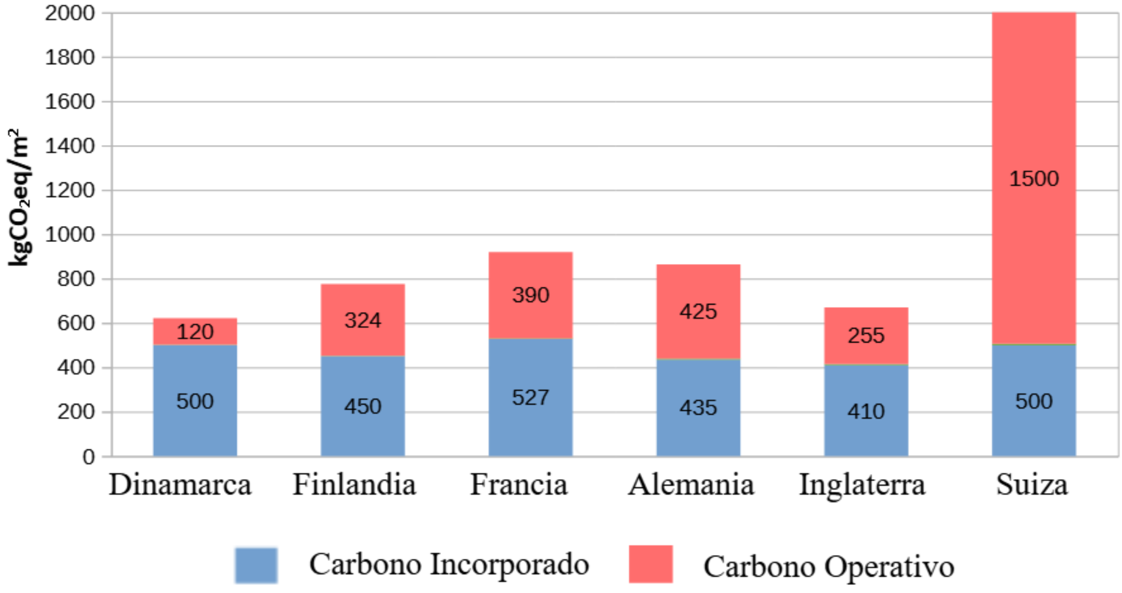


Figura 2. Valores límite de carbono incorporado y operativo propuestos en otros países, realizado por el autor con referencia a (Heeren et al., 2009), (Zimmermann et al., 2021), (Suomen Ympäristöministeriö, 2021), (Décret n° 2021-1004, 2021), (DGNB, 2021) y (UK Parliament Post, 2021)

Por otro lado, tanto para el Marco Level(s) como para los sistemas de certificación, la sostenibilidad de los edificios es más que limitar sus emisiones de GEI, y la descarbonización del sector requiere más que un valor de referencia, así como actuar en todos los materiales de construcción. En Europa y EE.UU. desde el siglo XX y específicamente en España desde 1927 el cemento fue sustituyendo los materiales de construcción previos, piedra, madera, cerámica y hierro (Casariego y Rozas, 2022), hasta constituir actualmente el material dominante en el 99% de la edificación (Arriaga, 2020). El consumo de cemento en España tuvo un máximo por encima de los cinco mil millones de toneladas en 2006, cayó por debajo de mil en las crisis de 2008 y del COVID en 2020, se recuperó hasta un total de 21.125.407 toneladas en 2021 y descendió un 2,1% en 2022 a 19.954.755 toneladas (INE, 2023). La fabricación mundial de 4,44 millones de toneladas de cemento en 2021 contribuyó con el 8% de las emisiones mundiales de GEI (Sverdrup & Olafsdottir, 2023). Substituirlo por madera reduciría las emisiones en la fase de fabricación de materiales de construcción de un edificio en un 69%, reduciendo las emisiones mundiales de CO_2 en un 9% (Himes and Busby, 2020). Sin embargo, no se ha encontrado ninguna cuantificación de la reducción de los impactos de ecotoxicidad por esta sustitución de materiales.

El estudio «Materiales de construcción y clima: construyendo un nuevo futuro» de la ONU pide al sector internacional de la construcción que evite lo superfluo, que use más madera y fibras vegetales, y que crezca anualmente hasta alcanzar un 50% de tasa de reciclado, que actualmente es del 4%, si pretende continuar un ritmo de producción de edificios equivalente al de todos los que hay en París, cada cinco días, y hacer esto mientras se mantiene dentro de un planeta habitable (Programme & Architecture, 2023). «*A safe space for humanity*» (Un espacio seguro para la humanidad) es la expresión repetida desde la definición de los límites planetarios (Rockström et al., 2009) hasta los últimos informes del Panel Intergubernamental sobre Cambio Climático acerca del patente curso de calentamiento global de +1,5ºC en este siglo (Intergovernmental Panel on Climate Change (IPCC), 2022). El último estudio sobre el estado de los nueve límites planetarios demuestra que hemos sobrepasado seis de ellos: los flujos biogeoquímicos, el cambio de usos del suelo, la integridad de la biosfera, el clima y los productos de síntesis química (novel entities) (Richardson et al., 2023). Con respecto a la media del Holoceno, el flujo de Nitrógeno en equilibrio (0 Tg) se encuentra en la actualidad en 190 Tg; queda sólo el 54% de los suelos (biomas) originales; la tasa de extinción de especies en los últimos 150 años se estima 10 veces por encima de la media del Holoceno; el límite de concentración de CO_2 atmosférico de 350 ppm, se encuentra en 423 ppm; y se desechan nuevos químicos sintetizados sin conocimiento de su impacto en el planeta. El planeta Tierra se encuentra en una zona de riesgo moderado, pero empeorando, respecto a los cambios de uso del suelo y de las aguas superficiales y marinas; de alto riesgo respecto al forzamiento radiativo y la concentración de GEI causantes del cambio climático, y también respecto a los flujos bioquímicos de nitrógeno y potasio; y de muy alto riesgo respecto a la integridad genética de la biosfera, aunque algo menor respecto a la funcional, así como sobre los nuevos compuestos físicoquímicos sintetizados por la actividad industrial humana, no por la naturaleza, como los microplásticos, los pesticidas o los residuos radioactivos (Richardson et al., 2023).

El 77% de las especies de plantas está en peligro de extinción (Antonelli et al., 2023) por la actividad humana industrial desde 1850, inicio del antropoceno (Ruddiman, 2013). Además, se advierte que la tendencia actual de pérdida de biodiversidad lleva los ecosistemas hacia un colapso similar al estudiado durante la extinción del Pérmico-Triásico (Huang et al., 2023). Los Objetivos de Desarrollo Sostenible (ODS) 14 «Vida marina» y 15 «Ecosistemas terrestres» experimentan amenazas directas para su consecución, y los ODS 2 «Nutrición» y 6 «Agua limpia», indirectas (CDB, 2020). El informe conjunto sobre el estado de la naturaleza en la UE, basado en las directivas Aves (2009/147/CE) y Hábitats (92/43/CEE), la red Natura 2000 y los objetivos 1 y 3 de la Estrategia sobre Biodiversidad europea UE 2020, confirman el continuo empeoramiento del estado de las especies desde el inicio de las observaciones en el año 2000. En 2012, el 32% de las especies se encontraban bajo presión o amenaza. En 2018, el 39%. También se detectó un 9% menos de aves invernantes en el mismo período. La conservación del hábitat también empeoró (75% en 2012, 81% en 2018), quedando solo el 15% de los 233 hábitats europeos en buen estado de conservación. La red Natura 2000 muestra una brecha de conservación del 12% para los hábitats, del 20% para las especies de aves y del 2% para las especies que no son aves. Además, el 31% de los hábitats forestales se encuentran en mal estado de conservación (EEA, 2020). El citado informe conjunto concluye que la biodiversidad en la UE continúa deteriorándose debido a los cambios en el uso de la tierra y el mar, la sobreexplotación y las prácticas de gestión insostenibles, así como la modificación del régimen hídrico, la contaminación, las especies exóticas invasoras y el cambio climático.

A escala global, el mundo pierde cada año el 1% de todas las especies de insectos. Las causas incluyen el cambio de hábitats como principal impulsor (49,7%), seguido de la contaminación (25,8%). El cambio de hábitats se deriva de la transformación de la tierra para proporcionar edificios, movilidad, industria o agricultura. Aunque la agricultura causa el 24% de la disminución de insectos, la urbanización es responsable del 11% y la deforestación del 9%. Aunque los herbicidas, insecticidas y fungicidas causan el 13% de la disminución, las aguas residuales urbanas e industriales son responsables del 3%. Las aguas residuales también causan eutrofización y acidificación. Asimismo, las especies invasoras se ven favorecidas por el cambio climático y la urbanización (Sánchez-Bayo y Wyckhuys, 2019).

El análisis del estado de arte actual muestra la necesidad de cuantificar los impactos ambientales en la construcción y del establecimiento de valores límites (por encima de las cuales no se puede llegar a emitir) y valores óptimos de sostenibilidad (los cuales serán referencias sostenibles). Esta tesis tiene el objetivo principal de **analizar los actuales valores existentes (1) y proponer valores de referencia de reducción factibles de las emisiones de carbono (2), los impactos sobre la biodiversidad (3) y el daño a la salud humana provocado por la edificación residencial.**

2.1 Justificación y relevancia de la investigación[R1]

La problemática identificada en esta investigación indica la importancia de establecer valores límite factibles de reducción del potencial de cambio climático, así como referencias de los impactos ambientales en la biodiversidad y salud humana de la construcción residencial Española. Baja de la escala mundial al ámbito europeo y, más concretamente, al sector de la vivienda español. Diferencia la actividad de obra civil, industrial e infraestructuras, de las de edificación, y se centra en la edificación residencial, no en el terciario y de oficinas. Teniendo en cuenta solo los hogares, las viviendas son responsables del 22% de la demanda energética del sector y del 17% de sus emisiones de CO_2 (UNEP, 2022). El origen antropogénico y doméstico del calentamiento global es ineludible.

Desde mediados del siglo XX, el sector de la construcción ha estado dominado por unos pocos materiales y técnicas constructivas altamente contaminantes, como el uso de cemento, responsable del 8% de las emisiones mundiales (Sverdrup & Olafsdottir, 2023). El incremento de población, así como la generalización de un estilo de vida más demandante de espacios, confort y equipamientos, ha convertido la construcción de edificios y ciudades en una actividad primordial en España, con un pico del 10,84% del PIB en 2006, reducido al 4,76% en 2022 (INE, 2023). Cada mes se construyen en el mundo 242 Bn m^2, el equivalente a la superficie construida en Nueva York (Adams et al., 2019), (UNEP, 2023). En 2006 en España se concedieron 736.269 nuevas licencias de vivienda (INE, 2011), casi tantas como en Gran Bretaña (208.980) (ONS, 2023), Alemania (160.960) (DESTATIS, 2023) y Francia (373.000) (INSEE, 2023) juntas (742.940), aunque la suma (202.900.667) de la población de estos tres países (60.803.700, 81.177.817, 60.919.150 respectivamente) más que cuatruplicaba (x4,56) la población española (44.442.831) en 2006 (MACROTRENDS, 2023). Construir tiene consecuencias ambientales a escala local, regional y mundial. A escala planetaria, el sector de la construcción es responsable del 37% de las emisiones de gases de efecto invernadero, del 40% de la demanda energética y produce el 30% de todos los residuos (UNEP, 2022). Además, la vivienda es un foco de desigualdad, injusticia y daño ambiental (López et al., 2020).

La justificación genérica de la necesidad de cuantificar el impacto del potencial del calentamiento global del sector residencial es evidente: desde comienzos del siglo XXI, hay evidencia científica de que el cambio climático es real y afecta a la capacidad de carga planetaria (Pugh, 2003). En el año 2000, los medios de comunicación de masas adoptaron la visión de consenso de que el calentamiento global está causado por la actividad humana (Fisher, 2007). En el año 2006 las publicaciones sobre cambio climático aumentaron gracias al Informe Stern, la película de Al Gore y el Premio Nobel del

IPCC (Pasquare Mariotto, 2018). En un análisis de 120.000 publicaciones sobre el tema de entre 2001 y 2018, se identifican cinco áreas de investigación: ciencias físicas, paleo-climatología, ecología del cambio climático, tecnología climática y política climática (Fu & Waltman, 2022). Esta tesis pretende ofrecer al sector científico y a las políticas residenciales valores de indicadores sobre el cambio climático de la vivienda, midiendo el efecto en el clima y las posibilidades de reducción que ya ofrecen algunas técnicas constructivas existentes y materiales tradicionales como la tierra apisonada, las balas de paja o las soluciones estructurales en madera.

Mediante la revisión bibliográfica realizada a lo largo de esta tesis se han identificado 147 estudios dedicados a los impactos de la edificación residencial colectiva, en particular analizando los 15 que desde 2001 se centran en la huella de carbono. También se ha revisado el alcance de aplicación del Análisis de Ciclo de Vida (ACV). La comunidad científica lo utiliza en múltiples campos, reconociendo su fiabilidad, credibilidad y capacidad para aportar datos cuantitativos útiles para los responsables de la toma de decisiones de sostenibilidad (Baitz et al., 2013). Pero los resultados de un ACV deben ir acompañados de una visión de la sostenibilidad y de una toma de decisiones multicriterio específicas para cada sector (Kumar et al., 2021). Resulta una de las metodologías preferidas de entre 64 métodos de evaluación de impacto sobre la biodiversidad (Damiani et al., 2023), que facilita comparativas en los 15 estudios sobre huella de carbono de edificación residencial y está recomendada por los agentes políticos y sectoriales en los estándares europeos como Level(s) y en las certificaciones de sostenibilidad de última generación.

Esta Tesis aplica ACV en el sector de la edificación, en línea con otros estudios del grupo de investigación Life Cycle Thinking Group de la Universidad del País Vasco/Euskal Herriko Unibertsitatea que incluyen ACV en los sectores de los electrodomésticos (Alejandre et al., 2022), de las baterías de almacenamiento eléctrico (Iturrondobeitia et al., 2022), de los productos de limpieza (de Lapuente Díaz de Otazu et al., 2022), del transporte (Montoya-Torres et al., 2023), o de la educación universitaria (Erauskin-Tolosa et al., 2021). Esto se une a los estudios con metodología input-output (Leontief, W., 1987) aplicada para el cálculo de huellas eléctricas (San Salvador del Valle et al., 2022) y para huellas de consumo energético de modelos de vida comunitarios (Villamor et al., 2022).

3. Objetivos

El objetivo principal de la tesis es cuantificar la capacidad de reducción de impactos ambientales de los materiales y técnicas de construcción sostenibles, en edificios de viviendas unifamiliares y de apartamentos. La cuantificación se muestra con indicadores como el potencial de calentamiento global, la salud humana y la pérdida de biodiversidad. La herramienta de cálculo es el ACV.

Para lograr este objetivo se considera necesario perseguir los siguientes objetivos específicos:

1. Comparar cómo los cinco sistemas de certificación de la sostenibilidad más relevantes en Europa contribuyen con la descarbonización del sector, siguiendo las pautas de la norma EN15978, del Marco Level(s) y de la Directiva sobre eficiencia energética de los edificios.

2. Medir la reducción del Potencial de Calentamiento Global de un apartamento representativo del parque de edificación residencial colectiva española cuando se sustituyen materiales y técnicas convencionales como una viga de hormigón por otra con las mismas prestaciones, de madera; o como una ventana corredera de aluminio por otra de madera y doble vidrio. Se proponen valores de referencia para un apartamento de 73 m^2 de superficie útil.

3. Medir la reducción de otros impactos ambientales además del Potencial de Calentamiento Global, de una vivienda unifamiliar representativa del parque español de unifamiliares. Se comparan la ecotoxicidad, la protección de la biodiversidad y la salud humana de una vivienda unifamiliar convencional de hormigón y ladrillo, y superficie construida media de 180 m^2, emplazada sobre una parcela de 800 m^2, dentro de la zona climática D3, con equivalentes de paja, madera y tierra apisonada (tapial).

Tabla 0.1. Esquema resumen de objetivos

1. Analizar los valores de referencia que las certificaciones están proponiendo para la descarbonización del sector.	2. Proponer un valor de referencia para las emisiones de CO_2 de la edificación residencial colectiva española.	3. Identificar y medir otros impactos ambientales de la vivienda unifamiliar española, como la pérdida de biodiversidad y el daño en la salud humana.

4. Hipótesis

La tesis parte de tres hipótesis:

1ª. Faltan referencias óptimas de las emisiones de CO_2 del sector.

Pese a la baja penetración de mercado (1%) de los edificios certificados con alguno de los cinco sellos identificados como más relevantes (NF Habitat HQE, VERDE, DGNB, BREEAM-NL, y HPI), el hecho de introducir el ACV y de haberse alineado con el Marco Europeo Level(s), genera unas buenas prácticas ejemplarizantes que demuestran al sector que es posible edificar reduciendo significativamente las emisiones de carbono. Sin embargo, se observa la falta de valores de referencia para la descarbonización del sector, y se observa una generalización de las prácticas propuestas sin cifras específicas en Europa.

2ª. Existen materiales y técnicas constructivas disponibles en el mercado capaces de reducir las emisiones de la edificación residencial colectiva.

Aunque, por razones de mercado, la construcción convencional no abandona el ladrillo y el hormigón armado, la tradición preindustrial, los nuevos materiales industrializados y el cálculo con ACV demuestran que introducir fibras vegetales en los edificios residenciales, incluso de la forma más sencilla, en ventanas y suelos de madera y aislamiento de corcho en las paredes, reduce significativamente las emisiones de carbono de cada apartamento. Cuando se aplica la normativa de eficiencia energética, se reduce aún más.

3ª. Existen materiales y técnicas disponibles no convencionales que pueden reducir no sólo las emisiones, sino también otros impactos ambientales importantes de las viviendas unifamiliares.

El uso de técnicas constructivas sostenibles ya existentes pueden reducir los impactos de emisiones de calentaminto global de la vivienda unifamiliar y a otras categorías de impacto ambiental como la ecotoxicidad, la pérdida de biodiversidad y el daño a la salud humana; y que en vivienda unifamiliar es factible ir más allá de ventanas, suelos y aislamiento, construyendo con paja, madera estructural o tierra apisonada, y reducir significativamente los impactos.

5. Metodologías y datos

La principal metodología utilizada a lo largo de los tres artículos es el mencionado Análisis de Ciclo de Vida, ACV. Se ha llevado a cabo principalmente con el software OpenLCA y con la base de datos de Ecoinvent más actualizada disponible en cada momento. Se ha seguido en todo momento el estándar de aplicación del ACV para edificios EN15978 (*CEN TC 350 - Building level standards*, s. f.). Además del uso del software OpenLCA combinado con la base de datos Ecoinvent, se ha hecho una comparativa de resultados con otra herramienta online, OERCO2 (Solís-Guzmán et al., 2018), que permite modelar de una forma más aproximada y ello agiliza la obtención de resultados en comparación al software OpenLCA, aunque sólo aplicable a la primera fase de la EN15978, pero en lugar de con datos genéricos de Ecoinvent, con datos específicos del mercado español, más concretamente andaluz. Los datos energéticos también han sido datos oficiales del Instituto para la Diversificación y Ahorro de la Energía, IDAE. El software OpenLCA 1.11 ha alimentado con la base de datos Ecoinvent 3.9 (Pamu et al., 2022) la metodología ReCiPe 2016 (H) por su inclusión de 18 categorías de impacto intermedio y 23 de impacto al final de la cadena causa-efecto, así como por sus métricas compatibles con los indicadores de Level(s). Ecoinvent, del Centro Suizo de Inventarios del Ciclo de Vida, es utilizado en la industria de la construcción en toda Europa (Martínez-Rocamora et al., 2016). ReCiPe aplicada en los puntos finales de impacto incluye ecosistemas, uso de la tierra y una taxonomía de ocho especies. Además de ReCiPe, también se calculó la Demanda Energética Acumulada (CED) de la edificación residencial colectiva. En todos los casos se ha elegido el criterio «*Cut-off*» para la asignación de cargas ambientales de materiales.

En todos los cálculos, se han extraído datos reales de edificios a partir de sus mediciones de proyecto arquitectónico de ejecución obtenidos de los equipos de arquitectos firmantes del correspondiente proyecto de ejecución, con el desglose de todos los materiales y sus cantidades ejecutadas para la finalización funcional del edificio. El inventario de materiales resultante ha incluido el 99% de las mediciones de los componentes del edificio dejando fuera elementos singulares e insuficientemente definidos en el proyecto como cerraduras, manillas, válvulas y mecanismos eléctricos. Este inventario (180 mediciones) se ha agrupado en flujos de entrada (70) directamente identificables en la base de datos de Ecoinvent, haciendo uso de materiales primarios modelados en la base de datos. Se han agrupado los resultados siguiendo la norma EN15978, que denomina A la etapa de producto y del proceso constructivo, B la de uso y C la de fin de vida. Cada etapa la subdivide en módulos: A1 extracción, A2 transporte a fábrica, A3 fabricación, A4 transporte a obra, A5 construcción; B1 uso, B2 mantenimiento, B3 reparación, B4 rehabilitación, B5 sustitución, B6 energía operativa, B7 agua operativa; C1 derribo, C2 transporte de residuos, C3 procesamiento de residuos y C4 Vertido. Se ha hecho uso de los flujos de mantenimiento (B2) y reparación (B3) asumidos por Ecoinvent. Sin embargo, a raíz de la baja tasa (0,3%) de rehabilitación española y los estudios de adecuación de los períodos de ciclo de vida a 50 años, no se incluye el módulo B4 (rehabilitación) de la EN15978. Además, ante la incertidumbre en el modelado de los datos de cálculo del módulo B5 (sustitución), que además, en la construcción española se antepone a la rehabilitación, se ha optado por añadir en los edificios de vivienda colectiva un 8% al carbono embebido, proveniente de medias de la revisión bibliográfica (Lavagna et al., 2018). Los límites del sistema de ACV se consideran «de la cuna a la tumba», incluyendo las etapas A, B y C de la EN15978 con las salvedades mencionadas.

La representatividad de los edificios considerados como escenario base se basa en la tipología convencional del parque edificado, sea de vivienda colectiva o unifamiliar, en función del año de construcción, materiales y técnicas constructivas y superficies medias. En el inventario de materiales, el hormigón armado (grava, arena, acero, cemento y agua en orden decreciente de peso por unidad) y la cerámica (ladrillos en particiones y fachadas, tejas y pavimentos cerámicos) tienen el mayor peso, según datos de estadísticas oficiales del parque edificado español presentes en la Estrategia de Rehabilitación española a largo plazo, ERESEE (MITMA, 2020). En el apartado *Definition of the average Spanish building modelled,* de (Izaola et al, 2022) se define en detalle el escenario base de edificio residencial colectivo, y en el apartado *Description of scenarios*, de (Izaola & Akizu, 2023) se define el escenario base de vivienda unifamiliar. Los 4 escenarios con menores impactos en los apartamentos (con ventanas de madera y doble vidrio, ó suelo de madera, ó aislamiento de corcho y con la combinación de estos tres) y los 3 escenarios en las unifamiliares (construcción con madera, con paja y con tierra apisonada), provienen de las respectivas revisiones literarias, así como de tipologías y casos no convencionales citados por ERESEE y alineados con estudios locales (GBCe, 2022) e internacionales (UNEP, 2023). En ambos edificios colectivo y unifamiliar, el escenario base ejemplifica el edificio representativo o «convencional» de su caso. Los otros escenarios ejemplifican edificios menos convencionales, pero igualmente factibles, no teóricas «mejores prácticas», sino edificios viables técnica y comercialmente, con datos reales. Se trata de edificios con más presencia de la madera (de más fácil ejecución en todos los casos), ventanas y aislamientos de mejores prestaciones (más amortizable por su ahorro energético), y en el caso de las unifamiliares, con otros materiales naturales y locales como la tierra apisonada y la paja embalada, más difícil de generalizar, pero no excluidos de la edificación residencial colectiva.

La superficie construida de cada edificio se reparte entre su número de viviendas y la superficie útil media de éstas, y la división de las métricas obtenidas en OpenLCA entre esta superficie de vivienda, se constituye como unidad funcional, por m^2. Esta unidad es común en la literatura científica, así como en la redacción de políticas sobre edificios. En el proceso de elaboración del estudio sobre vivienda unifamiliar, así como en un estudio de referencia para esta tesis y para el conjunto de las políticas europeas (Röck, Martin et al., 2022), también se sugiere dividir las métricas ambientales entre el número de habitantes, para obtener resultados «*per cápita*», pero finalmente se ha dejado fuera de publicación de esta tesis la unidad funcional por habitante, aunque está recogida en las hojas de cálculo de los escenarios de vivienda unifamiliar.

Además de todo lo anterior, se han utilizado otras metodologías, especialmente respecto a los sistemas de certificación, con el fin de contextualizar la investigación. En todas las fases del estudio se ha realizado una revisión de la literatura científica relevante más actual. En la primera se ha enfocado la transformación del sector derivada del reconocimiento de sus impactos ambientales a partir de la ya mencionada Perspectiva Multinivel (MLP) (Geels, 2019), la cual también ha servido para identificar nichos de transición y escenarios de comparación en los edificios colectivo y unifamiliar. También con respecto a los sistemas de certificación se realizó un mapeado y *gap-analysis* sobre el grado de cumplimiento de los sistemas con los indicadores del Marco Level(s), así como una serie de entrevistas a personas expertas, que también alimentó el MLP. En el caso de los edificios residenciales colectivos se compararon resultados de los escenarios, calculados con OpenLCA y con OERCO2, para extraer conclusiones respecto al uso de herramientas de cálculo rápido pero parcial. En el caso de las viviendas unifamiliares se calcularon indicadores de puntos intermedios y finales para comunicar resultados de ACV de manera más clara y transparente, siguiendo recomendaciones de expertos (Gomes et al., 2022).

Tabla 0.2. Esquema resumen de metodologías, herramientas y datos

Metodologías	1. Revisión de literatura científica	2. Aplicación de ACV	3. Perspectiva Multi-Nivel	4. Mapeado y gap análisis	5. Encuesta a expertos	6. Análisis de escenarios	7. Tipologías edificatorias
Herramientas y datos	OpenLCA con Ecoinvent	ReCiPe 2016 (H)	OERCO2	EN15978	ERESEE	IDAE	Proyectos de arquitectura reales

6. Comparativa de certificaciones ambientales (Artículo 1)

6. ARTÍCULO 1

Life Cycle Analysis Challenges through Building Rating Schemes within the European Framework

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Citation: Izaola, B.;
Akizu-Gardoki, O.; Oregi, X. Life Cycle Analysis Challenges through Building Rating Schemes within the European Framework. *Sustainability* **2022**, *14*. https://doi.org/10.3390/su14095009
Academic Editors: Steve Kardinal Jusuf and Soh Chew Beng

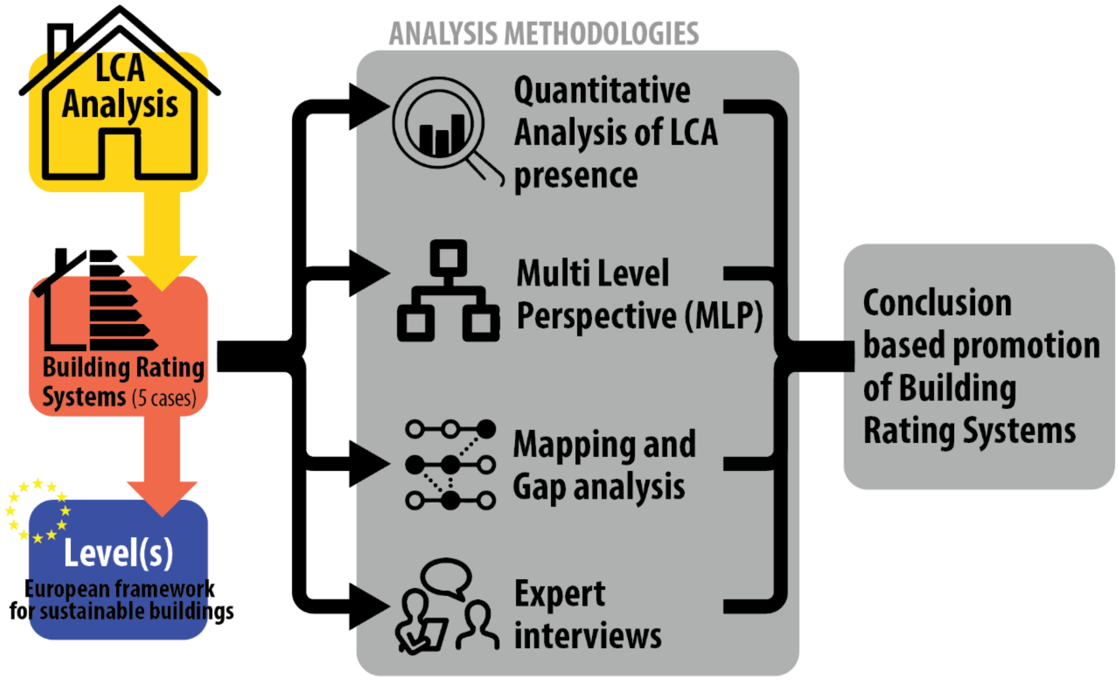
Received: 24 March 2022, Accepted: 18 April 2022

ABSTRACT

The decarbonisation of buildings is a crucial milestone if European cities mean to reach their mitigation targets. The construction sector was responsible for 38% of the GHG emissions in 2020. From these emissions, 11% is calculated to be currently embodied in building materials. In this context, an evaluation from a life cycle perspective is becoming increasingly necessary to achieve the objectives set. Currently, there are different building rating systems (BRS) at European level that allow the evaluation of the degree of sustainability of buildings. During this study, the authors have evaluated to what extent and how the most extended five BRS (NF Habitat HQE, VERDE, DGNB, BREEAM, and HPI systems) in the European framework have integrated the life cycle methodology during their evaluation process. Four methodologies have been used in the research in order to analyse these five systems: quantitative assessment, multi-level perspective, mapping–gap analysis, and expert interviews. Although each methodology has produced different results, the need to harmonise the evaluation criteria at the European level, the insufficient consistency of data software, and the availability of skilled LCA professionals for wider LCA market penetration, among others, should be highlighted. The quality and harmonised data of construction products is required for LCA to give aggregated and transformative results.

Keywords: life cycle assessment; green building rating systems; multi-level perspective; decarbonisation; sustainability; sustainable transition

GRAPHICAL ABSTRACT



INTRODUCTION

The Global Impact of Buildings

The decarbonisation of buildings is a crucial milestone if European cities mean to reach their mitigation targets and become sustainable. But other environmental impact categories are also key in the reduction of the harmful effects of the European construction industry: greenhouse gas (GHG) emissions, abiotic depletion, acidification, eutrophication, energy footprint, water consumption, solid waste production, or the various social impacts. The new Circular Economy (CE) Plans boosts the reduction of these impacts, especially in terms of waste management (European Commission, 2020a). This and other strategies bring Life Cycle Assessment (LCA) to the forefront of the European buildings' framework.

The construction sector is responsible for 39% of the GHG emissions (Adams et al., 2019), updated to 38% in 2020 (UNEP, 2020). From these emissions, 11% is calculated to be currently embodied in building materials and released before the infrastructures are used. Concrete, iron, and steel alone are responsible for ~9% of this 11%. Also, according to the Global Alliance for Buildings and Construction (UNEP, 2019), in the 2010-2018 period, the new built area increased by 24%, while GHG emissions and PE grew at a lower rate, by 6%. It has been estimated that embodied GHG emissions could reach up to 50% of the total emissions of the construction sector by 2050 (Adams et al., 2019). Being aware of the need for decarbonization throughout all the life stages of a building, 2010 in Europe was marked by the first version of the Energy Performance of Buildings Directive (EPBD) (Fernbas, 2019), which made it mandatory for all new buildings to be Nearly Zero Energy (NZEB) by 31/12/2020 (Paoletti et al., 2017). For decarbonization and energy efficiency purposes, rating systems, performance standards and a plethora of databases, codes, regulations and building solutions need to become part of the designing, erecting and managing of buildings (Liang et al., 2021).

The construction sector also accounts for 36% of global PE use, meaning that international efforts need to be made in this sector in order to meet the global climate ambitions set forth in the Paris Agreement (Abergel et al., 2017). They have also estimated that by 2030 the energy intensity per square metre must be reduced by 30% in relation to the 2015 values. While energy efficiency policies are successful during the use stage of buildings, the sector has recently started to take into account the embodied carbon emissions and energy consumption of building materials and building processes, which have seen a rapid growth since 2015 (Hu and Milner, 2020). Integration of the analysis of embodied energy impacts is still barely integrated within LCA in points 9, 10 and 11 of the EN15978 (CEN, 2011). When this applies to building products, the EN15804 or environmental Product Declaration (EPD) is particularly noteworthy.

Concerning Construction and Demolition Waste (CDW) generation, the European Union (EU) construction sector produced 923 million tonnes of waste in 2016 (European Commission, 2020). This represents the largest waste stream in the EU, 30% of all waste generated, of which scarcely half was recycled, but aims at a 70% target (European Commission, 2020). Although the EU's Circular Economy strategy is improving the situation, LCA of CDW is being applied, and best practices in the field are on the rise, the overall landscape of construction stakeholders lacks internal common drivers (Gálvez-Martos et al., 2018).

The Historical Perspective

Briefly revisiting the evolution of buildings, primal builders had an intuitive and territorial approach to the efficient use of materials, the comfort of occupants and indoor hydrothermal balance. Thus, vernacular architecture studies show a growing research interest in the sustainable features of traditional buildings across the globe (Nguyen et al., 2019). Recalling ancient knowledge, architects and anthropologists are engaged in a comprehensive mutual understanding of urban environments (Stender, 2017), aiming at an integrated examination of building sustainability (Vellinga, 2013). Both historical and current challenges, together with technical and policy solutions, are understood from a wide and well-founded cultural analysis focused on the people and the culture of a given place (Gonsalves, 2020).

This applies to everything from an understanding of the complementary roles of builders, architects and engineers in key construction achievements (Fenske, 2016), to the assessment of sustainability indicators in vernacular architecture (Olukoya and Atanda, 2020), and the emerging futures where artificial intelligence might replace human labour (Ingarden, 2019). Industrialization and demographic changes have turned the traditionally nature-integrated scenario into a vast and complex business, which at its peak of production in Europe (2005-2008) was producing more than 1.5 million homes per year (Eurostat, 2019) and the equivalent in office floor area. The European construction sector amounts nowadays to a 66% share of the total internal market trade in goods and services between EU Member States (European Commission, 2019a). However, the world's main concentration of building impacts —and their reduction challenges— lies in current globalized market trends and perspectives (Pauliuk et al., 2021), where the LCA gains relevance and it is becoming unavoidable.

The European Standardisation and Level(s) Framework

While local voluntary initiatives and best practices have historically led sustainability efforts within the sector, national and European policies are now taking over. At the heart of the Circular Economy and Renovation Wave strategies, the European Joint Research Centre (JRC) has created the Level(s) Framework (European Commission, 2019b) geared towards transforming the sector (JRC, 2017).

Level(s) is a voluntary reporting framework to improve the sustainability of buildings. Using existing standards, it provides a common EU language and approach to assess performance in the built environment. The first version was published in 2017 and tested in 83 buildings across Europe in 2019. The second version appeared at the light of the Renovation Wave plan in October 2020 (Dodd, 2020). It focuses on six ‘hotspots’ through the whole building life cycle: greenhouse gas emissions, resource efficiency, water use, health and comfort, resilience and adaptation to climate change, and cost and value. Its 16 indicators can be used at design, construction and operational levels, giving the Framework its name and bringing usability to various stakeholders. Relevantly here, Level(s) is the only framework covering all LCA stages (BPIE, 2021).

One of the many activities for the penetration of Level(s) into the EU building market (DG Env, 2020) is to take advantage of the fittest and most innovative Building Rating Systems (BRS) in the EU. In this study, five BRS have been chosen to run against Level(s). Both BRS and Level(s) had to share a voluntary basis, a set of tools and datasets where Life Cycle Thinking (LCT) is central. As eligibility criteria, they are second generation BRS and fully integrated in their national sector. They represent a variety of European building cultures. They have been active in the development of Level(s). Other researchers have studied BRS but excluding Level(s) and with different purpose and eligibility criteria (Polli, 2020), (Bernardi et al., 2017). Research about Level(s) within BRS has just begun and only on specific issues (Del Rosario et al., 2021).

Building Rating Systems (BRS)

The issue about how many BRS exist worldwide is still open, in spite of the much quoted (Reed et al., 2009) and regularly updated (Reed and Krajinovic-Bilos, 2013), (Doan et al., 2017) report from BRE (Horner, 2004). At that time, more than 600 tools that in some way measured or evaluated the environmental, economic or social dimensions of the sustainability of buildings were reviewed. Some covered 1, 2 or all 3 dimensions. The types differed; 147 were selected as environmental tools. Of these, 41 were checked and only 25 fully evaluated: 7 for urban planning, 3 for design, 7 for buildings, 7 for LCA and one for infrastructures. Nowadays, the World Green Building Council has evolved to become the main corporate body, updating what are called “Green Building Rating Tools” (GBRT). In 2016, their 55 GBRTs worldwide had certified 1.04Bn m^2 of sustainably built floor area (WGBC, 2020a).

Lately, scientific research has paid attention to whether “Green” BRS can be compared, how they have evolved and how many aspects of sustainability they include (Reed et al., 2017). Primarily Asian researchers have shown an interest in the regional differences of the prevailing Green BRS and their future research directions (Shan and Hwang, 2018). Also in Europe, the importance of “Green” BRS to attain sustainable buildings is coming into research focus (Sánchez Cordero et al., 2019) under similar premises (the most common BRS compared in scoring terms), with the added value of Level(s). However, LCA has not yet been placed at the centre. In our research, the updated version of Level(s) is analysed and 5 BRS are mapped against it with a focus on LCA and decarbonisation potential in Europe. The idea of harmonising existing BRS has been scanned before, however not taking Level(s) into account (Erten, 2018), concluding that (BRS) “which do align with a common framework would be very helpful for creating an assessment method/process capable of allowing comparison and benchmarking of buildings internationally.”

For the reasons discussed, some mainstream BRS have not been included: LEED because it is rooted in the building culture of the USA and because LCA weighs only 3% of the total credits (3 out of max 110) (Morrison, 2014); GreenStar and CASBEE since they are used in the southeast Pacific and are relatively minor (Jensen and Birgisdottir, 2018). Another study (Díaz López et al., 2019) selected the 36 most representative BRS and compared them using 4 items: phase of Life Cycle applied; sustainability aspects assessed; categories considered; and the type and status of the building assessed. The results showed that many BRS do not assess all aspects of sustainable building. Many assess energy and the quality of the interior environment, but few assess relevant social and economic aspects. Our 5 chosen BRS do qualify in all these aspects. The discussion below will show to what extent their results are aggregable.

The name Building "Rating" System has been favoured over other frequent terms, such as "assessment" or "evaluation" because the chosen BRS make use of the more academic "assessment" for rather commercial "rating" purposes. The terms "certification", "scheme", "method" or "tool" come under "system" because in fact, at this level of maturity, they form parts of an interrelated system. A prefixed adjective such as "green", "environmental" or "sustainable" has also been avoided, as the selected BRS include process, climate, health and cultural aspects on top of the environmental, economic and social aspects common to sustainability approaches. Although "Green BRS" (GBRS) is frequently used in research and market activity, and has become a Taxonomy concept aimed at clarifying the role of BRS in relation to sustainability and climate change mitigation (*Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (Text with EEA relevance)*, 2020), the term is still ambiguous and prone to "greenwashing". For this reason, we prefer to simply use "BRS". Nevertheless, our focus lies on the ongoing evolution of the defining keywords for this subject. An extensive bibliometric analysis of 4,203 records of "Sustainable Building Assessment Methods" from 1975 to 2017, assesses the importance of said keywords in the evolution of the topic (Díaz-López et al., 2019).

The Life Cycle Assessment (LCA)

Adding LCA to the sustainability indicator toolkit addresses the increasing presence of embodied impacts in buildings, especially as building energy efficiency improves and energy use in the operation of buildings decreases (Hernandez et al., 2019). If in current buildings, the use phase contributes to an 80%–85% share in the total life cycle energy use (Oregi et al., 2015) and, at the same time, other authors claim that their embodied impacts account for 50%–70% of the total (Cabeza et al., 2020). Once Nearly Zero Energy Buildings (NZEB) are the norm, the embodied energy and carbon in buildings will be key to understanding how sustainable or "green" a building is, and the right proportion between direct and embedded energy consumption to minimize impacts. This will be also the key to transit towards energy positive buildings (Magrini et al., 2020), carbon sinks (Pomponi et al., 2020), or renenerative buildings (Quintana Gallardo, 2023).

Nevertheless, a differentiation appears when sustainability (rather qualitative) merges with LCA (more quantitative) into a Life Cycle Sustainability Assessment method, as opposed to Sustainable Building Certification (Llatas et al., 2019), less evolved than the BRS chosen in this paper. For our purpose, it is relevant to underline that embodied carbon or decarbonisation have not previously been treated as key concepts. Our LCA approach is rooted in all environmental interventions and impact categories (Verones et al., 2017). The UNEP-SETAC Life Cycle Initiative is improving an LCT approach to social issues, decision-making support, harmonization and uncertainty reduction, as well as further developing LCIA, buildings included. Consequently, the European building construction sector is currently undergoing a Socio-Technical Transition (STT) impulsed by climate change (Wang et al., 2018), European policies (European Commission, 2019c) and the building sector evolution (Fotiou et al., 2019).

The Goal of the Study

These building rating systems (Table 1.1) are holistic and close-to-the-market managing bodies, which are key in identifying the real impacts of buildings. European Green Building Councils (GBCs) are at the forefront of this challenge. A goal of this research has been to analyse and compare the five most relevant European BRS, all managed by their respective country's GBC in their newest version (2020). The study has implemented and combined four different methodologies in order to achieve this objective. They have been selected among other European-born methods for their maturity, representativeness, and market adoption. According to their marketing figures, more than 7000 European buildings have been certified using these BRS, more than 6000 consultants see that their specific skills are increasingly valued by the market, and more than 3000 market actors are associated with their corresponding association.

Table 1.1 Basic impact metrics of selected BRS. Information provided by the World Green Building Council Member Value Survey 2020 (WGBC, 2020b).

Consultants (October 2020)	Associated Professionals (July–November 2020)	Associated Corporate Entities (July–November 2020)	Certified Buildings (October 2020)	BRS (1st Version)	Country (Association)	
N/A **	267	91	N/A *	NF Habitat [56] (2013)	France (HQE)	1
192	202	107	132	VERDE [57] (2011)	Spain (GBCe)	2
4820	73	1266	6232	DGNB System [58] (2010)	Germany (DGNB)	3
879	N/A ***	370	317	BREEAM-NL [59] (2007)	The Netherlands (DGBC)	4
55	30	170	350	HPI [60] (2016)	Ireland (IGBC)	5
6046	639	2438	7031	TOTALS		

* Not disaggregated from other NF certifications.
** +1000 not specified.
*** Only entities are accepted.

Structure of the Study

In the next Section, the applied research techniques are listed so as to display the wide range of specifications of the five BRS and to draft a framework for comparing them against Level(s). Then, the quantitative and qualitative results of the different analyses are shown. Afterwards, the results are contextualised. Under Conclusions, the section provides clear information to policymakers and experts of the building sector to boost the sustainable transition of the present construction industry. It is not the purpose of this paper to describe in depth the BRS or the Level(s) framework, but to understand their potential for the harmonisation and aggregation of data more concretely in the light of Level(s) and regarding LCA integration. If this proves useful, a boost in these building sustainability assessment tools and an improvement in the sustainability of buildings can be expected. The challenges are complex, and this research and innovation strives to approach them leaving none aside. We also aim to make recommendations to strengthen the links between LCA, BRS, Level(s), and sustainable buildings.

MATERIALS AND METHODS

The following four complementary methodologies have been used in the research in order to achieve a deeper perspective of current environmental impact analysis standardisation in the European framework:

1. A quantitative analysis of the presence of the LCA approach in BRS;
2. A multi-level perspective (MLP) was followed to contextualise BRS and the Level(s) framework within the building sector and sustainability-related systemic challenges;
3. A combined mapping–gap analysis of the Level(s) indicators was performed to check the compliance of the BRS with Level(s);
4. Expert interviews were run parallel to provide first-hand data and contextual interpretation from the managers of the BRS.

Quantitative Analysis of the State of the Art

The 5 BRS selected for this study are the closest to the European market, as they derive less from academic or public administrations, and more from National sectorial associations (WGBC, 2020b). These 5 alone include more than 2,400 associated corporations and 650 professionals from the sector. They are well interrelated, as the associations where they are carried out (European GBCs from France, Spain, Germany, The Netherlands and Ireland, respectively) work closely together. These GBCs are active until 2022 in two current R&D projects running in the field: Building Life (Building Life Project, 2020) and LIFE Levels (LIFE Levels Project, 2019). The work is LCA-inclusive and easily adaptable to Level(s), as they are aligned with European directives and policies transposed into national law. As a result, these BRS are mature in the European construction sector. Of these, BREEAM is present globally, but is adapted to the Netherlands, while the others are mainly national or spread by language/culture. DGNB (Germany) is widely present in its neighbouring countries and is the most developed in terms of sustainability balance and LCA weight. Its international version, examined here, has been tested in other continents too.

When running applied research projects, a common barrier is the limitations to market penetration within the wide scope of its scientific objectives. In the wider field of sustainability, science has provided in-depth awareness of the targets and theoretical processes to reach a balanced ecosystem or a clean, fertile and thriving environment. Concerning buildings, optimal techniques, materials and sustainable designs are available. However, market, assignment and professional realities don't always follow. A gap appears between the expected and real results. However, this poses an opportunity to learn and improve the methodology. Science can reappear to explain said gaps. When this iteration has sufficient items or the procedure has run similarly in other contexts, there arises another opportunity for comparison, analysis or testing. Mapping these generates new knowledge in a visual form that provides a general overview and allows for rapid conclusions and recommendations.

Moreover, from a bibliometric (Visentin et al., 2020), scientometric (Darko et al., 2019), down to a very concrete approach at the encounter between the construction sector's circular economy and LCA, (Dieterle et al., 2018), (Hossain and Ng, 2018), the combination of a mapping and a gap analysis enables the researcher to discover patterns and trends as well as missing strategies, processes or skills.

Then, it recommends steps to help meet the proposed goals. This research, after experiences analysing hundreds of items (Bionova, 2018), (Díaz López et al., 2019), focuses on a few concrete and applied items in the narrower geographical scale of five European countries, which still define a representative muster of the field.

The chosen BRSs through their websites/platforms, technical and administrative guidelines and profile of customers and providers have been compared to understand both the technical and the operational aspects. As a result, we shall see that they follow common entry points, glossary, strategy of implementation, a set of check points, consultants' profiles and insights that improve the sustainability of the building within its specifications. The effort, price and need to engage other experts vary. The marketing, communication and exploitation of the outcomes and rating differ too. Sadly, due to data protection and extra data processing efforts, figures aggregated in a harmonised manner, fit to inform the national and European markets and policymaking, are few and difficult to obtain.

Multi-Level Perspective (MLP)

A remarkable methodology for sustainability transitions research -—and one that is insufficiently applied to buildings—- is the Multi-Level Perspective (MLP) (Geels, 2004), (Geels and Schot, 2007), (Geels, 2019). Using MLP helped place focus on one relatively unseen but key transition of the building sector: namely, that national BRS paired with the European Level(s) are slowly becoming "normal"; which has even inspired policies and Green Public Procurement (GPP) practices. Based on the assumption that (only) regulations make agents change, one would argue that as they are voluntary, BRS would never become mainstream; or that merely rating, without the legal power to exclude items below a certain threshold, does not remove the lowest rated items from the sector; or that, in any case, buildings are solely Real Estate (RE) assets and not cultural and climate resilience artifacts. Conversely, sustainable buildings are becoming the new norm, setting minimum values and accounting for optimal location, market opportunity, and capacity to accommodate a thriving and resilient society. This methodology helps to connect the different scales of action and change. It starts by differentiating three levels, each of which comprises one or more socio-technical aspect (including science, the market and sectorial actors and actions), which this study proposed to apply to the subject as shown in Table 1.2.

Table 1.2. Overall adaptation of MLP to the subject of research.

Life cycle assessment of individual buildings.	Niche	Micro-Level
Standardisation and typification of buildings through building rating systems (BRS).	Regime	Meso-Level
Evolution of BRS through the European Level(s) framework	Landscape	Macro-Level

By coupling LCT with a systemic approach to rating buildings, as the selected BRS, buildings can become mainstream artifacts ready for a healthy, resource-efficient future. They can put an end to the "old" 3D (Dirty, Dangerous and Demeaning) sector (Hamid et al., 2013); responsible for vast hazards on land, underground, in the atmosphere, and in the water; irrespective of comfort, fair distribution, and the right to thrive of all living beings; and alienated from the social value of housing, place, community, liveability and sustainability. They embody a regime shift that explains many changes occurring. We will adapt Rip & Kemp's representation of the multi-layered backdrop of novelty and irreversibility (Rip and Kemp, 2000), and their earlier concept of Technological Regime. This allows us to identify niche artifacts like LCA as "technologies at work": niches where the technological innovation and the socio-technical environment evolve into innovative artifacts. MLP can dissect and reconnect these issues as shown in Figure 2 in the results section. It will prove helpful to map the many trends of the sustainability transition of the building sector, in time and scope, which this paper attempts.

Moreover, following Geels' three interrelated conceptual dimensions of STT (Geels, 2004), a proposal is applied to our subject as described in Figure 2 in the results. The dynamic exchange between actors and rules is driven in the socio-technical transition creating the system which in turn defines and causes actors and rules to evolve. Continuing with Geels (Geels and Schot, 2007), the niche-innovations applied in our context are the very specific actions BRS and Level(s) are taking to align and become trendy for European buildings: actions leading us to understand the importance of LCT at building design, construction and management, actions aimed at raising awareness of the health factors of the building, with special focus on indoor air quality and actions calling for the public procurement of buildings to introduce these criteria as GPP.

Going further into the methodological detail of MLP applied to BRS, the Transition pathways (Geels, 2019), (Rosenbloom, 2017) for the success of BRS in collaboration with Level(s), speak of an endogenous regime transformation out of its very own unsustainability. This has special significance for the financial sector. As already occurred with the surge of the electric car industry, we are observing a "selective translation" (Geels, 2018) between green niches such as BRS and the regime of the building sector. MLP helps to identify other issues like the political struggles and innovations around building codes: should these BRS stop being voluntary and become part of the body of the building codes? The way forward is probably to adopt "policy mixes" (Kern et al., 2019).

The issue of the cultural value of buildings remains open to anthropology—not only monuments are "heritage". Common buildings are the locus of peoples and their cultures over generations. The way a country shapes its identity lies very much in the building codes and best practices it gives itself. What kind of society will be born out of resilient, decarbonised buildings and cities? What artifacts, rules, and systems will define its conceptual framework and shape its walls and roofs? In a global world ruled by corporations, which business struggles (among competitors but also in relation to nation states and regions) will ease or redirect transition pathways towards niches, such as BRS? Will corporations make a case for LCA in buildings, creating their own standard? Will different business models coexist in diverse sustainability niches?

Applying MLP here aims to identify the transitions between the niche of BRS and the next regime. The effects at a landscape level have been identified and are visible. However, this paper refers to the lower level of the technical struggles and dependencies between the chosen BRS and Level(s). While policies are fully present as GPP recommendations and the influence of BRS on the national decarbonisation roadmaps, we focus on arguably the most promising dependency: of that between LCA and the sustainability rating of buildings. MLP serves to identify and reframe the gaps, compliances, and challenges that appear at the crossroads of Level(s) and BRS in the field of LCA. Thus, the next step for the methodology is to map and analyse the gaps in these dependencies.

Mapping Procedure and Gap Analysis

The applied mapping procedure has been performed with a spreadsheet to identify how the Level(s) indicators align and conform to the indicators within the BRS. It calculates the percentage "degree of compliance" for the LCA indicator and others within a detailed quantitative conformity assessment. It also gives a rough overview of compliance through a qualitative conformity assessment of all Level(s) indicators. This feeds the gap analysis between Level(s) and the BRS. In addition, it shows compliance with Level(s) at the three levels. For the quantitative procedure, a deep dive into the

Level(s) indicators was necessary to break them down into their "methodological aspects" (building scope, system boundaries, and reference standards). The official report on "How to make performance assessments using Level(s)—Part 3 for office and residential building" (JRC, 2017) and its related spreadsheet "Level(s) common reporting format for all indicators and tools, release v1.3" are the reference for this procedure. For the qualitative procedure, the approach was a brief set of questions sent to the BRS managers. For each item, the choice is "compliant" or "non-compliant", and each "compliant" is awarded with 1 point and then added to the spreadsheet. Table 1.3 shows the "degree of compliance" (in %), calculated as the ratio of the achieved points to total possible points, following each one of the headings referenced in the above-mentioned reports. The degree of compliance is calculated for all three levels and sets up the gap analysis.

Table 1.3. Awarding system for analysing BRSs degrees of compliance with Level(s) framework.

degree of compliance (Green) 100%−95	Similar
degree of compliance (Yellow) 95%−80	Minor deviation
degree of compliance (Orange) 80%−50	Major deviation
degree of compliance (Red) 50%−0	Missing

Finally, for the qualitative assessment, the level to be considered is chosen, and a subjective input is provided as "similar", with "deviation" or "missing", with the possibility to add a comment. The levels of knowledge of the building assessment, the BRS used, and Level(s) are high. A wider mapping procedure was performed in the research project (32 items); however, in this article, the 3 indicators related to LCA analysis have been compared: Indicator 1 "Use-stage energy performance", Indicator 2 "Life cycle Global Warming Potential", and Indicator 3 "Life Cycle Costs".

Expert Interviews

The managers of the five BRS have been contacted per online videocall to fully understand the relationship between the BRS and Level(s) and to check availability and aggregability of data. The same interview pattern has been used to ask them how LCA is taken into account, about the impact of the scheme, and the exploitability of results. A brief questionnaire had been sent in advance by email. The conversations took place in May 2021 with Martin Mooij from BREEAM-NL, Nadége Oury from NF HQE, Paula Rivas from VERDE, Levan Ekhvaia from DGNB, and with Pat Barry from HPI. These interviews aimed to test the validity of the MLP approach and gain in-depth knowledge of the BRS, as well as its compliance with Level(s). The stakeholder constellation and their BRS was briefly discussed and confirmed the proposed view. Some recommendations for further improvements were also collected and will be discussed in the final sections.

RESULTS

Quantitative Analysis of the State of the Art of BRS

A quantitative analysis of the relative weight of LCA in the studied BRS has been carried out in Table 1.4 to effectively assess how and to what extent LCA is taken into account. Other LC tools related to costs or social aspects are less present across the BRS and are not quantified. These can be better seen as the effect of including more or fewer stages, impact categories, and building elements. BRS have a range of credits or points for rating items, such as LCA in this case. Rating is sometimes linear (DGNB, VERDE), sometimes stepwise (HPI, BREEAM, and HQE). Positive action is mandatory for

DGNB, VERDE, and HPI, but not for HQE and BREEAM. Figures below correspond to the latest versions for new buildings. Values from older versions can be different for rehabilitation works, offices, and other building types. When a BRS is adapted to second countries, figures also vary: the German version of DGNB has higher values, another country's version of BREEAM rates up or down. Benchmarks are not yet fully integrated into BRS. This was a subject of debate at the interviews: European policies, with the Nordic countries as frontrunners, are proposing to limit values that will influence the BRS. The exchange between actors, rules, and tools is presented and discussed below. Finally, indicators or aspects related to LCA do not follow an identical approach. VERDE and BREEAM focus on the bill of materials, HQE divides the item in several strands, and HPI and DGNB follow an orthodox LCA. The need for harmonisation will be discussed later as a stand-alone issue.

Table 1.4. LCA weights in the BRS.

Share on Total Points	LCA Development	Building Elements	Impact Categories	Stages	Indicator code/Name	BRS: Country (Entity)
0%	Min	Potentially any	Related to the indicators	N/A	Indicators PE1.4.4, RCE4.1, REM2.4.1, DEC1, and DEC2	NF Habitat: France (HQE)
2.12%	Max					
2.80%	Min	Envelope, inner partitions	GWP, ADP	A1, A2, A3	RN 11 Impacto de los materiales de construcción	VERDE: Spain (GBCe)
4.50%	Med	All	GWP, ADP	Plus A4, A5, B4, C3, C4		
5.60%	Max	Plus 10% reduction	+AP, EP, POCP, ODP	Plus A4, A5, B4, C3, C4		
1%	Min	Foundation + structure, envelope, HVAC	GWP, ODP, POCP, AP, EP	A1, A2, A3	Building life cycle assessment (ENV1.1)	DGNB-System international 2020 for buildings: Germany (DGNB)
4%	Med	All at design	Plus PE, WU, ADP	+ B2, B4, B6, B7, C3, C4		
9.50%	Max	Plus CO2 neutral, plus no halo-hydrocarbons	All Impacts	Plus D		
0.80%	Min	At least three materials	GWP	A1, A2, A3, product-based	MAT1: material specification	BREEAM NL: The Netherlands (DGBC)
4%	Med	Environmental impact of materials used is at least 30% lower than reference	At least two more			
8%	Max	Idem 60% lower	At least four more			
4%	Min	Whole building	GWP	A1, A2, A3	EN:7.0 embodied impacts of homes and LCA, plus exemplary points	HPI: Ireland (IGBC)
6%	Med		Plus as many of ODP, AP, EP, or POCP as possible	Plus A4, A5		
8%	Max	+100% embodied offset		+ all B + all C		

Multi-Level Perspective (MLP) Study

Figure 1.1 is a synthetised proposal of the MLP applied to this research. A set of conceptual, technical, and sociological innovations happen in time and scope. Moving from the left-bottom corner to the upper right, we find: initial prototypes or singular best practices in individual buildings, tools or EPDs that are performed by few actors in short cycles and accumulated over time, creating what the MLP conceptualises as a "regime". The tools become systems and standards; the wider scale turns into an attainable policy framework intended to be adopted as common practice. A wider scope appears, with a longer-term perspective involving strategies. Over time, policies become structural patterns or cultural expressions; strategies transform the landscape (the construction sector, in our case), and a new (ideal) healthy and resilient scenario appears. A very interesting "diagonal" shift (arrows) occurs as wider scope items accelerate, enriching their vertical and horizontal evolution. This expanded view takes a huge leap from the starting point in Table 1.2).

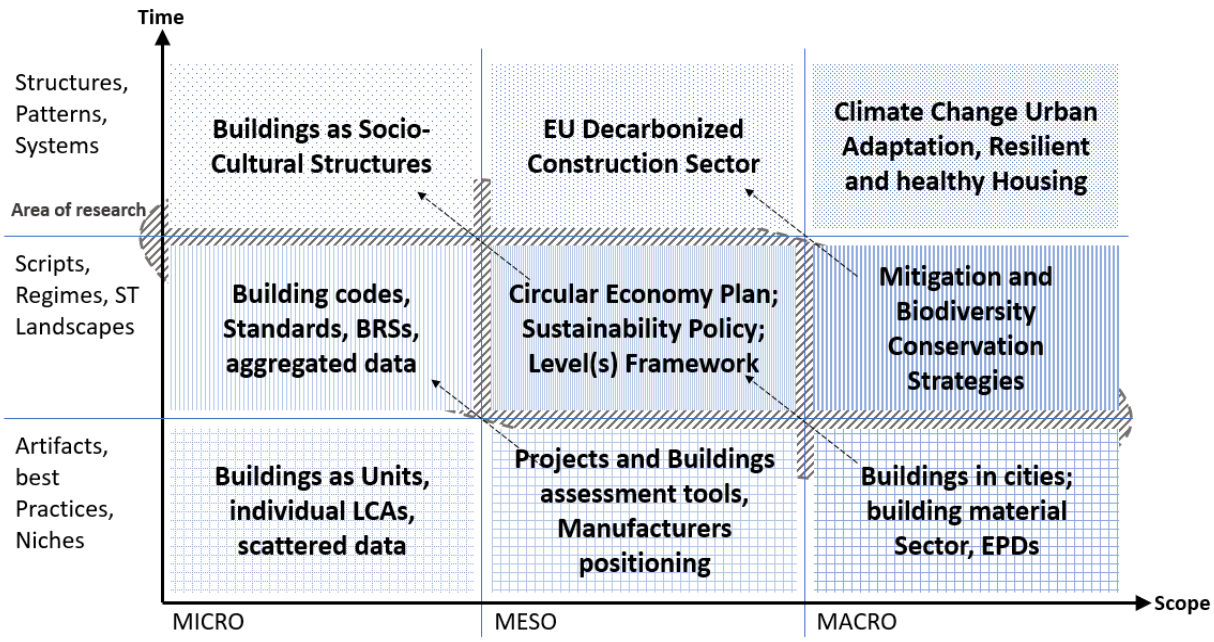


Figure 3. *Multi-layered backdrop of technological innovation in building LCA, elaborated by the author and adapted from (Rip and Kemp, 2000).*

While Figure 3 is open to discussion, it offers a few lessons: the area of research looks at the policies rather than at the BRS, and while rooted in the present wider scope, it sees ahead to discuss patterns and scenarios. Therefore, another standalone discussion will take place around the decarbonisation of the building sector. Additionally, the already announced discussion on the need to harmonise tools, databases, and processes finds its place here. Seen as columns, the scattered data need to aggregate in order for us to grasp their potential. Meso-scaled pioneering positions need a framework to transform the sector. As niches grow in size, they need to engage in strategies to produce regenerative outcomes. Seen as rows, we can observe a process of the "commoning" of the particular phenomena so that they generalise and become the "new" normal. This process seems to happen not only as time passes but also as the scale increases. However, a progress line from the here and now to the furthest and widest does not seem to appear. An array of best practices does not create a structure, nor does aggregating data and standards decarbonise the sector per se, nor are the tools or the tactical positions enough to sustain a promising strategy. As progress happens in a zigzag, this exercise reaches its limits, and another dimension emerges.

Following Geels (Geels, 2004), a 3D approach helps to enrich the above analysis. If in Figure 3 the two-dimensional approach fails to explain a linear progress, the three interrelated conceptual dimensions of STT applied to our subject, as proposed in Figure 4, intend to clarify why: actors were missing. A more accurate term would probably be "agents". Actors do play a role, but we are analysing the script. While agents do play a role, they also engage in writing the script—for themselves and for other actors. Mutual exchange happens not by chance, nor is it explained solely by the context. Rather, it is a circular interdependency that permeates all processes and better explains the transition.

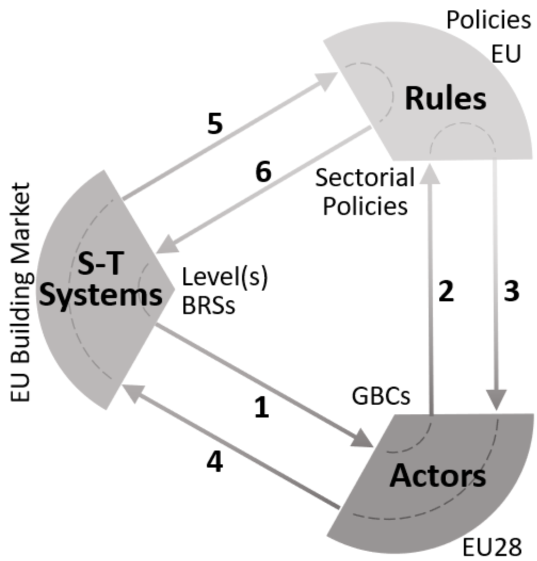


Figure 4. *Dimensions of socio-technical transitions (STT) from BRS to Level(s). Elaborated by the authors and adapted from (Geels, 2004).*

The proposal on how specifically BRS can leverage the transition to a rolled-out Level(s) framework is described:

1. BRS are socio-technical systems for the sustainability assessment of buildings in GBCs;
2. Sustainability pioneers within the construction sectors merge under climate change and circular economy policies;
3. RE interests in the EU counteract one another;
4. Demand for building materials manufactured in the European market increases;
5. National sectorial inertias (but also progresses) retain (and also inspire) bigger goals at EU policy level;
6. More ambitious and applicable sustainability assessment systems of buildings are the result, such as the Level(s) framework.

This exercise could be rewritten for other cross-boundary processes, as proposed in Figure 1.1. It is important to bear in mind that actors are agents, rules, and scripts. Perhaps the crucial aspect here is the script; currently, politics, industries, and social influencers exploit "storytelling". These narratives are so powerful that both actors and systems fall into the script. This will be discussed later in its own standalone discussion. However, it is important to notice that the transition is not at all free of resistances, pressures, and failed attempts. As the purpose of a system is to perpetuate itself, following Anthony Stafford Beer's "POSIWID" (the purpose of a system is what it does), the purpose of a regime is to lock path dependencies. Change is precisely brought about by unlocking them. Alternatives are rarely welcomed by regimes. Explanations have been proposed, such as technological channelling, path dependence, and "lock in" and "lock out" (Berkhout, 2002). If Path dependency means that choices for present situations are made based on past behaviour, knowledge, and history—in other words, based on the regime—path dependencies serve to explain the barriers and challenges of the STT of the building sector.

The existing regime is locked in the list of path dependencies proposed in Table 1.5. If they sound similar to typical assumptions, they appear within quotation marks. Others are presented as open questions. They are not independent from one another, but mutually reinforcing. Some assumptions, beliefs, and regime paths are facing powerful alternatives or seem obsolete. Nonetheless, because they are not from the regime, the alternatives do not reinforce one another. Niche construction and empowerment is still needed for the STT to mature, and this is achieved through socio-political work (Raven et al., 2016). However, as transparent reporting practices such as Level(s) and BRS are on the rise, the patterns of the regime might change and complete the transition.

Table 1.5. Path dependencies in the socio-technological transition of the building sector.

Vested interests in the RE market and Urban developments.	Economic
Sunk investments from the 2008 crises, worsened by the current post-COVID-19 crises, being swallowed by investment funds.	
"Sustainability is expensive and does not pay-off".	
Blind beliefs such as the ever-growing RE surplus and sustainable assets becoming even more profitable.	Social
Although climate awareness is raising socially demanding adapted buildings and cities, "climate change does not affect us", and weather events are "normal".	
The "austerity" policies of the 2008–2019 period, and the more homely lifestyle forced by the lockdown, were necessary to remain competitive and safe.	
Activism in climate, health, and housing rights remains unheard by politicians.	Political
Local administrations and manufacturers pioneering sustainability practices do it for global marketing or greenwashing, and without local citizenship support.	
The Green New Deal—does it come to renew the deal with the multi-nationals or to shake the regime foundations?	
The EU construction industry is strong, both inside and internationally (although lacking one million skilled workers).	Sectorial
The occurrence of Level(s) as a side entry (from the circular economy corner) into the sector raises suspicion from BRS and manufacturers—does it support their interests?	

Stretching the MLP methodology in this undergoing reconfiguration of the regime, a window of opportunity appears for niches of radical innovation, such as the entry of Level(s), which is accompanied by European-funded projects, such as LIFE levels. In the peripheries of the regime, volunteer-best practices and pioneering actors have gained visibility, either under the focus of European or national sustainability awards, or under the bottom-up claim of local communities. At a wider level, climate awareness, coupled with the injection of recovery funds, might signify a window of opportunity for European policy, understood as the Renovation Wave. New dependencies are being designed there, at the taxonomy with Level(s), meaning that no financing will be ready to refurbish buildings which are not "green", as defined in the taxonomy. If they do not report being within its thresholds, following the Level(s) reporting, they fail. As BRS are driving the adoption of and compliance with Level(s), and it turns around LCA, the new paths seem clear: perform LCA within a Level(s)-compliant BRS and your building will succeed in the transition to sustainability. Will it? To answer this question, we have mapped it in detail.

Mapping Procedure

Table 1.6 shows the results from the detailed quantitative study of the LCA-related indicators. A degree of compliance of the BRS with the steps of Level(s) reporting at the three levels is presented as a percentage. The colour code in the table below helps to visualise data: 100% green, 80–99% yellow, 50–79% orange, and 0–49% red. As can be seen, the BRS are not as fit as expected, nor do they follow homogeneous trends. The results were shown to the BRS managers, and some upcoming improvements are presented later.

Table 1.6. Overall degree of compliance per BRS on selected indicators and related metrics, per level (awarding system and colour definition from Table 1.3).

HPI	BREEAM-NL	DGNB Score	VERDE	NF HQE	Level of Compliance	Indicator
60%	90%	90%	60%	63%	Level 1 degree of compliance:	1 Use-stage energy performance (kWh·m−2·yr−1)
25%	100%	100%	25%	83%	1. Step-by-step instructions	
100%	80%	80%	100%	92%	2. Checklist of design concepts	
0%	100%	100%	0%	0%	3. Reporting	
72%	94%	89%	72%	77%	Level 2 degree of compliance:	
77%	92%	85%	69%	63%	1. Step-by-step instructions	
100%	100%	100%	100%	88%	2. Comparability of results	
67%	100%	100%	100%	92%	3. Optimisation steps	
0%	100%	100%	0%	0%	4. Reporting	
58%	58%	92%	58%	86%	Level 3 degree of compliance:	
64%	55%	91%	64%	92%	1. Step-by-step instructions	
0%	100%	100%	0%	0%	2. Reporting	
14%	100%	79%	29%	63%	Level 1 degree of compliance:	2 Life cycle Global Warming Potential (CO2 eq·m−2·yr−1)
29%	100%	100%	14%	83%	1. Step-by-step instructions	
0%	100%	67%	50%	92%	2. Checklist of design concepts	
0%	100%	0%	0%	0%	3. Reporting	
56%	100%	88%	38%	77%	Level 2 degree of compliance:	
69%	100%	92%	38%	63%	1. Step-by-step instructions	
0%	100%	100%	0%	88%	2. Comparability of results	
0%	100%	0%	100%	92%	3. Optimisation steps	
0%	100%	100%	0%	0%	4. Reporting	
No instructions provided					Level 3 degree of compliance:	
0%	42%	100%	0%	63%	Level 1 degree of compliance:	3 Life cycle costs (€·m−2·yr−1)
0%	33%	100%	0%	56%	1. Step-by-step instructions	
0%	60%	100%	0%	71%	2. Checklist of design concepts	
0%	0%	100%	0%	63%	3. Reporting	
0%	50%	94%	0%	50%	Level 2 degree of compliance:	
0%	64%	100%	0%	56%	1. Step-by-step instructions	
0%	0%	100%	0%	43%	2. Comparability of results	
0%	0%	100%	0%	0%	3. Optimisation steps	
0%	0%	100%	0%	50%	4. Reporting	
0%	0%	89%	0%	44%	Level 3 degree of compliance:	
0%	0%	100%	0%	56%	1. Step-by-step instructions	
0%	0%	100%	0%	29%	2. Reporting	

The mapping procedure was carried out regarding new construction rating schemes. This has led to a slight confusion with the "at-occupation stage" aspects of Level(s). This is because BRS predominantly address the "at-design" and "post-completion" stages. Moreover, some GBCs (e.g., DGNB) operate separate "Building in Use" BRS which cover the "at-occupation stage" aspects of Level(s), which were not part of this research. Finally, a methodological question arose as to whether the compliance would be consistent for the three levels. Additionally, NF-HQE required a slightly different aggregation method.

The results show that the adoption of LCC is not yet mature, except for DGNB. Indicators 1.1 and 1.2 behave very similarly, which is positive for the consistency of LCA. However, work is to be performed for VERDE, HPI, and NF HQE. Furthermore, Level(s) must provide instructions for level three of the GWP indicator. It should be noted that the second entry level for LCA indicators rates better than the first (conceptual design). This could mean that other sustainability approaches might be more useful at early design stages than LCA, and LCA could make more sense once the project is fully designed, rather than as it is being projected. More meaningful insights appear when the gaps are seen in the whole picture of the Level(s) indicators.

Gap Analysis

If the mapping procedure shows where and how Level(s) is present at the BRS, complementarily, the gap analysis aims at finding where and how the BRS miss Level(s) and what can they do to reconnect. Doing this would increase conformity, as was presented to the BRS managers. Regarding indicators with a deviation, the following options were recommended accordingly: (a) suggestions concerning further developments of the Level(s) framework; (b) possible conversion of the data submitted in the BRS certification process to be adapted into Level(s) procedures; and (c) adjustments to the BRS to comply with Level(s). Some general recommendations were also identified, including adjusting LC stages (Level(s) suggests scenarios instead, which do not easily define the system boundaries of a building), adjusting reference study periods, or adding abiotic depletion potential for fossil fuels. Table 1.7 shows results of the gap analysis for all five BRS in 12 analysed indicator categories, all of them divided into Level 1, 2, and 3 degrees of compliance.

Table 1.7. Gap analysis results of BRSs for all Level(s) indicators. Colour code: red (X), disconnected from Level(s) framework; yellow (empty), deviated; green(V), harmonised.

HPI			**BREEAM-NL**			**DGNB**			**VERDE**			**NF HQE**			**Green Cells are "Compliant" with Level(s)**
L3	**L2**	**L1**	**L3**	**L2**	**L1**	**L3**	**L2**	**L1**	**L3**	**L2**	**L1**	**L3**	**L2**	**L1**	**Entry Levels Indicators (1st Version)**
X	V	V	V	V	V	V	V	V	V	V	V	X	V	V	1. Use-stage energy performance
X					V				X	X	X				2. Life cycle GWP
X		V	V	V	V										3. LCA for: bill of materials
X		V	V	V	V				X	X	X	V	V	V	4. LCA for: building and elemental service life planning
X	X	X	V	V	V							X		V	5. LCA for: design for adaptability and refurbishment
X	X	X							X					V	6. LCA for: design for deconstruction, reuse, and recycling
		V	V	V	V						V			V	7. Construction and demolition waste and materials usage
X					V				X	X	X				8. LCA for: cradle-to-cradle life cycle assessment.
X	V	V	V	V	V					V	V		V	V	9. Use-stage water consumption prediction
X		V	V	V	V		V	V			V		V	V	10. Time out of thermal comfort range
X	X	X	V	V	V	X	V	V	X	X	X	X			11. LCA for: Scenarios for projected future climate condition
X	X	X							X	X	X	X			12. Life cycle costs analysis

The relevant key findings are:

- Deviations appear in particular in the "goal and scope" aspects;

- Degree of compliance is consistent across the three levels;
- “Boundary and scope” aspects have a high degree of compliance;
- Deviations across the three levels are caused predominantly because of “at occupation stage” aspects at Level 2 and Level 3.

Expert Interviews

Finding relevant quantitative data to support the described research has been met with several barriers:

- The private character of LCA within rating schemes;
- The untraceable variety (free choice) of tools and databases used;
- The variation of approaches, scope, and inclusion criteria of LCA in the last 10 years;
- The scarcity of fully assessed buildings under comparable typologies.

Early in the research process, it was seen as necessary to gain knowledge from direct sources. The conversation with the managers of each BRS was friendly and insightful for all. Summing up the feedback, we could not find data about the real performance of the certified buildings. This was also asked of another key agent, Josefina Lindblom from DG Env, but data from the buildings tested by Level(s) from 2019 to 2020 could not be accessed due to the fact that the relationship with the testers was finished or for privacy reasons. Anyway, some initial figures are provided with the following limitations: while NF HQE numbers are very high (over 60,000 homes certified), no aggregated figures were available; BREEAM provided reference benchmarks of their “excellent”-rated buildings; and HPI provided average rating qualifications, which have been transformed into their own suggested comparable units. VERDE was able to provide real figures from the 2008 to 2015 period, while DGNB facilitated figures from the 2015 to 2017 period. In both cases, averages have been drawn from the data provided. Some figures for offices were also provided but have been left aside in this study. Two significant data sets have been harmonised as much as possible in Table 1.8 and averaged for new homes: primary energy demand (PED) and global warming potential (GWP), and both were limited to the surface area of the building (yearly, in the case of energy demand).

Table 1.8. Average PED and GWP per BRS.

GWP ($CO2$ eq·m−2·yr−1)	PED (kWh·m−2·yr−1)	Averages
N/A	N/A	NF-HQE
40.49	29.22	VERDE
18.22	61.10	DGNB
Between 15 and 35	Between 25 and 40	BREEAM NL
<300	<42	HPI

This is in line with a recent critical literature review on environmental benchmarks for buildings found at the closing of this paper (Trigaux et al., 2021). It proves that rated buildings from the BRS perform better than average buildings. This is not sufficient to draw conclusions, but gives a hint to the consistency of LCA aggregated results which are used by the Taxonomy and the Nordic countries (Kuittinen and Häkkinen, 2020).

Concerning the mapping-gap analysis, some insights were identified by the experts. Firstly, not everyone was fully acquainted with the second version published in October 2020. All had been involved in the test phase between the first and second versions and were aware of the improvements. All agreed that many improvements in the second version can be credited to the dialogue between the BRS and the Level(s) development teams at DG Env and JRC. In practical terms, it means that the results presented are not fully updated to the second version. This does not affect the validity of the results. The gaps identified in the analysis were welcomed by the experts, who suggested future improvements within their respective BRS. For indicators 1.2 and 2.4, filling in these gaps means to add impact categories, add result interpretation, adjust cut-off rules, adjust reference study periods, and in the case of BREEAM-NL, adjust life cycle stages. Finally, for indicator 6.1, there is a need for all to adjust discount rates, reported costs, and add scenarios.

The issue of the reference study period remains open. British and Irish cultures favour a 60-year period, but continental Europe marks 50 years for the use-stage of a building and is thus applied in LCA calculations. The first version of Level(s) used 60, but after the test phase, the second version functions with a 50-year study period. This reduction influences final LCA values. Furthermore, the question of making all life cycle stages as well as all impact categories mandatory remains open. While carbon metrics are best known and accepted, and climate mitigation uses GWP and GHG in CO2 eq units as a star indicator, buildings have equally dire impacts on acidification, ozonification, and very clearly on abiotic resource depletion, including minerals, metals, and fossil fuel. In addition, its water footprint is well known but seldom included in LCA. Last, but not least, the GWP of land use and change (LULUC) might be as important as the energy-related GWP. The common understanding is that GWP acts as a spearhead for all the other impacts wherever relevant.

Including all stages is more easily solved. In the detailed mapping and in Table 1.4, it is clearly identified how all BRS except BREEAM demand all stages for the best rated buildings. The effort to calculate LCA for all stages, as well as to include all impact categories, is high and might not be needed for early design. Once more, the three entry levels of Level(s) make sense. A final issue that arose during the interviews was that related to including all building elements in the LCA calculation, only BREEAM-NL failed to solve this, at least for the best rating. It is commonly agreed that it is not enough to include a few materials with EPD. Even all materials with EPD would not necessarily lower the LCA result. The life cycle of all building materials and elements should be analysed to call it a building LCA. This raised another challenge, namely the insufficient availability of data, which are the very basis of LCA.

The MLP methodology was not known to any of the interviewees. The GBCs, where they are active, are, in fact, key agents in the transition. This was well understood and accepted. Nevertheless, while acknowledging a positive recent evolution, all informed that their national markets offer resistance. They identify themselves as pioneers.

DISCUSSION AND FUTURE STEPS

For wider LCA market penetration, the insufficient consistency of data software and availability of skilled LCA professionals are weak points. Harmonised data availability and transparency in the processing of data within the calculation tool (not necessarily a complex software but simple spreadsheets might be enough) are urgent needs. There are open source and free solutions, but their databases are not that easy to obtain or they are not tailored for buildings (Steubing et al., 2020). Proprietary tools are well adapted but are not free. Some countries (Netherlands, Germany, France) have national databases, and there is an ongoing discussion regarding whether, for a building sector to provide reliable figures, a national database is necessary. Were this to be the case, it must not hinder aggregation. However, Level(s) does not come with a Europe-wide database. Although for LCA stages A and B this could easily be adjusted with national energy and transport impacts, for stages C and D, national policies vary enormously. The taxonomy establishes “Do No Significant Harm” waste benchmarks, which are impossible to accomplish quickly in some countries. Findings from the MLP teach us to recommend that all these artifacts need to evolve in parallel so that the regime changes.

More concretely, some key manufacturers, namely steel and cement producers, play a crucial role: they are at the same time the heaviest polluters and energy demanders, and the biggest investors in sustainable innovations. If they do not diminish their impact, they might fall outside of the regulations, but they are also prone to greenwashing, to swallowing huge public funds, and they are, inevitably, resource predators. A change in the regime inevitably means a change in their role. However, no more than 75 years ago, reinforced concrete was not a relevant building material. Can it lose relevance again? Are low-carbon materials such as timber and mud a real alternative? Market and scientific studies answering this (Orsini and Marrone, 2019) are, however, outside the scope of this paper. Nonetheless, it can be stated that, as mentioned in the introduction's brief historical review, vernacular architecture was and may once again be the solution. On the other hand, if in the present regime architecture falls in the realm of RE, a deep regime shift must happen for up-to-date vernacular architecture to be understood as an alternative.

Recently, the regulatory framework has been pushed by the EC through the JRC. The result has been a profound methodological transformation at the product level, from EN 15804 + A1 to EN 15804 + A2, and at the building level, with the revision of EN15978 and of Level(s). Will the regulations be effective to deal with the challenges it poses, mainly for the construction industry, but also for the professionals in the sector? Are the standards and tools mature enough to face these challenges? Evidence found in this paper suggests hard work will be required to meet expectations.

While in Europe only 2.5% of the total built area (Bionova, 2018) is certified, highly developed and densely built countries, such as Singapore, have 1/3 of their building stock certified (mainly with the BCA Green Mark). However, Europe is leading the way to integrated policies, voluntary schemes, and market value in favour of sustainable buildings and LCA. The success of EPBD policies and Level(s) by introducing LCT in its objectives and indicators paves the way to decarbonising new European buildings (Röck et al., 2020). If the path dependencies described in the MLP results are further unlocked, the European building sector might find itself already in a deep transition.

Three other issues deserve a specific discussion:

Harmonisation of BRS and Data at European Level

If we agree that Level(s), present standards, and norms mark the future methodology for the sustainability assessment of buildings, the evaluation of products and buildings should follow these standards, both at the product level and at the building level. However, its adoption and application still need to be harmonised. As mentioned before, all stages, impact categories, and building elements need to be equally included. If this succeeds, either in BRS or as criteria for GPP, it can support the regulatory evolution of the different national building codes and turn progressively from voluntary to mandatory. Remaining voluntary might weaken the momentum to shift the regime. The need for harmonisation must clarify the inclusion of other relevant issues; crucially, the health and comfort aspect. Initiatives such as the IEQ-Compass (Larsen et Al, 2020) or the TAIL scheme (Tanasa et Al, 2020) attempt to upgrade this issue and further relate IEQ parameters with energy performance and life cycle metrics, following ISO 1772-1, EN 16798-1, and EN 16798-2. Under a scenario of normalised NZEBs, life cycle costing must also optimise IEQ to reach long-term climate targets. While this area of research is not new, it remains open for future investigations.

In Level(s), several levels of data quality are allowed and subsequently categorised. Different levels of evaluation are established, whose choice depends on the phase of the project and the objective of the assessment. Categories are based on a quality score averaging between its relevance and its accuracy. The degree of (un)certainty or reliability is provided by the origin of data, mainly local

EPDs. Generic default data is less accurate and is penalised with very high load factors to encourage manufacturers to generate their own data. The geographical and technological representativeness of the data implies that data must be localised. However, there is a huge amount of data generated in different contexts (tools, databases, European projects) that is essential to add value, and could be integrated into a European database in the near future, once its quality and adaptability to all regions has been verified. National databases, whether they exist yet or not, need to align with European ones, and BRS are fit to use one or the other. The International Open Data Network for Sustainable Building is managing to convince all data developers and providers, as well as all LCA software providers, that harmonised data is a must.

Pathways to Building Decarbonization

According to the WGBC's "Bringing Embodied Carbon Upfront" Report (Adams et al., 2019), the world's total global floor area of buildings is projected to double by 2060, a growth of 230 Bn m^2, which is equivalent to the size of New York City every month, mostly in the Global South. There are also equally huge retrofit requirements in the Global North: In Europe, an estimated 97% of the building stock is not efficient enough to comply with the Paris Climate agreement. If business goes as usual, embodied carbon could make up half of total new construction emissions between now and 2050. As the energy performance of buildings improves, the impact share of embodied carbon will increase.

The mentioned study (Röck et al., 2020) on the balance between operational and embodied carbon shows results based on the LCA of 238 buildings: while there is a reduction trend in LC emissions due to improved operational energy performance, an increase is demonstrated in the relative and absolute contributions of embodied carbon (emissions arising from the manufacturing and processing of building materials), particularly for residential buildings. Some (Negishi et al., 2019) add a dynamic indicator (cumulative radiative forcing and global mean temperature change) to LCA, for all the climate scenarios to 2050, within a time function for climate change of 500 years. The main outcome of the comparison between Dynamic LCA and LCA is that the results can be greatly different, especially when biogenic carbon is present from low carbon materials. Their methodology calls for a temporal dimension of the inventory and the impact indicators. This links building science closely with climate science, which will necessarily become a cross-cutting field of research. In this context, basic actions to design new low-carbon buildings and their respective reduction in GHG emissions are identified (Orsini and Marrone, 2019). Its effect needs to be analysed under a cohesive and harmonised building LCA.

However, these studies are neither known nor demanded by the building sector. Manufacturers are doing EPDs within the EN 15804. It is worth underlining the exponential evolution in EPDs in the construction sector in the last 10 years. From less than 100 EPDs, developed by three countries, we now see more than 7000 developed by 25 agents/countries. While the EPD might be no more than a strategy to sell their products, baselines are needed for the building to limit its overall value of decarbonisation and other impacts. This can be performed with sectorial or generic EPDs, provided they contain all impact categories. As mentioned in the results, carbon metrics must be the spearhead of all other impacts. Climate change affects not only the atmosphere, but also the land, watersheds, and biodiversity, which are as important, and arguably more crucial, for human life. Any transition needs to understand the relationships between at least air, soil, water, and life, but also the continuity between the individual, society, and the ecosystems. While green may be the colour of chlorophyl, just as important are the red of oxygenated haemoglobin, the brown of humic acid, and the transparency of clean water.

The Storytelling Flaws of the Green Socio-Technical Transition

The regime of the building sector, in synergy with the energy, financial, and urban facilities and services sectors, ignoring pioneers and volunteers, is profiled by a diffuse value chain, dominated by a few huge construction industries that possess great influence on the policy agenda, and which have gained cultural storytelling hand in hand with the RE business. Overshadowed by these, science and user demand become secondary players. For the regime, green is just a colour, used and abused to hide its grey emissions. In Europe, there are (figures from 2019) about 50.000 companies in the construction sector (buildings and infrastructures), with 12 million employees and a yearly turnover of around EUR 1.5 billion. The top 100 companies' share of the turnover is one third of the total, while the accumulated turnover of the top 10 reaches EUR 235 billion (15%). Alone, the three top French companies (Eiffage, Bouygues, and Vinci) amass over EUR 100 billion (Ingling, 2020). A critical eye is needed when reading news about their green investments. It would be equally unsustainable for BRS, LCA, EPDs, and the green innovations to lay at the feet of their interests. If green buildings become a privilege for a few, the sector will have failed in its transition.

The financial sector entered into sustainable assets before the mainstream RE did (the niche of the highest standard RE already considered green-certified buildings, and LEED has been a key marketing lever for this, notwithstanding a degree of greenwashing). There has been a huge shift of RE assets to "vulture funds", which has created a reaction among local governments and society, as well as other handlings that exceed the purpose of this paper, but are part of the landscape. Many European buildings, especially in the city centres, have not undergone integral refurbishment and lack the basic features of current building codes and lifestyles. All these internal changes have fed the surge of the BRS and the demand for sustainable buildings. Materials and buildings passports can boost and track this necessary deep renovation. However, where building is not necessary, the most sustainable m^2 is one that is not built, just as the cleanest kWh is one that is not consumed. Green finance must be at the service of protecting life, not buildings.

The European Construction Sector Observatory regularly analyses and carries out comparative assessments on the construction sector in all 27 EU countries and the UK, to provide policymakers and stakeholders with up-to-date information on market conditions and policy developments. Its five priorities are financing and digitalisation, skills and qualifications, resource efficiency (focusing on low-emission construction, recycling and valorisation of construction, and demolition waste, and is thus related to this paper's focus), the regulatory framework, and international competition. It does not reject green storytelling when placing as much interest in digitalising and going abroad as in resource efficiency and upskilling. The heads of the regime are both policymakers and the CEOs of big companies. Perhaps policymakers need to step down first.

Pioneering processes and results provide a regular drip of extraordinary buildings whose inherent value, after a short marketing "shooting star" effect—or no marketing at all—is either swallowed by the regime or remains anonymous. However, as BRS gain marketing value, the rating leaves less and less space for fakes, and as the climate challenges highlight best practices, more windows of opportunity and increased momentum is attained by truly sustainable buildings. The European Taxonomy Regulation and delegated acts were published in July 2020 to set four overarching conditions that any economic activity (including buildings) must meet in order to qualify as environmentally sustainable (Taxonomy, 2020). However successful all this appears, if it falls into the green narrative and it can easily be washed away. Pioneers must meet, collaborate, and aggregate knowledge, potential, and results so that the niche they create transforms the regime.

The exogenous context is shaped by climate change mitigation (the decarbonisation of the building sector and stock) and very recently by the pandemic and the mandatory home lockdown. While regulatory pressure on energy efficiency has been growing for 10 years, it was in 2021 that NZEB became compulsory. NZCB are a central concept for national and European decarbonisation goals. In this scenario, Level(s) stands as the cornerstone for the decarbonisation strategy, the circular economy package, and the resilience of the European building stock. If the national building sectors were reluctant to take action, and the overall decarbonisation strategies did not consider buildings as a key issue, it is the very socio-technical landscape that is marking the route for future developments. Decarbonisation cannot be prey to greenwashing or it will fail to pave the way for the other just-as-important impact categories.

CONCLUSIONS

Approaching the challenges of a complex methodology such as LCA in an equally complex sector such as that of buildings, under the lens of Europe's complex regulatory framework, and targeting not one single aspect, but all those present, has been a complex quest. Nonetheless, simplifying it by reducing the scope or depth or selecting—by any criteria—one single aspect, neither seemed to fit the size of the impacts of the sector nor the obvious transition it is undergoing.

Quality and harmonised data of construction products are required for LCA to give aggregated and transformative results. These are necessary to comply with current and future legal and voluntary requirements and to foster the decoupling of the building sector from the current consumption of resources and generation of impacts. Data and software providers are asked to collaborate and facilitate access. Upskilled experts are needed.

According to the standard, LCA for buildings must follow a modular approach, reporting the full set of impacts and stages where they occur, so as to avoid a transfer or denial of loads. It needs to include all building elements. All impacts must follow the carbon footprint as being the most known impact, and their relevance for the sector featured. The loss of biodiversity, land occupation, and water usage impacts need urgent attention.

The Level(s) framework, with its due compliance to the Renovation Wave and the taxonomy, is a powerful changemaker, able to deter greenwashing, misleading financing, and obscuring information. The European building sector is attentive to its evolution and the academy is researching on its potential and adoption pathways. Level(s) needs to become mainstream and complete tools, data, benchmarks, and interpretation criteria.

BRS are well equipped connectors between Level(s), the market, public procurement, and society. They are adopting the framework, filling in the gaps within their systems in order to provide, together with the rating, a "Level(s) compliant" seal. This effort is also driving the harmonisation of data and LCA. Playing a voluntary role might be heavily challenged if mandatory rules appeared. These BRS are exploiting their national niches at their limited but steadily growing Green Building Councils, which are pioneering their markets as key agents, writing a new script for the building sector. However, they need to expand in scope and to continue evolving. They might be too young to shift the path dependencies of their sectors, making socio-political action key for them to mature and lead the transition of the sector.

The multi-level perspective methodology proves fit to understand and explain the innovation niches, the path dependencies of the regime, and the STT that the European building sector is undergoing towards a sustainable pattern. It must decarbonize, adapt to climate change, and provide healthy indoors and regeneratively built environments. Should it fail, its own unsustainability might lead it to collapse.

Author Contributions: Data curation, B.I.; Methodology, B.I.; Supervision, O.A.-G. and X.O.; Writing—original draft, B.I.

Funding: This research was funded by the research project LOCAL-REGEN (PID2019-104871RB-C22), supported by the Spanish Ministry of Science and Innovation (Ministerio de Ciencia e Innovación) – State Research Agency/10.13039/501100011033.

Data Availability Statement: The data that support the findings of this study are available on request from the main author (Izaola B.—borja.izaola@gbce.es). The data are not publicly available as to not the compromise of privacy of the research participants and the five BRS institutions present in the research.

Acknowledgments: The work presented in this paper belongs to the research projects LIFE Level(s) (GIE/ES 1000911) project, whose aim is to accelerate the penetration of the Level(s) Framework into markets; and Project LOCAL-REGEN (PID 2019-104871RB-C22), funded by the Ministry of Science and Innovation - State Research Agency/10.13039/ 501100011033. Moreover, this research work is part of the main author's (Izaola B.—borja.izaola@gbce.es) Doctoral Thesis that aims to investigate on the applicability of LCA to European buildings.

Conflicts of Interest: The authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest, or non-financial interest, in the subject matter or materials discussed in this manuscript.

7. Impactos ambientales de apartamentos (Artículo 2)

7. ARTÍCULO 2

Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building

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ABSTRACT

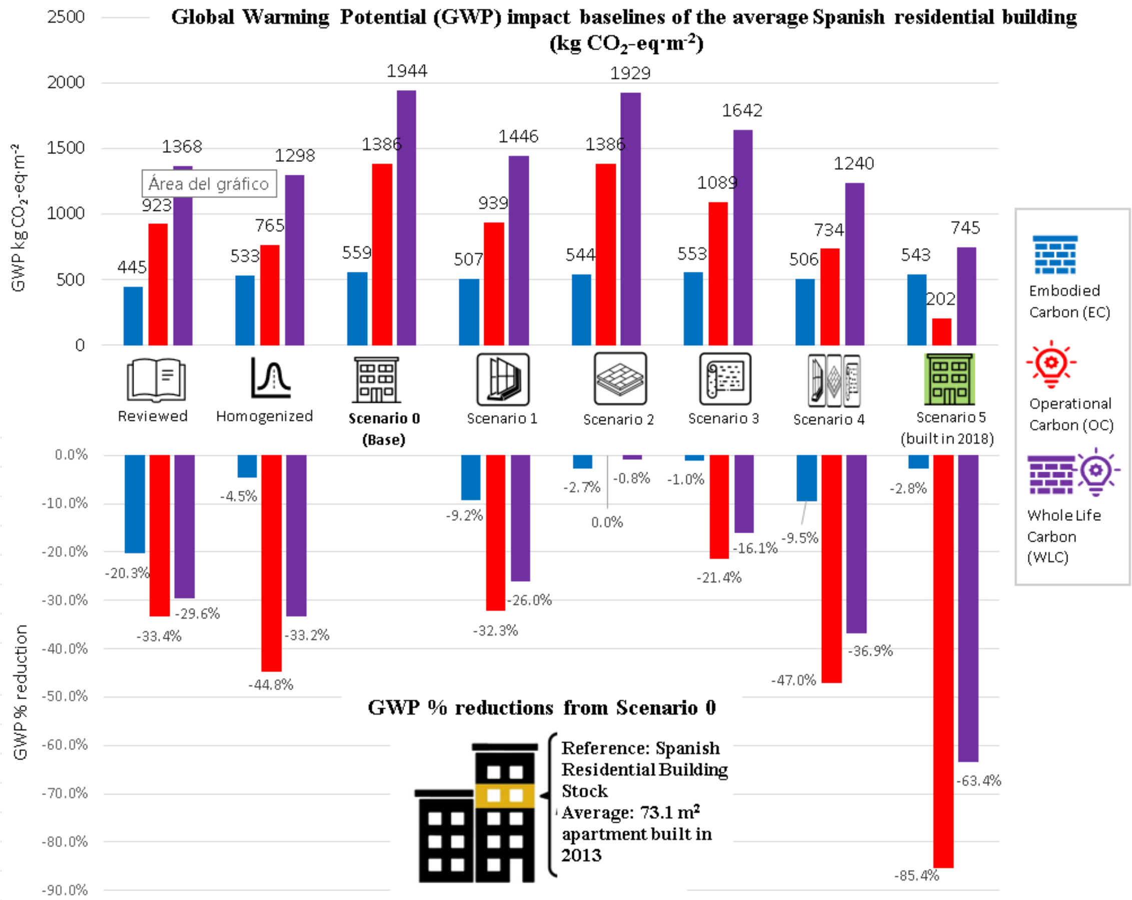
The construction sector, responsible for 37% of global greenhouse gas emissions and 36% of global energy consumption, is transitioning towards a low-carbon and low-energy model. Measuring and optimising Operational Energy and related emissions in the use phase of buildings has entered both markets and regulations. However, the Embodied Energy within construction materials and respective maintenance and end-of-life Operational Carbon is still in the research phase. To advance in this transition, Global Warming Potential baselines per built square metre needs to be defined in the construction sector, integrating operational and embodied impacts. This research has the main goal of identifying for the first time the Whole Life Carbon emissions of the average Spanish apartment (built in the period 1981-2010), broken down into Embodied and Operational Carbon. Methodologically, first, a regular average and homogenised average of existing European baselines was performed; next, the average building of the Spanish residential building stock has been defined and modelled with a real sample from year 2013, and its emissions calculated as Scenario 0; and finally, five new scenarios have been compared in order to understand variations in Whole Life Carbon and their Embodied and Operational contributions. This research shows for the average multifamily building apartment in Spain, with a mean net floor area of 73.1 m^2, a Whole Life Carbon baseline of 1944 kg CO_2-eq/m^2, 30.8% (559 kg CO_2-eq/m^2) being Embodied, and the remaining 69.2% Operational. In Scenarios 1 to 3, the following are identified: a Whole Life Carbon reduction of 26.0% (9.2% Embodied) by using wood window frames, 0.8% (2.7% Embodied) by laying a wood inner floor, and 16.1% (1.0% Embodied) by insulating walls with recycled cork. All three items are calculated together in Scenario 4, giving a 36.9% Whole Life Carbon reduction (9.5% Embodied). Finally, Scenario 5 was modelled upon Scenario 4 materials, complying with the upcoming European Energy Performance of Buildings Directive as if built in 2021, reaching a potential Whole Life Carbon reduction of 63.4% (2.8% Embodied) from the original Scenario 0. Reductions of more than

80% are also derived from other impact categories, such as Ionising Radiation, Marine Eutrophication, and Water Consumption, while Freshwater Ecotoxicity increases by 15%. The 18 ReCiPe Midpoint indicators plus Energy Footprint, are reduced by an average of 50.4%. These figures support technical and policy trends towards minimising the impacts of buildings. Focusing on Global Warming Potential, decarbonisation goals of over 60% appear feasible with existing market solutions.

KEY WORDS

Life-Cycle Assessment, Greenhouse Gas Emissions, Whole Life Carbon, Building Decarbonisation, Operational Carbon, Embodied Carbon

GRAPHICAL ABSTRACT



ACKNOWLEDGEMENTS

The authors are grateful for the support provided by the Life-Cycle Thinking Group (LCTG) with the grant funded by the University of the Basque Country (GIU21/010).

The authors are grateful for the funding provided by the Department of Architecture of the University of the Basque Country.

INTRODUCTION

The environmental impacts and energy consumption trends of the construction sector must be reduced in order to face the climate emergency. In 2020, the construction sector worldwide emitted 11.7 Gt CO_2-eq of Greenhouse Gases (GHG) (8.6 Gt for the operation of buildings and infrastructures and

3.1 Gt for the erection of both), altogether 37% of 35.26 billion tonnes of global CO_2 equivalent emissions. In 2020, the sector's energy consumption was 35,278 GWh, 36% of the global 97,994 GWh Primary Supply (UNEP, 2021). In 2021, the sector's emissions reached 13.6 Gt CO_2-eq (10 Gt for operations and 3.6 Gt for the erections). Its energy consumption was 37,500 GWh (UNEP, 2022). Residential buildings are responsible for 22% of the sector's energy demand and 17% of the related CO_2eq emissions (the rest being infrastructure, industry and equipment). Hence, US$184 billion were invested in the energy efficiency of buildings in 2020 (US$230 Bn in 2021) (UNEP, 2021). After the relative break in 2020 due to COVID, figures are back to trends from previous years. Moreover, the emissions embodied in the materials and the construction works remain.

Assessing both embodied and energy-related emissions can help reduce the resource use and environmental impacts of buildings over their whole lifecycle. Applying Life-Cycle Assessment (LCA) from design onwards shows a high potential to benchmark environmental targets. When the chosen metric is GHG emissions, the focus lies on Whole Life Carbon (WLC), including Modules A to C as defined in EN15978 and EN15804 (CEN/TC350, 2022). This encompasses the Embodied (Modules A, B1-B5 and C) and the Operational carbon (B6) (WGBC, 2022). Although these concepts are not yet common practice, a WLC paradigm could become as important a performance and investment metric as energy efficiency in order to achieve a net zero carbon built environment (McConahey, 2022).

The enacting of the EU Energy Performance of Buildings Directive (EPBD) (European Commission, 2021a), and its enforcement via national building regulations, set a comprehensive path to reduce the Operational Carbon of European buildings, via more efficient appliances, more on-site renewables and demand reduction at the envelope. It has evolved into a Deep Renovation standard and been incorporated into Energy Performance Certificates (EPC), all marking WLC emissions. Art 7b of the EPBD states that the life-cycle Global Warming Potential (GWP) of new buildings will be calculated as of 2030 in accordance with the Level(s) Framework, informing on the whole Life-Cycle emissions of new constructions. It indicates maximum thresholds, from 2021 on, for Nearly Zero Energy Buildings (NZEB) of 60 $kWh \cdot m^{-2} \cdot y^{-1}$ for residential buildings (less than half that of current practice) in the Mediterranean and Oceanic European climate zones (European Commission, 2021b). While energy performance approaches are more common and harmonised, providing consistent benchmarks for operational energy use, LCA is required for a more holistic environmental performance assessment of building stocks (Mastrucci et al., 2017).

NZEBs highlight both the relative and the actual extent of Embodied Carbon. As the share of Operational Carbon diminishes, the share of the Embodied Carbon grows (Röck, Martin et al., 2022). The new challenge is to reduce Embodied Carbon while keeping Operational Carbon low. The EPBD chooses GWP as a numeric indicator for each life-cycle stage, expressed as kg CO_2-eq$\cdot m^{-2}$ (of useful floor area), averaged per year in a reference study period of 50 years, in accordance with EN15978 and the Level(s) Framework. The leadership of the EU in building GWP regulations and their role in promoting circular building design is indisputable (Attia et al., 2021). However, it provides no Embodied Carbon reference values of buildings yet. Also, the energy footprint of the European lifestyle consumes Hidden Energy Flows from abroad (Akizu-Gardoki et al., 2018), (Akizu-Gardoki et al., 2020), which are not yet present in the circular economy policies of buildings (Giorgi et al., 2022).

According to EUROSTAT, in 2020 there were 223 million residential buildings in Europe. But the literature review identified barely 7000 of these with LCA. Although it is a growing trend, the practice of building LCA is still negligible and heterogeneous. Even with the same initial information (i.e., bill of quantities and technical drawings), all the subsequent subjective choices and assumptions that a modeller must make have a profound influence on the numerical outcome. As a result, considerable variations are observed across all Life-Cycle stages. A simple cradle-to-gate (A1-A3) assessment leaves out 30 to 40% of the GHG emissions (Pomponi et al., 2018). Moreover, when data are abundant – such as the Embodied Carbon coefficients of common construction materials (cement, steel or glass)– the variability detected in the literature review is difficult to explain in terms of contextual variations such as location or technology.

For instance, the analysis of min and max Embodied Carbon weight for Module A3 of the main structural building materials (concrete, steel, masonry, timber) shows variations ranging between 284 and 1044% (Pomponi and Moncaster, 2018). The choice of materials in buildings leads to ranges of Embodied Carbon from 420 to 1350 kg CO_2-eq·m^{-2} (Chastas et al., 2018), 250 to 750 kg CO_2-eq·m^{-2} (Wolf and Lieve, 2014) and, in a study akin to this research (typical Spanish multifamily buildings), 603 to 627 kg CO_2-eq·m^{-2} (Solís-Guzmán et al., 2018). But these figures need to be disaggregated among the LCA modules to grasp their relative impacts and support the goals of the review. Steel, concrete and timber structures of multi-storey buildings distribute their GWP very differently along modules: A1-A3 (46 to 81%), A4+C2 (11 to 19%), C1 (3 to 11%) and C3-C4 (0 to 32%) (Hart et al., 2021). A more detailed study from Italy takes statistical results from 24 building typologies (including the choice of this study) at three representative climate zones, suggesting A1-A3= 21.29%; A4= 1%; A5= 0.71%; B6= 74%; B7= 4.4% and C3-C4= −2.93%, as benefits from recycling and incinerating materials at C3-C4 were included in the system boundaries, albeit with a certain rate of uncertainty (Lavagna et al., 2018).

Green Building Rating Systems are progressively introducing an approach to WLC benchmarks (Amiri et al., 2021), harmonised with regulations such as the Level(s) Framework (Izaola et al., 2022) and in accordance with national roadmaps for the decarbonisation of the building sector, worldwide (Mata et al., 2020), EU-wide (Building Life Project, 2020) and per sector, like the use of steel and cement (Karlsson et al., 2020) or glass (Griffin et al., 2021). This clears the path to normalising Embodied Carbon and Operational Carbon baselines.

EN15978 presents the structure and definition of stages in the Life Cycle of buildings according to the European standard for the sustainability of construction works, assessing the environmental performance of buildings. EN15804 defines how to create the Environmental Product Declaration (EPD) of building materials, enabling WLC reporting. EN15643-5 outlines how to assess the sustainability of buildings and civil engineering works. A study (BPIE, 2021) on WLC measurement at new buildings compared the scope of various European policy instruments (Energy Performance of Buildings Directive-EPBD, Energy Efficiency Directive-EED, Construction Products Regulation-CPR, Ecodesign standards, Waste Framework Directive-WFD, Emissions Trading Scheme-ETS, Level(s) Framework and Taxonomy) against LCA modules. It concluded that only Level(s) embraces a full LCA approach, a potential inclusion under the Do-Not-Significant-Harm-DNSH criteria of Taxonomy and basic requirements in the Construction Products Regulation (CPR). All of the above is aligned with the relevant Product Category Rules (PCR). The following Spanish sectorial panels for building products following Norm EN15804 have been checked at AENOR (official operator): Steel products for construction, Ceramic finishes, Cements, Gypsum-based products, Mortars and Bricks (AENOR, 2022). These standards have been respected during LCA modelling.

The aim of this paper is, therefore, to advance in finding consistent WLC baselines for European residential buildings, assessed using a representative average building of Spain's residential built stock. For this purpose, a Scenario 0 (Base) was modelled and compared with four new scenarios with different practices for construction. A fifth scenario has been modelled for an updated building, now complying with standards of NZEB (European Commission, 2021b). Scope, stage, functional units and choice of materials when applying LCA are scrutinised to provide comparable values of average multifamily buildings, typical in the built stock of southern Europe and Spain. Scenario 0 is compared to all others which include lower market-ready Embodied Carbon solutions that are progressively Operational Carbon compliant with the EPBD.

This article is underpinned by a literature review, identifying the aforementioned building WLC baselines, as reviewed (Average reviewed value), and attempting to homogenise their values (Average homogenised value). The performed methodology is defined in Section 3, describing the analysed scenarios in Section 3.1. European standards for the Spanish representative stock characteristics (Section 3.4) help define Scenario 0. In the Results section, Embodied Carbon, Operational Carbon and WLC from all scenarios are compared, and another 18 indicators are considered. Under Discussion, a comparison is made with the current state-of-the-art, and the final conclusions are shown, where policy implications for decarbonisation strategies are drawn.

LITERATURE REVIEW

While baselines are minimum or starting points used for comparisons, such as the average level of energy performance of current buildings, benchmarks can be understood as a value of reference against which things may be compared (Lavagna et al., 2018). ISO 21678:2020 defines benchmarking as the process of collecting, analysing, and relating performance data of comparable buildings. A benchmark can become a target, as has been achieved with the building energy certifications developed in the EPBD (European Commission, 2021a). For Spain, the classification is presented in Table S1 of the Supplementary information.

The main reason to update the current status and future plans of environmental benchmarking for buildings is linked to the 1.5 °C target stipulated in the Paris Agreement (Frischknecht et al., 2019), (Trigaux et al., 2019), (Trigaux et al., 2021), (Martínez-Rocamora et al., 2021). Reporting frameworks as Level(s) puts the focus on normalising parameters; for instance, a lifespan of 50 years. Also, when considering Operational Carbon, functional unit variations (gross floor, usable floor, net floor, built-up, living, conditioned and heated area), net heated floor area is taken into account when relevant, and otherwise Net Floor Area (NFA) is used (Dodd, 2020). The range of NFA Embodied Carbon emissions lies between 179.3 and 1050 kg CO_2-eq·m^{-2}, with a variation of 585.6 %, and Operational Carbon between 156 and 4049.9 kg CO_2-eq·m^{-2} (in 50 years). This reflects an Embodied Carbon share of between 9% and 80% of WLC. The energy efficiency standards of different buildings indicate an Embodied Carbon share of between 9% and 22% for conventional buildings, between 32% and 38% for PassivHaus, between 21% and 57% for low-energy buildings and up to 71% in the case of NZEBs (Chastas et al., 2018).

If NZEBs are to become norm, and their Embodied Carbon represents 71% of the total GWP (Wiik et al., 2018) of the building, due importance must be paid. When offsetting GHG emissions through the generation of on-site renewable energy is limited, achieving low Embodied Carbon is decisive, be it via material reduction, application of reused and recycled materials, using low-carbon materials, sourcing local materials, or adopting materials with high durability and a long service life (Wiik et al., 2018). The next step detected will be to regulate Net Zero Carbon Buildings (NZCB) (Pan and Pan, 2021).

Embodied, Operational and Whole Life Carbon baselines.

In this research, 15 studies are analysed and respective values of Embodied Carbon, Operational Carbon and WLC used to extract the Average and Homogenised values. Table 2.1 summarises all the literature review results.

- ***Averaged Value:*** this figure was calculated by performing an average from among the 15 studies. Embodied Carbon has a specific value in most cases, but WLC comes from the average of the range of Operational Carbon values.
- ***Homogenised Value:*** these figures were calculated following the homogenisation of the values of the studies reviewed, interpolating missing Modules of EN15804 so that all stages could be shown. Only Module B5 (Refurbishment) has been left out meaning that in the LCA period of 50 years no full refurbishment had been performed.

These 15 studies were selected for their geographic (Europe) and typology (multifamily residential buildings) representativeness, use for national policy-making and availability of data, via Sciencedirect, within the years 2005-2022.

Table 2.1. Overview of reviewed articles and regulations on Embodied, Operational and Whole Life Carbon of buildings.

Stage C	**Stage B**	**Stage A**	**Whole Life Carbon kg CO_2-eq·m^{-2}**	**Operational Carbon kg CO_2-eq·m^{-2}**	**Embodied Carbon kg CO_2-eq·m^{-2}**	**Nr of buildings assessed**	**Country**	**Author**
	B6	A1-3	2050	300-3000	400	650	EU	(Röck, Martin et al., 2022)
C3-4	B4,6	A1-3	620	11-230	500	60 new	Denmark	(Zimmermann et al., 2021)
C1-4	B3,4,6	A1-5	774	324	450	4000+	Finland	(Suomen Ympäristöministeriö, 2021)
C1-4	B4-5	A1-4			580	1232	Eastern EU	(Oneclick LCA, 2021)
					530		Western EU	
					350		Northern EU	
C1-4	B4-5	A1-4			303	659	EU	(Pasanen and Castro, 2019)
C1-4	B1-4,6	A1-5			527	stock	France	(Décret n° 2021-1004, 2021)
C1-4	B1-5	A1-5			470	stock	Germany	(Rietz et al., 2019)
C1-4	B1-5	A1-5			435	stock	Germany	(DGNB, 2021)
	B1-6	A1-5	2000	500-2500	500	stock	Switzerland	(Heeren et al., 2009)
C1-4	B1-4,6	A1-5	665	255	410	stock	UK	(UK Parliament Post, 2021) and (LETI, 2020)
C1-4	B1-7	A1-5	2408	1033-2850	467	6	Europe	(World Business Council for Sustainable Development, 2021)
C1-4	B1-7	A1-5	985	670	315	3	Portugal	(Bastos et al., 2014)
		A1-5			443	244	Global	(Pan and Teng, 2021)
			1368.2 (763.6 - 53.8%)	922.8 (754.1 - 81.7%)	445.3 (79.6 - 17.9%)	Average Standard Deviation		
			1298.4	765.1	533.3	Homogenized		

	(378.8 - 29.1%)	(345.4 - 45.1%)	(102.1 - 19,1%	Standard Deviation	

Average WLC emissions are as high as 600 kg CO_2-eq·m^{-2} for individual houses and 700 kg CO_2-eq·m^{-2} for multifamily housing (Röck, Martin et al., 2022). The study analyses houses built in the years 2001-2021 with case studies in Belgium (105 buildings), Denmark (72 buildings), Finland (59 buildings), France (487 buildings), and the Netherlands (50 buildings). Before the building is used, at stages A1-A5, and depending on the typology, structure and material used, emissions average 400 kg CO_2-eq·m^{-2} (Röck, Martin et al., 2022).

In Denmark, a suggested WLC emissions limit of 12 kg CO_2-eq·m^{-2}·y^{-1} has been recommended as a voluntary baseline for new buildings from 2023 (Zimmermann et al., 2021). The study analysing 60 new buildings larger than 1000 m^2 recommends introducing CO_2-limit values for new buildings. It suggests a limit value of 8.5 kg CO_2-eq·m^{-2}·y^{-1} from 2023 to 2030. In 2021, the government passed into Danish legislation the *National Strategy for Sustainable Construction*, including both the mandatory and the voluntary limit values (Danish Ministry of Interior and Housing, 2021). Modules A1-3, B4, B6 and C3-C4 were taken into account when calculating Embodied Carbon (Danish Ministry of Interior and Housing, 2021). The Swedish authority for community planning, construction and housing drafted a proposal to calculate values on climate declarations for buildings (Boverket, 2020) with reduction targets to be introduced from 2027. Norway has engaged into a similar strategy, both adopting the Danish baselines.

The Finnish Ministry of the Environment commissioned OneClickLCA to analyse over 4,000 current buildings (Suomen Ympäristöministeriö, 2021) resulting in an accepted WLC baseline of 774 kg CO_2-eq·m^{-2} for residential buildings, and taking into account Upfront (A1-A5), Repairs (B3), Replacement (B4), Operational Carbon (B6) and End of Life (EoL) (C1-C4). OneClickLCA has also analysed 3737 recent European buildings (1,232 residential) by screening a total dataset of over 15,000 building LCA projects (One Click LCA, 2021). As a result, residential Embodied Carbon averages of 580 kg CO_2-eq·m^{-2} in Eastern Europe (with more carbon-intensive materials and fewer secondary materials), 350 kg CO_2-eq·m^{-2} in Northern Europe (with a significant share of timber and low-carbon concrete standards) and 530 kg CO_2-eq·m^{-2} in Western Europe (with a general use of efficient materials) taking A1-A4, B4-B5 and C1-C4 into account, are baselined.

Meanwhile, a different approach, looking for voluntary comparison of buildings considered low carbon, was the *2018 Carbon Heroes Benchmark* programme across Europe. According to this, an average of 303 kg CO_2-eq·m^{-2} was reached for apartments (Pasanen and Castro, 2019), including A1-A4, B4-5, C1-C4 for a 60 year lifecycle.

The French legislation RE2020 (Décret no. 2021-1004, 2021) introduced a 640 kg CO_2-eq·m^{-2} limit value in 2022 to be tightened down to 415 in 2030 for detached and attached houses, and from 740 to 490 kg CO_2-eq·m^{-2} for social housing; taking modules A1-A5, B1-B4, B6, C1-C4 and D into account (thus approximating full Embodied Carbon). In addition, RE2020 introduces a new threshold of 4 kg CO_2-eq·m^{-2}·y^{-1} for the Operational Carbon of new residential buildings. From 2030 on, it proposes an Embodied Carbon threshold of 100 kg CO_2-eq·m^{-2}, introducing a dynamic LCA calculation method which favours biobased materials, and includes Module D estimations in view of upcoming EN15978 requirements.

Germany introduced the Sustainable Building Assessment System (BNB) in 2013 (Rietz et al., 2019) as a requirement for new public buildings, achieving a holistic evaluation of the WLC of public buildings (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2020). The BNB defines a bottom-up based reference value of 9.4 kg CO_2-eq·m^{-2}·y^{-1} for WLC emissions, thus aligning with the DGNB certification system benchmark. More recently, new bottom-up based reference values for the DGNB system were determined, resulting in a 2022 benchmark of 8.7 kg CO_2-eq·m^{-2}·y^{-1} (DGNB, 2021).

Based on the 2000-Watt Society model, the Swiss Society of Engineers and Architects produced the SIA 2040 report, in which a WLC value of 6.4 kg CO_2-eq·m^{-2}·y^{-1} was proposed for an efficiency scenario, coming down from the baselined 20.1 kg CO_2-eq·m^{-2}·y^{-1} (Heeren et al., 2009). The 2000W model goes beyond building LCA by including the carbon footprint of a building's occupants.

In 2020, the use of *RICS* WLC methodology from cradle to grave (A-C), annualised for 60 years, enabled UK policies to set an Embodied Carbon benchmark of 13.3 kg CO_2-eq·m^{-2}·y^{-1} for all buildings; while the 2025 target is 10.8 kg (UK Parliament Post, 2021). Similarly, their own RIBA Climate Challenge Estimates, based on the RICS standard, propose a WLC benchmark of 625 kg CO_2-eq·m^{-2} by 2030 (RIBA, 2021). Moreover, the London Energy Transformation Initiative's (LETI) Embodied Carbon Primer report establishes a current baseline of 1,000 kg CO_2-eq·m^{-2} (A1-A5) and a target for new buildings from 2020 to 2030 of 600 kg CO_2-eq·m^{-2} (down to 350 kg CO_2-eq·m^{-2} from 2030-2050, and net zero from 2050 onwards) (LETI, 2020). It includes Module D too.

The WBCSD commissioned ARUP to research 6 buildings (4 office, 2 residential) and assess their WLC. It found an average WLC (normalised to 50 years) of 1,500 kg CO_2-eq·m^{-2}, with 50% Embodied Carbon, of which six materials were responsible for 35% (World Business Council for Sustainable Development, 2021). It also gives reference values per building works chapter. For our purpose, A1-A5 was targeted down to 334 kg CO_2-eq·m^{-2} from the baselined 467. B1-B5 averages 279 kg CO_2-eq·m^{-2}. B6-B7 for residential buildings baselines 63 kg CO_2-eq·m^{-2}·y^{-1} based on the 2019 UK grid, targeting 10 kg CO_2-eq·m^{-2}·y^{-1}. C1-C4 averages only 12.5 kg CO_2-eq·m^{-2}. The baselined WLC residential value of 3,908.50 kg CO_2-eq·m^{-2} is shared as A1-A5=11.95%, B1-B5=7.14%, B6-B7=80.59% and C1-C4=0.32%. Market verified target comes to 1,126 kg CO_2-eq·m^{-2} of which A1-A5=29.68%, B1-B5=24.79%, B6-B7=44.42% and C1-C4=1.11%. This implies a reduction benchmark between baseline and target of 71.20%.

Here, three neighbouring Portuguese multifamily residential buildings from 1940 undergo full LCA with temporalities of 50 and 75 years (this one including B5). For the 50 year LCA, Embodied Carbon came to 315 kg CO_2-eq·m^{-2}, average Operational Carbon to 670 kg CO_2-eq·m^{-2} and resulting WLC to 985 kg CO_2-eq·m^{-2} (Bastos et al., 2014). This study offers results lower than average, due to the older, non-insulated constructions, mainly built with brick masonry, wooden beams and planks for the floors as well as for the window frames, with single glazing.

244 case studies worldwide are normalised under 11 variables, resulting in an Embodied Carbon of reinforced concrete buildings of 443 kg CO_2-eq·m^{-2} (Pan and Teng, 2021). Cross-checking on other world regions gives similar figures: the International Living Future Initiative estimates a 500-kg CO_2-eq·m^{-2} (A1-5) (Living Future, 2020), and the same figure appears in another Embodied Carbon benchmark study (Carbon Leadership Forum, 2017).

In order to calculate a homogenised[1] single value of Embodied Carbon, Operational Carbon and WLC for the studies analysed, the data were disaggregated across stages A, B and C. Fully present, relevant

[1]The literature review presents studies with different approaches to Whole Life, Embodied or Operational carbon. In order to create averages that include an identical number and approach of Lifecycle stages and modules, an "homogenization" process has been run. Assumptions are described here until the end of section 2.1. The homogenised average values of the relative weight of the EN15978 modules appears at the Supplementary Information in Table S2.

average percentages per module in (LETI, 2020), (Hart et al., 2021) and (Lavagna et al., 2018) were used to complete the Embodied Carbon of reviewed studies, and to homogenise all modules (see Supplementary information, Table S2). The following assumptions and decisions were taken: A5 was missing in (Röck, Martin et al., 2022), (Zimmermann et al., 2021), (Oneclick LCA, 2021) and (Pasanen and Castro, 2019) and a homogenised 3.7% weight was added to their Embodied Carbon. B1-B3 was missing in the 4 studies mentioned above, as well as (Suomen Ympäristöministeriö, 2021) and a homogenised 7.4% weight was added to their Embodied Carbon. B5 (refurbishment), available only in (Oneclick LCA, 2021), (Pasanen and Castro, 2019), (Rietz et al., 2019), (DGNB, 2021), was not taken into account for the present study, and has been substracted. Benefits at Modules C3-C4 appear as negative in all studies except (Suomen Ympäristöministeriö, 2021), (Décret no. 2021-1004, 2021), (World Business Council for Sustainable Development, 2021) and the present study, resulting in -0.5% of the homogenised Embodied Carbon. B4 is missing in (Röck, Martin et al., 2022) and the present study, but a homogenised 8% weight was added to their Embodied Carbon. B6 values range between 300 and 1,161.3 kg CO_2-eq·m^{-2} and lack an energy profile in the studies, but represent the climate and insulation reality of buildings and have not been homogenised. B7 (water use) values appear only in (World Business Council for Sustainable Development, 2021), (Bastos et al., 2014) and the present study, but a homogenised 2.5% of the OP has been included for the rest. (Pasanen and Castro, 2019) and (UK Parliament Post, 2021) have been normalised from a 60-year lifespan to 50 years. (Bastos et al., 2014) with buildings from the 1940s and (Pan and Teng, 2021) with buildings outside of Europe fall outside the time or geographic scope, but within the average data.

The total standard deviation of Homogenised Embodied Carbon is 19.15% (102 out of 533.32 kg CO_2-eq·m^{-2}), and falls within a useful range of certainty, as stated in recent systematic uncertainty studies such as that by Feng (Feng et al., 2022). This homogenised baseline is 17% greater than the first averaged value of 445.3 kg CO_2-eq·m^{-2} (with a standard deviation of 17.9%). It also provides an average WLC of 1,298 kg CO_2-eq·m^{-2}. (See Supplementary information, Table S3.)

Measures to reduce emissions.

While insulating buildings potentially improves their energy performance, LCA studies show that, with better insulation alone, the use phase still contributes between 65% and 76% of the WLC in the case of a detached house (Lechtenböhmer and Schüring, 2011). GHG emissions remain high in cold climates where energy used for heating and domestic hot water comes from fossil fuels. Therefore, the key measure for decarbonisation is to stop using fossil energy (Quintana-Gallardo et al., 2021). Operational Carbon can be reduced by up to 40% with current best practices, with the even greater potential reductions of 80% by year 2030 and 93% by year 2045 (Karlsson et al., 2021).

As net zero Operational Carbon is accomplished, reducing Embodied Carbon becomes more and more relevant for the choice of materials in new buildings (as in Module A of EN15978), but also for Modules B and C of existing buildings. During the stages of maintenance (B2), replacement (B4) and refurbishment (B5), building materials are discarded, depending on their durability. Construction and Demolition Waste (CDW) at stage C1 (deconstruction) represents 40% more waste than at stage B5. But CDW is often out of LCA scope and considered urban solid waste. However, when it is included, the effectiveness of reducing, recycling and reusing strategies can be improved, both at municipal and building level (Marrero et al., 2020). Moreover, establishing a strategy for upcycling and a design for disassembly, mainly of the short-lived elements, reduces the building's GWP (Rasmussen et al., 2019). Including stage D can bring a circular economy approach that provides adaptability and reusability of the building components, further decreasing the building Embodied Carbon (Dams et al., 2021). The latest EN15978 update makes it mandatory to report on Module D by separating data on the Reuse, Recycle and Recovery of materials (D1) from that on Exported Utilities (D2) generated during the building phase (energy and water). EN15978-1:2021 has been published (AENOR, 2021) but has not yet forced the withdrawal of the previous version (EN15978:2011) (CEN/TC350, 2022).

Once the EPBD's mandatory energy reduction measures have been implemented, suggested starting points for the reduction of Embodied Carbon reduction in Spain include the following three market-ready items, which are valid both for new constructions and refurbishment: wood flooring instead of ceramic, stone, or concrete; wood window frames instead of aluminium or PVC; and insulation with natural materials such as cork instead of mineral or oil derivates. They outline a reduction pathway developped later. A deep renovation scenario with more measures would reduce impact more notably, but it would be complex to standardise, and falls outside the scope of this paper.

Based on 18 comparisons, it has been found that substituting conventional building materials for mass timber reduces stage A GWP by 69%, an average reduction of 216 kg CO_2-eq·m^{-2}. Scaling up low-carbon construction, assuming mass timber replaces conventional building materials in half of expected new urban constructions, could provide as much as 9% of the global emissions' reduction needed to keep global warming below 1.5°C (Himes and Busby, 2020). Using Cross-Laminated Timber (CLT) to replace concrete floors in steel structural systems shows GWP savings of between 20 and 80 Mt CO_2-eq with an average of 50 Mt CO_2-eq should this construction system be taken up fully by 2050. It does not include carbon sequestration, which would make savings even greater. CLT would represent a 1.5% reduction of the annual global construction GHG emissions, helping to reach NZCB (D'Amico et al., 2021). Prefabricated wood housing can also halve the emissions of stage A4, limit stage A5 to 23 kg CO_2-eq·m^{-2}, and reduce stage C emissions to 2.5 times less than those of conventional reinforced concrete structures. Embodied Carbon of these wood houses can be as low as 244 kg CO_2-eq·m^{-2} (Al-Najjar and Dodoo, 2022). Furthermore, (Geng et al., 2017) suggest that one easy way to reduce the Embodied Carbon of floors, and offset part of it in both new construction and floor substitution, is by laying hard laminated wood tiles instead of ceramic tiling on the floors of the heated areas.

In regard to window frames, embodied CO_2 of aluminium shows that the frame has a higher impact than the glazing: 70% of total embodied impact. PVC and fibreglass frames are responsible for 58-86% of the embodied impacts for single-glazed windows, 46-54% for double-glazed and 22-40% for triple-glazed. The contribution of wood frames to the whole window (29% in the worst case) is the smallest, halving that of aluminium (Saadatian et al., 2021). They can also reduce heat transmittance, reducing energy demand at the envelope.

Biogenic materials other than timber include dirt, cork and straw. They were standard until the post-WWII recovery and the appearance of oil-derivates. For instance, using adobe with ashes instead of brick, 5% GWP at stages A and B, and 4% energy consumption may be saved. Savings would increase when considering WLC, since adobe is more easily collected and reused without any treatments compared to fired clay bricks (Muñoz et al., 2021). A light-frame wood structure coupled with straw bale walls can reduce emissions by 96.75% compared with conventional reinforced concrete structures in rural areas. The total Embodied Carbon of such rural houses can be reduced by 39.54%. (Li et al., 2021). Cork (raw and recycled) is marketed as insulation panels at a mass scale and used both in cavity walls and as external thermal insulation, common in facade renovations. It shows good performance, especially in temperate climate producer countries, such as Portugal and Spain (Monteiro et al., 2020).

A final emissions reduction aspect that is beyond the scope of this research, but worth mentioning, is behaviour. Energy use in buildings with the same function differed by a factor of 3 to 10, owing to behavioural issues. Future lifestyle changes in developed countries are expected to result in significant energy use reductions of up to 50% by 2050. Various demand patterns, comfort standards and direct energy uses, can help understand behavioural solutions such as active or passive management and operation, demand flexibility, sufficiency at comfort levels, circular and sharing economy, and organisational and social innovations (Mata et al., 2022). Moreover, a desirable addition to LCA is Social LCA. Together with Life-Cycle Costing, it can make the case for a circular economy in the building sector and outline future pathways (Larsen et al., 2022).

METHODS, DATA AND TOOLS

The methodology used for this research is Life Cycle Assessment (LCA). Standard EN15978 specifications for LCA of buildings were followed to reach the Goal of reporting the GWP of a functional unit of one square metre of an average apartment (NFA: 73.1 m^2) in a 50-year lifespan. The Scope is the Cradle-to-Grave LCA from stage A to stage C. The System Boundary is a representative Spanish multifamily residential building (NFA: 1700 m^2) (see Section 3.4 and Figures S1 and S2 at the Suplementary Information file). The Inventory includes the bill of quantities, input and output flows (see Supplementary Information, Tables S6-S8) of a showcased building of the chosen representative typology. 19 LCIA Impact Categories following ReCiPe and Cumulative Energy Demand are analysed, focusing on GWP. Two tools with their respective databases were used to perform the calculations: OpenLCA with Ecoinvent database, and OERCO2 with the Andalusian building products database.

Description of Scenarios

Scenarios have been modelled using a reference building of year 2013, each with variations:

Scenario 0: Residential building from year 2013 (50 years lifespan) with 4 floors and 14 apartments, with an average Net Floor Area (NFA) of 73.1 m^2 per apartment (minimum NFA of 51 m^2, maximum NFA of 96 m^2) and a total built area of 1,700 m^2 (more information in the methodology section and Supplementary Information Figures S1 and S2). Windows are double-glazed in sliding aluminium frames, with a transmittance (U) of 2.8 W/m^2K. Inner floors are made of ceramic tiles. Insulation in cavity walls is a 3 cm-thick mineral wool mat with a thermal conductivity (λ) of 0.03 W/mK. The building envelope U is 1.3 W/m^2K, demanding an energy consumption of Natural Gas of 2,554 kWh/year for heating and 1,272 kWh/year for hot water (30% from a 6 kWp solar thermal installation on the roof) and Electricity, 3,847 kWh/year; and a total energy demand of 7,673 kWh/year (See Table 3.2.).

Scenario 1: Residential construction built in 2013, with the same characteristics as Scenario 0 but with pinewood window frames (U is 1.3 W/m^2K) instead of aluminium ones. Building U is 1.15 W/m^2K.

Scenario 2: Residential construction built in 2013, with the same characteristics as Scenario 0 but with inner floors made of hard laminated wood tiles instead of ceramic.

Scenario 3: Residential construction built in 2013, with the same characteristics as Scenario 0 but with wall insulation of 4 cm-thick recycled cork (λ is 0.04 W/mK) instead of mineral wool, giving a new building U of 1.2 W/m^2K.

Scenario 4: Residential construction built in 2013, with the same characteristics as Scenario 0 but with the windows, floors and insulation of Scenarios 1, 2 and 3. This gives a new building U of 1.05 W/m^2K.

Scenario 5: New building (year 2021) with Scenario 4 characteristics but compliant with NZEB standards (non-renewable <60 $kWh·m^{-2}y^{-1}$) from the EPBD climate zone B of Spain. The average electric consumption per apartment is 2,430 $kWh·y^{-1}$ for heating and hot water (30% solar thermal, 1701 $kWh·y^{-1}$ non-renewable) plus 4,000 $kWh·y^{-1}$ for electric appliances (50% photovoltaic (PV), 2000 non-renewable); making up a total energy consumption of 6,430 kWh/year (non-renewable 3701 $kWh·y^{-1}$ or 52.9 $kWh·m^{-2}y^{-1}$) for the average 73 m^2 apartment. The building includes a roof-flat PV installation of 30 kWp, also added to the LCA model.

OpenLCA software with Ecoinvent database.

From among the different LCA databases, the Ecoinvent database (Frischknecht et al., 2005) developed by the Swiss Centre for Life Cycle Inventories has been chosen for its transparency in the development of processes (reports, flow diagrams and methodology), consistency, references and, in particular, for the fact that it merges data from various databases of the construction industry (Martínez-Rocamora et al., 2016). The version of the Ecoinvent database used (v3.8) was released on 21/09/2021. It included 360 new datasets, and 700 updated datasets as well as new products for the building and other sectors (Ciroth et al., 2021). It included the new system model, 'allocation, cut-off, EN15804', allowing practitioners to comply with the EN15804&A2:2019 standard (CEN/TC350, 2022).

36 input flows and 18 output flows were introduced at the OpenLCA model of the building. An estimation of 99% of the over 180 measured items from the original bill of materials of the studied building were grouped in 70 streams and included with few adjustments at the inputs. As the building data did not include replacement details, only 50% output flows are addressed, leaving out module B4 completely (which was added after the homogenisation exercise). No maintenance and repair flows were specified other than those assumed by the database. For the energy streams (Natural gas and electricity), Spanish data from the construction year (2010) onwards have been introduced, and projections from Table 2.3 for the 2022-2060 period. However, for water consumption, data from the database remain. Concerning the provider's origins of the material flows, European sources have been chosen whenever possible, but ten come, as Ecoinvent words it, from the "rest of the world". Only one Environmental Product Declaration (EPD) has been used, namely that of Saint-Gobain glass wool mats in Scenarios 0, 1 and 2.

In OpenLCA, all the flows have been modelled with specific values from the sample building. However, EN15978 stages cannot be calculated immediately. Still, stages A1-A5, B6 and B7, and partially C1-C3 were identified as a result of the calculations. The rest was adapted after the homogenisation exercise. OpenLCA outputs can follow various impact methodologies, in this case ReCiPe (18 impact categories) and Cumulative Energy Demand (1 category: total energy footprint), with a focus on GWP. OERCO2, on the other hand, looks at stages A1-A5 and provides only GWP data. However, it arranges information following building material families and the taxonomy of an architectural project (project chapters). Its database (from Andalusia) includes a menu of common materials and construction techniques, not as wide as the Ecoinvent database Flows, but fitting the scope of this study. The measures faced a reality check in the OERCO2 database and confirmed the three items: wood window frames, cork insulation, and hard laminated wood tiles. These were introduced when making OpenLCA calculations, demonstrating the positive effect of substituting more environmentally impactful materials (aluminium frames, cement tiles and rock wool insulation) with low-carbon ones.

Different LCA software programs provide different LCA results. For instance, there are discrepancies in GWP, with an almost 60% higher SimaPro than that of OpenLCA (Iswara et al., 2020). Recent studies propose OpenLCA as a consistent and usable tool thanks to its accessibility, possibility to manually adjust parameters, up-to-dateness, interoperability with databases and ease of interpretation of results (Lopes Silva et al., 2019), (Pamu et al., 2022). Moreover, there are great synergies between OpenLCA and the Ecoinvent database. The version used is OpenLCA v1.10.3, which has an add-on for configuring EPDs according to EN15804 (Ciroth and Arvidsson, 2021). Decisions upon applying OpenLCA to this research are:

1. To use the ReCiPe LCIA method at Midpoint (H) 2016 and Cumulative Energy Demand (CED). ReCiPe derives characterisation factors from emissions, resource extractions and other inventories into 18 midpoint impact categories, as can be seen in Table 7. This method started in 2008 and was updated in 2016 extending its representativeness from European to Global. While endpoints reflect damage to human health, ecosystem quality and resource scarcity, midpoints help understand the cause-impact pathway. Hierarchy (H) approximation was used, which is closer to the usability of baselines and applies to GWP metrics (Huijbregts et al., 2017). One more impact category was added, reaching a total of 19 indicators, with Cumulative Energy Demand method which allowed us to calculate the Energy Footprint (EF) of the building.
2. To choose the Cut-Off criteria for the allocation of environmental burdens of materials. According to this model, waste is the producer's responsibility, following the principle "the polluter pays". There is also an incentivisation to use recyclable products, since these are available burden free. It is an attributional approach determining the share of each input and burden assigned to the reference products. Consequently, recyclable products are available burden-free for recycling processes, while recycled products bear only the burden of the recycling processes. Other intermediate exchange is classified as allocatable (most products), recyclable or simply waste. This is common use, mature at Ecoinvent database and properly applicable to buildings (Ecoinvent, 2017).
3. EU regionalisation. The Ecoinvent database offers numerous world regions as well as single countries and a global dataset. In our case, the preferred data used for processes are European, and energy data are from Spain's reference energy mix.

OERCO2 online software and database.

The OERCO2 online tool is an Open Educational Resource where the calculations of the equivalent CO_2 emissions in each phase of the building are unified, developed by the University of Seville in the frame of a 2016 Erasmus+ Project. After defining the volume, surface, uses and structure of the building, OERCO2 enables the definition of construction options for facades, partitions, floors, installations, HVAC, insulation, inner fittings and window types. It lists the most common options used in the Spanish building industry. It enables a quick simulation at cradle-to-site level (stages A1-A5) (Solís-Guzmán et al., 2018). Material flows are introduced from selection menus matching the representative building, thanks to the common building language used there and in the chosen executive project. Output data appear grouped in material families or project chapters (see Supplementary information, Tables S9 to S12).

Definition of the average Spanish building modelled.

The European Building Stock Observatory (BSO, 2020) shows factsheets, data and maps in order to better understand national energy performance characteristics, floor area, construction year, typology and degree of urbanisation. Building stock energy modelling is used by Annex 72 of the International Energy Agency to assess the current and future energy demand and environmental impact of building stocks (Nägeli et al., 2022). This is further broken down by single countries to create scenarios for energy savings and GHG reductions, like in the Norwegian NZEB deployment plan (Sandberg et al.,

2021) or, in the case of Switzerland, to develop decarbonisation polices for their residential stock (Nägeli et al., 2020).

According to the ERESEE (Spain's Long-Term Rehabilitation Strategy, LTRS) (MITMA, 2020), the typology of the dwellings in Spain can be characterised in tems of three factors, namely age, surface and type of building. (See Supplementary information Tables S4 and S5). Their energy and climate targets derive from the Spanish climate integrated plan (PNIEC, 2021). Spain experienced its baby boom between 1957 and 1977, with 14 million new births (going from 28.1 million inhabitants in 1950 to 37.7 million in 1980), aided by an improvement in the socioeconomical conditions of most of the population, but which resulted in housing overproduction. The period 1961-1980 amounts for the 34.37% of all current Spanish buildings (MITMA, 2020). The 1979 building code introduced energy efficiency parameters; insulated facades had not been standard before. In addition, elevators and garages became a common feature, making 8-storey buildings with more dwellings possible. National tourism and other global factors induced a Real Estate bubble which grew from 1994 to 2008, peaking in 2006 with over 900,000 new dwellings built. The crises thereafter cut the Spanish construction industry to 26% of its former productivity (MITMA, 2020). Nonetheless, the period 1981-2010 accounts for 47.75% of all Spanish homes (20.44% of average apartments as considered below). The 2006 building regulation requested energy performance indicators such as reduction in Primary Energy demand, inclusion of renewables, improved efficiency, new HVAC solutions and better building materials. For both demographic and regulatory reasons, the most representative period is considered that between 1981 and 2010. It also implies that these types of buildings entering their 40th year in 2022, now require common retrofitting measures which become mandatory if identified in a technical inspection.

Homes between 61 and 120 m^2 built in the years 1981 to 2010 represent 32.8% of all Spanish (MITMA, 2020). Those bigger than 150 m^2 correspond to detached or semi-detached houses, or, exceptionally, in multifamily buildings. Meanwhile, those smaller than 60 m^2 or bigger than 120 m^2 are not considered representative, and 70 m^2 homes are considered average for the period. Furthermore, the most common typology of residential buildings have between 10 and 16 dwellings per building and 3 to 5 storeys, and were built in the years 1981-2010. There are 4 million apartments of this kind, making up 20.44% of the total (MITMA, 2020). The case building for this research is an average building of these characteristics having average apartments of 73.1 m^2, with 4 stories, 14 dwellings and having been built in 2013 but with the same characteristics of the 1981-2010 period.

The ERESEE takes into account more characteristics of the buildings mentioned. It identifies average transmittances per climate area of the chosen typology (A: 1.5, B: 1.4, C, D and E: 1.3 [W/m^{2}K] where buildings in climate zones C, D and E constitute 80% of the Spanish total. While this would further constrain the sample, other considerations add unnecessary uncertainty, such as the province and city standards. The energy consumption of residential buildings tripled in the period 1990-2008, but has remained stable since then. According to the ERESEE, and based on the SECH-SPAHOUSEC project (IDAE, 2011), the average consumption per dwelling of the chosen typology is 7673 kWh/year (85.25 $kWh \cdot y^{-1} \cdot m^2$). These figures are 47.36% of the EU average (180 $kWh \cdot y^{-1} \cdot m^2$) (European Commission, 2016). In Spanish climate zones C, D and E, 85% of the homes used a Natural Gas boiler, 5.9% had a condensing boiler and 7.4% had electric radiators. Heat pumps, radiant floor, air conditioning and solar thermal together were less than 1%.

In this context, the selected multifamily building in this study's Scenario 0 is a real case building in Cartagena, Spain (climate zone B3) built in 2013, with a simplified inventory shown in figure according to the weight of the materials of the building. Figure 5 shows mortars and concrete alone weighting 76,69% of the total 3,131 Tons of the building. Interestingly, some materials are negligible in terms of mass, but relevant in terms of LCA impacts (see Table 2.6).

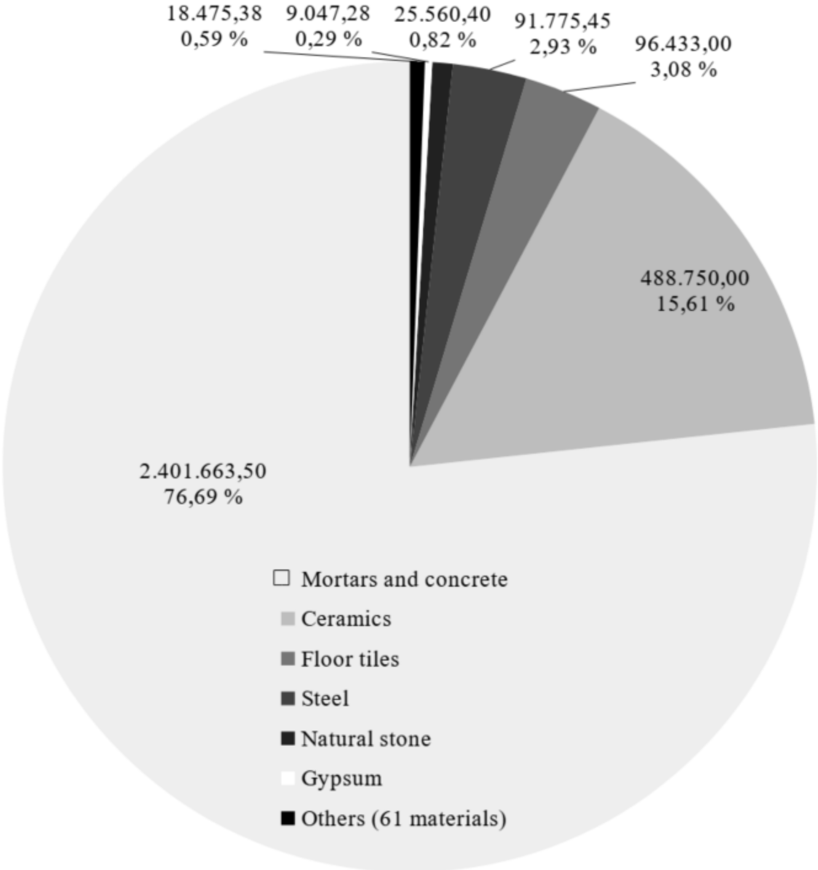


Figure 5: Simplified inventory of the case building. Elaborated by the authors from the Executive Project Chapters of the case building.

The building contains a solar thermal installation to satisfy 30% of domestic hot water demand, which became mandatory in 2006. An estimated 1% (in weight) of the materials has not been included in the OpenLCA model because their flows were too complex to determine and their amount negligible. Excluded items were electric and electronic mechanisms (switches, switchboards, metering boxes, fire detectors, fire emergency lighting, and similar), wooden doors of built-in wardrobes, some plumbing fittings (toilet and kitchen equipment, pressure groups, and similar) and a few roof finishes (cladding chimney caps). Fittings were included in the model, such as vents, all inner and outer doors, all wiring, piping, ducts, vertical paints and horizontal finishes.

Overall, it is built with the following constructive components: Foundations and structure are made of reinforced concrete with 275 kg/m^3 of cement type HA-25/B/20/IIb and steel type UNE-EN 10080 B 500SD. Non walkable flat roof slab, as shown below, is finished with a 3-cm mineral wool insulation, a waterproof membrane, geotextile fabric and 5 cm of loose gravel. Bidirectional reinforced concrete floor slabs have 30-cm concrete sheds and a distance between their axes of 82 cm. Inside floorings are ceramic tiles, artificial stone tiles in common areas and 15-cm laid concrete in garages. Double 11-cm brick facades have 3-cm mineral wool insulation, 1-cm cement mortar finish outside and 1.5 cm gypsum finish inside, with U 0.7 W/m^{2}K. Sliding sheet 4 cm-wide frame aluminium Climalit windows with double 4-6-4 glass, with U 2.8 W/m^{2}K. On average, there are 6 windows per dwelling, and 105 windows in total. The total proportion in m^2 of hollow vs wall by façade is 16.33%. 7-cm brick inner partitions are composed of 1.5 cm mortar, gypsum and painting finish on both sides, and partition walls (inside – out), of paint, gypsum, 1.5 cm mortar, 7-cm brick, 4-cm mineral wool insulation, 11-cm brick, and 1-cm cement mortar finish. The assumptions shown in Table 2.3 were made to calculate the Operational Carbon emissions. The evolution of energy demand in 50 years was calculated, adapted from the ERESEE projections, taking 2010 as year 0.

Table 2.3: Energy consumption and related Greenhouse Gas emissions estimates per apartment, used in the building model at OpenLCA.

30-49	15-29	years 0-14		Unit		Demand, consumption and emissions
1250	3000	2554		kWh·y–1	Natural Gas (NG)	Heating demand
2000	2500	1272		$kWh \cdot y^{-1}$	NG	Hot Water demand
4000	4200	3847		$kWh \cdot y^{-1}$	Spanish Mix	Electricity demand
65000	82500	57390		kWh	NG per period	Energy consumptions
80000	63000	57705		kWh	Electricity / period	
		204890		kWh	Total NG 50 years	
		200705		kWh	Total E 50 years	
11830	15015	10444.98	kg	CO_2-eq$\cdot y^{-1}$	Total NG	GHG Emissions
36000	28350	25967.25	kg	CO_2-eq$\cdot y^{-1}$	Total electric	
		37289.98	kg	CO_2-eq$\cdot y^{-1}$	Total NG 50 years	
		90317.25	kg	CO_2-eq$\cdot y^{-1}$	Total E 50 years	

RESULTS

Table 2.4 compares the Base Scenario with the other 5 modelled scenarios and Reviewed and Homogenised figures. Table 2.5 shows the economic investment in modules A1 to A5, most relevant for Embodied Carbon. Table 2.6 shows how different elements of the scenarios contribute to the impacts through the simplified contribution tree of results. Finally, Table 2.7 compares 18 indicators other than GWP, in order to understand the variations among impact categories. Original input and output flows of the building modelled at OpenLCA is available in Supplementary Information, Tables S7 and S8.

Table 2.4 shows how Embodied Carbon results performed with OpenLCA software (with Ecoinvent) are on average 15.4% greater (increasing from 13.9% to 17%, with a standard deviation of 1% across all scenarios) than those obtained with OERCO2. OERCO2 does not include impacts in stages B1-B3 or C1-C3. Thus, the WLC values in Table 2.4 are shown in two ways, one separately for the two software types, and the other as an average of both figures. It can be observed that averaged WLC values fall between 0.8% (Scenario 2) and 63.4% (Scenario 5) when compared with Scenario 0. Installing wood frame windows instead of aluminium gives the single greatest reduction (−26%), followed by a 16% reduction in the case of the recycled cork insulation and a 0.8% reduction with the wood floor tiles. This last case slightly lowers Embodied Carbon while maintaining the Operational Carbon of the building.

The average baseline of 454.64 kgCO_2-eq of the reviewed articles has been homogenised to include modules missing from the reviewed collection, by averaging and interpolating gaps, including full stages. It provides similar figures to Scenario 5 Embodied Carbon (533.32 vs 530.14) and Scenario 4 Operational Carbon (1,298 vs 1,240), corresponding to their respective constructive and energy solutions. Scenario 0 stays at the upper level of Operational Carbon of the reviewed literature (Heeren et al and WBCSD studies), over 1,000 kg CO_2-eq$\cdot m^{-2}$ (1385), in accordance with official Spanish

Government data (PNIEC, 2021). The Embodied Carbon values obtained with OERCO2 are aligned with the reviewed average figure (455.02 and 454.64 respectively). Scenario 1 brings about the best single results, lowering Embodied Carbon by 9%, by replacing aluminium with wood window frames, and Operational Carbon by 32% by improving on the envelope transmittance of Scenario 0. Scenario 2 shows little impact, as mentioned above.

Table 2.4. Global Warming Potential emissions per square metre of 5 scenarios modelled for the selected average building.

Share of Embodied Carbon [%]	Share of Operational Carbon B6-B7 [%]	Reduction from BASE	Averaged	LCA EN15978 Global Warming Potential			Software used	Scenarios	
		Whole Life Carbon [%]	Whole Life Carbon kg] [CO_2eq/m²]	Whole Life Carbon kg] [CO_2eq/m²]	Operational Carbon kg] [CO_2eq/m²]	Embodied Carbon kg] [CO_2eq/m²]			
31.5%	67.5%	29.6%–	1368	1,368.18	922.83	445.35	Various	R	Reviewed
40.9%	59.1%	33.2%-–	1298	1,298.42	765.10	533.32	Various		Homogenized
27.6%	72.4%	**0.0%**	**1,944**	1,913.78	1,385.52	528.26	OpenLCA		**Scenario 0 (BASE)**
				1,840.55		455.02	OERCO2		
34.0%	66.0%	26.0%-–	1,446	1,423.02	938.52	484.50	OpenLCA		Scenario 1
				1353.67		415.15	OERCO2		
27.3%	72.7%	0.8%-–	1,929	1905.65	1,385.52	520.13	OpenLCA		Scenario 2
				1817.09		431.57	OERCO2		
32.7%	67.3%	16.1%-–	1,642	1617.77	1,089.20	528.57	OpenLCA		Scenario 3
				1532.49		443.29	OERCO2		
39.8%	60.2%	36.9%-–	1,240	1219.54	734.23	485.31	OpenLCA		Scenario 4
				1149.69		415.46	OERCO2		
72.4%	27.6%	63.4%-–	745	731.86	201.72	530.14	OpenLCA		Scenario 5
				642.49		440.77	OERCO2		

Scenario 3's Embodied Carbon of 528.57 kg CO_2-eq·m^{-2} (above the corresponding Scenario 0 value) is due to the higher density of cork (120 vs 30 kg/m^3 of glass wool) and thermal conductivity (λ 0.04 W/m.K vs 0.03 of glass wool). Maintaining thermal features implied increasing the thickness of cork to a 4-cm panel (glass wool was 3cm). This all meant that the general weight of the external insulation input flow (for the modelled building) in OpenLCA is 1,001 kg of glass wool, but 160,200 kg of cork. Although the product GWP of cork (−0.004 kg CO_2-eq·m^{-2} versus 0.012 of glass wool) is negative thanks to its biogenic origin, the final Embodied Carbon result is higher than in Scenario 0 (528.26 kg CO_2-eq·m^{-2}). However, this improved the building envelope transmittance (from a U of 1.3 W/m^2·K with glass wool to a U of 1.2 W/m^2·K with cork), giving an Operational Carbon of 1,089 (21% less than in Scenario 0).

The combination of better construction solutions from Scenario 4 reduces the WLC of Scenario 0 by 36.9% by cutting both Embodied Carbon and Operational Carbon, but new energy standards from Scenario 5 go further. It can also be noticed that Scenario 4 improves the homogenised WLC value from the literature review, which was −33.2%. Finally, Scenario 5 further decreases this figure at the cost of a slight growth (530.14 vs 582.26) in Embodied Carbon due to the photovoltaic installation. As a result, the shares of Embodied Carbon and Operational Carbon values become inverted between scenario 0 and scenario 5. This can be seen in Figure 6, where Embodied Carbon and Operational Carbon lines cross.

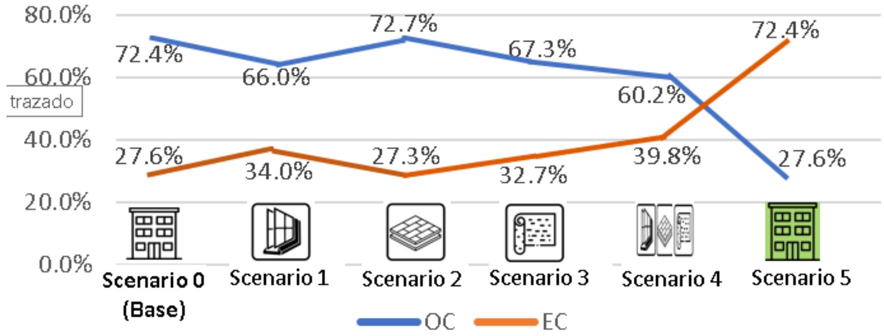


Figure 6. Share of Embodied Carbon and Operational Carbon across Scenarios 0 to 5.

Table 2.5 shows stage A1-A5 economic data calculated using OERCO2 software. Scenarios 1 to 4 barely reduce or increase the upfront cost of a new building (reductions of between 1.7% and 1.9 %) from the 603 €/m^2 of Scenario 0. Nevertheless, Scenario 1 is the only one that is both more sustainable and economically more efficient. Furthermore, Scenarios 2, 3 and 4 show how GWP reductions are not necessarily linked to increasing the original budget of the building. Rather, a significant investment appears in Scenario 5, linked with the photovoltaic installation. It was outside the scope of this article to run a full Life-Cycle Cost assessment of the model, which remains a point of interest for future research.

Table 2.5. Summary of A1- A5 total budget and reduction from Scenario 0, with OERCO2.

Budget invested in A1-A5 stages		Scenarios
of reduction from Scenario 0 %	**m^2/€**	
0.0%	603	**Scenario 0 (Base Scenario)**
1.7%-–	593	**Scenario 1**
1.8%	614	**Scenario 2**
0.4%	606	**Scenario 3**
1.9%	614	**Scenario 4**
25.9%	760	**Scenario 5**

The contribution of different materials and processes to the GWP of the WLC in Table 2.6 shows that the electricity consumed in the use phase tops the ranking, contributing between 46% and 55% in Scenarios 0 to 4. In Scenario 5, it is reduced to 24%. The second highest contributor is the use phase Natural Gas consumption for heating the building, contributing between 4.5% and 24%. It disappears in Scenario 5 with the ban on fuel combustion.

However, as electricity and gas decrease, the share of materials increases. Cement, steel and brick have a joint share of 16.2% in Scenario 0 but rise to 42% in Scenario 5. Cement and steel production needs high temperature furnaces reflected in a GWP of 118 and 111 kg CO_2-eq·m^{-2} respectively. The total weight of the input flows of these three materials (235, 91 and 435 tonnes respectively) speak for their high impact. Aluminium in window frames ranks 6th with 52 kg CO_2-eq·m^{-2}, but the wood ones have an impact of 25% (13 tonnes). Glass ranks 7th with a GWP of 46, even though it only represents 16.33% of the surface of the facades. In more glazed buildings, it would rank higher. When making the case for Operational Carbon, only B6 (energy use stage) without B7 (water use stage), one needs to observe here that tap water production consumed in the life cycle of a building (16 in

Scenarios 0 to 3, and 14 in Scenarios 4 and 5) ranks next, close to the first waste stream appearing in the list: reinforced concrete waste (15 kg CO_2-eq·m^{-2} for all scenarios). If we add the impact of roof tiles (ranking 10th) to that of bricks (ranking 5th), both ceramic materials add a GWP of 95. The remaining 40 flows of the contribution trees amount to between 86 (4.5% in Scenario 2) and 98 kg CO_2-eq·m^{-2} (13.4% in Scenario 5), a similar figure to that of ceramics. Finally, it can been seen that the photovoltaic installation in Scenario 5 contributes 6.3% of the total emissions of this scenario with a GWP of 45.

Table 2.6. Comparison of Global Warming Potential main flows according to the contribution trees of scenarios 0 to 5

Scenario 5		**Scenario 4**		**Scenario 3**		**Scenario 2**		**Scenario 1**		**Scenario 0**		**Main Global Warming Potential contribution tree flows using OpenLCA**
%	**kg CO_2-eq·m^{-2}**	**%**	**kg CO_2-eq·m^{-2}**	**%**	**kg CO_2-eq·m^{-2}**	**%**	**kg CO_2-eq·m^{-2}**	**%**	**kg CO_2-eq·m^{-2}**	**%**	**kg CO_2-eq·m^{-2}**	
100%	**732**	**100%**	**1220**	**100%**	**1618**	**100%**	**1,906**	**100%**	**1423**	**100%**	**1,914**	**Total**
24.4%	179	54.7%	668	46.0%	745	47.9%	912	52.1%	741	47.7%	912	market for electricity, low voltage | electricity, low voltage | Cutoff, U - ES
N/A	N/A	4.5%	55	20.3%	328	24.0%	457	12.8%	182	23.9%	457	market for Natural Gas | Natural Gas | Cutoff, U - ES
15.9%	116	9.5%	116	7.3%	118	6.1%	116	8.3%	118	6.2%	118	cement production, Portland | Cutoff, U - Europe without Sw
15.1%	110	9.1%	110	6.9%	111	5.8%	110	7.8%	111	5.8%	111	reinforcing steel production |Cutoff, U - Europe without Austria
11.1%	81	6.6%	81	5.0%	81	4.2%	81	5.7%	81	4.2%	81	market for clay brick | clay brick | Cutoff, U - GLO
N/A	N/A	N/A	N/A	3.2%	52	2.7%	52	N/A	N/A	2.7%	52	market for window frame, aluminium, U=1.6 W/m2K | Cutoff, U - GLO
6.3%	46	3.8%	46	2.9%	46	2.4%	46	3.3%	46	2.4%	46	market for glazing, double, U<1.1 W/m2K | Cutoff, U - GLO
1.9%	14	1.1%	14	1.0%	16	0.8%	16	1.1%	16	0.8%	16	market for tap water | tap water | Cutoff, U - Europe without Sw
2.1%	15	1.2%	15	0.9%	15	0.8%	15	1.1%	15	0.8%	15	market for waste reinforced concrete | Cutoff, U - Europe without Sw
1.9%	14	1.1%	14	0.9%	14	0.7%	14	1.0%	14	0.7%	14	market for roof tile | roof tile | Cutoff, U - GLO
1.8%	13	1.1%	13	N/A	N/A	N/A	N/A	0.9%	13	N/A	N/A	market for window frame, wood, U=1.5 W/m2K | Cutoff, U - GLO
6.1%	45	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	photovoltaic flat-roof installation, 30kWp, single-Si, on roof | Cutoff, U
13.4%	98	7.1%	87	5.6%	91	4.5%	86	6.0%	85	4.7%	91	Remaining flows

In Table 2.7, 19 environmental impact indicators are shown, and 18 impact categories are calculated using the ReCiPe Midpont Hierarchicalmethod, plus the total energy footprint (TEF) using the Cumulative Energy Demand method, all using OpenLCA software. Although GWP is the main focus of this paper, other impact categories appear relevant, especially those related with ecotoxicity. It has been detected that the proportion of the five joint ecotoxicity indicators, expressed in Dichlorobenzene (kg 1,4-DCB), is on average 4.5 times greater than that of GWP. TETP alone is 3 times higher and HTPnc 1.1 times higher.

In general, Scenario 5 reduces impacts by 50.4% from those in Scenario 0; Scenario 4 reduces impacts by up to 33.3%, and Scenario 1 by up to 25.3%. The highest reductions (above 80%) are WCP, IRP and MEP in Scenario 5. Seven other Scenario 5 impact categories cause reductions of between 60% and 80%. Exceptionally, FETP increases by 14.9%. Reductions of between 0 and 15% also appear exceptionally in Scenario 5 (ODP), Scenario 3 (FETP, HTPnc, TETP and TEF), and Scenario 1 (FETP). However, Scenario 2 shows 16 out of 19 reductions below 1%. Out of the average −1.1%

here appear only WCP (−10.1%) and SOP (−4.7%). Across all scenarios, WCP is reduced the most in Scenario 5, with a scenario average of −43.5% and a maximum of −91.8%. On the other hand, FETP is reduced the least in Scenario 5, with a scenario average of −5.3% and the aforementioned growth of 14.9%. GWP variations across all scenarios serve as proxy for the average variations, with standard variations below 8% except in Scenario 5 (28.26%). The impact category falling most out of standard deviation is FETP on the upper extreme, and WCP on the lower.

Table 2.7. Comparison of all impact categories at all scenarios

Scenario 5		Scenario 4		Scenario 3		Scenario 2		Scenario 1		Scenario 0	Impacts per m²	
variation	Impact	variation	Impact	variation	Impact	variation	Impact	variation	Impact	Impact	Unit	Impact Category
76.2%-	211.4	43.6%-	498.0	20.2%-	707.7	0.3%-	882.9	31.4%-	611.6	889.3	kg oil eq	Fossil resource scarcity, FFP
4.7%-	0.0	40.8%-	0.0	18.0%-	0.0	0.1%-	0.0	28.9%-	0.0	0.0	kg CFC11 eq	Stratospheric ozone depletion, ODP
61.7%-	731.9	35.9%-	1,219.5	15.2%-	1,617.8	0.0%	1,905.7	25.8%-	1,423.0	1,913.8	kg CO_2 eq	Global warming potential, GWP
59.4%-	1.5	33.9%-	2.4	15.4%-	3.1	0.3%-	3.6	24.0%-	2.8	3.6	kg PM2.5 eq	Fine particulate matter formation, PMFP
48.2%-	119.3	34.6%-	149.8	28.0%-	165.4	0.7%-	227.9	30.9%-	159.7	230.5	kg 1,4-DCB	Human carcinogenic toxicity, HTPc
14.9%	206.1	17.4%-	147.3	8.8%-	163.2	1.0%-	176.9	14.3%-	154.2	179.6	kg 1,4-DCB	Freshwater ecotoxicity, FETP
91.8%-	5.3	44.5%-	35.7	29.5%-	45.5	10.1%-	57.9	41.4%-	38.0	64.7	m^3	Water consumption, WCP
63.7%-	1.9	34.8%-	3.5	15.9%-	4.5	0.0%	5.3	24.7%-	4.0	5.4	kg NOx eq	Ozone formation, Human health, HOFP
63.8%-	2.0	34.7%-	3.5	15.8%-	4.6	0.1%-	5.4	24.6%-	4.1	5.5	kg NOx eq	Ozone Formation, Terrestrial ecosystems, EOFP
41.7%-	9.1	32.8%-	10.4	22.2%-	12.1	4.7%-	14.8	30.7%-	10.9	15.6	kg Cu eq	Mineral resource scarcity, SOP
20.0%-	181.5	29.7%-	158.4	15.4%-	191.5	0.3%-	225.4	26.5%-	167.2	227.0	kg 1,4-DCB	Marine ecotoxicity, METP
41.9%-	1,068.8	24.3%-	1,385.7	11.1%-	1,633.9	0.0%	1,834.6	17.3%-	1,526.9	1,842.7	kg 1,4-DCB	Human non-carcinogenic toxicity, HTPnc
61.1%-	0.2	33.7%-	0.4	15.1%-	0.5	0.1%-	0.6	23.7%-	0.4	0.6	kg P eq	Freshwater eutrophication, FEP
84.1%-	111.6	45.4%-	381.8	20.3%-	559.2	0.0%	700.7	31.9%-	480.4	703.7	kBq Co-60 eq	Ionizing radiation, IRP
88.5%-	0.0	35.1%-	0.0	16.1%-	0.0	0.0%	0.1	24.7%-	0.0	0.1	kg N eq	Marine eutrophication, MEP
36.1%-	22.9	30.0%-	24.9	14.0%-	30.7	0.0%	35.6	21.5%-	28.2	35.8	m^2a crop eq	Land use, LOP
66.9%-	2.9	37.3%-	5.4	17.1%-	7.2	0.4%-	8.6	26.4%-	6.4	8.7	kg SO_2 eq	Terrestrial acidification, TAP
37.8%-	3,088.8	22.2%-	3,841.4	12.0%-	4,362.2	0.4%-	4,930.0	16.9%-	4,138.8	4,970.0	kg 1,4-DCB	Terrestrial ecotoxicity, TETP
24.9%-	1,753.4	21.3%-	1,826.9	7.6%-	2,154.5	2.0%-	2,280.6	15.5%-	1,979.3	2,337.4	kWh	Energy footprint, EF
50.4%-		**33.3%-**		**16.7%-**		**1.1%-**		**25.3%-**		**Average variation compared to Scenario 0**		
28.26%		**7.79%**		**5.6%**		**2.45%**		**6.61%**		**Standard deviation**		

DISCUSSION

This paper shows that national regulations can lower WLC, Embodied Carbon and Operational Carbon. The homogenisation effort in this research proves that strategies on EN15978 modules at national scale (in geographic and regulatory terms) may be more applicable than the LCA of individual buildings. GWP baselines for buildings can be found for several European markets and a feasible Embodied Carbon of 500 kg CO_2-eq·m^{-2} and an Operational Carbon tending towards NZEB standards are suggested here for the Spanish residential construction market.

Specific decarbonisation measures need to undergo a comparative analysis before being chosen. Wood window frames, for instance, reduce the GWP of a building by 26% in comparison with aluminium frames. Also, considering budget analyses, lower Embodied Carbon materials do not increase the costs, but technical equipment does. New renewable energy equipment reduces Operational Carbon from 734 to 201 kg CO_2-eq·m^{-2}, but also increases Embodied Carbon from 485 to 530, when comparing the Scenarios 4 and 5. Scenario 4 reduces WLC by 36.9% in comparison with Scenario 0. In addition, as seen in Table 7, reductions in impact categories other than GWP are in the order of 33%.

It is important to note that assumptions from modellers can be very different and untraceable. This paper tries to keep track of all decisions taken. According to estimations, Module B5 (Refurbishment) might add 25% of new material flows but would save 75% of the Embodied Carbon of the equivalent new building for the next 50 years. Module B4 (Replacement) from the reviewed articles, makes it possible to estimate an average share of Embodied Carbon of 8.5%. Both modules have not been included here to reflect the reality of the Spanish building stock, with its poor maintenance, replacement and renovation culture. Including Stage D would reduce the weight of B4 and B5 and help implement circular economy strategies. Wood construction can help include these kinds of benefits in Modules B4, B5 and D. All decisions are interconnected.

Should the NZEB scheme be implemented and generalised, Operational Carbon could be cut by 85% (from 1,385 to 201 kg CO_2-eq·m^{-2} as in Scenarios 0 and 5) and phase out the current 20% share of Natural Gas for heating and hot water. But these measures cannot be exclusive of new buildings. A deep renovation of the building stock is necessary to reach climate targets and reduce the current 37% of global GHG share of the sector.

In the lack of original harmonised results, taking care to respect EN15978 and carry out especially transparent and exhaustive reporting of assumptions is key to reducing uncertainty. Also, quick tools are needed. Before and after homogenisation, the present study shows that the current literature and national regulations' baselines are aligned with a real case. In Table 2.3, the initial Embodied Carbon reviewed baseline of 454.64 kg CO_2-eq·m^{-2} mirrors Scenario 0 OERCO2 value (455.02). The homogenised value of the reviewed studies (533.32) mirrors the OpenLCA value (528.26). The proximity of all figures demonstrates the validity of quick LCA tools like OERCO2 and the stability of upfront carbon (A1-5) ahead of Embodied Carbon, at least when B4 and B5 are not taken into account.

Bearing this in mind, an Embodied Carbon baseline of 500 kg CO_2eq/m^2 (540 including B4 and 650 including B4 and B5) is feasible and aligned with Danish and French regulations. Implementing other reduction measures as suggested below gives many options to halve this value by further choosing local, low-carbon materials and appropriate renovation strategies to double the lifetime of a building. If benefits and gains from modules C4 and D are taken, values can drop again, although this needs new industrial processes, markets, and behaviours to further proceed towards a NZCB target and the decarbonisation of the building sector. Regarding Operational Carbon, the Scenario 0 value of 1,385.52 kg CO_2eq/m^2 is almost halved (743.23 kg CO_2eq/m^2) only through the three chosen reduction measures (aligned to the homogenised value of 765.10 kg CO_2eq/m^2) and reduced by 85% (201.72 kg CO_2eq/m^2) if EPBD is applied as in Scenario 5. With better insulation and the addition of heat recovery at ventilation, as with the PassivHaus standard; adjusting energy demand as proposed in the EPBD, and balancing the result with carbon compensation as suggested by carbon markets, would make the case for 0-emissions energy buildings at the use phase.

Furthermore, LCA application standards are developed for specific processes or products, as is the case of EN15978. These are generic (as OpenLCA) or specific (as OERCO2). OpenLCA software (with Ecoinvent database) is widely used, exhaustive, flexible, and gives all impact categories and contribution trees as an outcome, but it requires a long processing time, and demands preparatory work to model the building and subsequent effort to fit outputs into EN15978 modules. OERCO2 (as well as other tools specific to buildings with internal or plugged-in data) is very easy to feed with standard building project data, is both online and lightweight, quick to run and generates a ready-to-use carbon footprint per material family as well as per project chapter (as well as Spanish-fit economic budget and working hours, a streetlamp-like impact viewer and automated graphics). However, it is closed, focused only on GWP, restricted to modules A1-5 and is little used.

Mitigating climate change is one of the many current environmental needs and challenges. LCA provides 18 impact categories, and weighting procedures such as the JRC proposal or using tools such as OpenLCA help understand if at a global, regional, or local scale one impact is more relevant than the others. In this regard, GWP is becoming a popular impact category. Decarbonisation roadmaps were presented in most European countries in 2022, manufacturers are publishing net-zero carbon plans, which is very positive, but must not draw our attention away from other dire impacts. Rather, GWP must become the spearhead of all other impact categories.

CONCLUSIONS AND POLICY IMPLICATIONS

This study shows a 63% reduction of Whole Life Carbon (WLC), from an average residential building from the Spanish most representative stock typology, to a similar one that has been improved with market-available low-carbon solutions and complying with the European Energy Performance of Buildings Directive (EPBD). Operational Carbon is reduced by 85%. The Life-Cycle Assessment (LCA) methodology applied here suggests a credible WLC benchmark of 745 kg CO_2eq/m^2 (202 Operational Carbon, equivalent to Class A in the EPBD). The key concept of Embodied Carbon is underlined for its relevance to accomplish climate targets. Easily attainable material choices fall at 500 kg CO_2eq/m^2 of Embodied Carbon and can be lowered if all Modules of EN15978 are taken into account. The more the electricity mixes are decarbonised, the bigger the Operational Carbon reduction from the current average of 1,386 kg CO_2eq/m^2. However, the share of Embodied Carbon can grow due to more energy-related technologies.

NZEB standards are feasible, viable and can reduce the impact of Spanish residential buildings by up to 85%. European markets and regulations are leading the way with credible measures for 2030 and 2050, as reviewed cases from the northern countries and France demonstrate. Every reform or substitution that does not entail a deep renovation of the building would be a lost opportunity to start solving the global climate emergency now. Local low-carbon materials and renewable energies are crucial and urgent. Establishing a value chain for recycling and reusing obsolete building components is as necessary as creating maintenance standards to extend the lifespan of building products. Urban mining markets are needed. New buildings must be carefully justified, or the required new uses located in a refurbished old one.

While GWP is becoming common language, other environmental impacts created by buildings are pinpointed here too. Marine, freshwater, terrestrial and human ecotoxicity impacts show a heavy poisoning of ecosystems for which buildings are responsible. Better buildings like that of Scenario 5 in this study reduce GWP by 63%, but also Water consumption (WCP) by 91%, the Marine eutrophication (MEP) by 88% and the Fossil resource scarcity (FFP) by 76%. LCA can set baselines and benchmarks for these and other impact categories. It can also provide figures for existing ideas, such as urban mining, to help create a 'bank of materials' profile of existing buildings which, better than being demolished and mixed, can re-enter other buildings' input flows, and reduce many impact categories.

The general WLC indicator makes sense when disaggregated into Embodied Carbon and Operational Carbon. Embodied Carbon indicates meaningful features of the building sector and therefore proves useful in decarbonising the national sectors and building stocks. Different LCA tools and databases have a specific niche, and their results need harmonisation before being compared. Even more important is transparency regarding the assumptions taken upon modelling the building. To comply with EN15978, specific building LCA tools and databases are more useful for the sector than general ones. However, in order to dive into impact categories, stages and more comprehensive policy making, general tools such as OpenLCA are crucial.

In both cases, the values will need interpretation and comparison with relevant studies. A reference value needs these studies to be valuably inserted into policies. When both specific and general tools and databases are combined, the strongest conclusions can be drawn and their consistency proved. The task of harmonising the application of LCA tools and databases is key to provide credible and agreeable policies, especially when considering LCA outcome variations due to end-of-life stage activities. In order to avoid double counting of loads and benefits, it is crucial to consider complete LCA.

8. Impactos ambientales de unifamiliares (Artículo 3)

8. ARTÍCULO 3

Biodiversity burdens in Spanish conventional and low-impact single-family homes

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ABSTRACT

Biodiversity loss caused by housing is not a well-defined sector of environmental impact. This research quantifies effects on biodiversity of an average Spanish Single-Family House (SFH) with 180 m^2 built surface. The Spanish SFH stock Global Warming Potential (GWP) amounts to 1.16 Gt CO_2eq in a 50-year life cycle, 40% of which is embodied in the building materials and the rest emitted using the building. It also pollutes with 10.2 Gt 1,4-DCB, drives 6,052 species extinct, and accounts for 3.03 M years of life lost due to premature death or lived with a disability.

The article compares a reference conventional building against three low-impact cases, to understand how different building techniques and materials can reduce biodiversity loss. Scenarios include a standard brick and concrete house (SC0, Base), a timber Passivhaus (SC1), a straw-bale house (SC2), and an earth bioclimatic house (SC3). An initial GWP analysis was performed to relate previous building Life Cycle Assessment (LCA) studies with biodiversity metrics. Three biodiversity metrics; ecotoxicity, biodiversity loss and Human Health (HH) have been considered.

Compared to SC0 with 1292 $kgCO_2\text{-eq}\cdot m^{-2}$ (516 embodied) of GWP, we found that SC1 emitted −47.0% of that, SC2 −41.4% and SC3 −80.9%. Concerning ecotoxicity, where SC0 has 11,399 kg 1,4 DCB, the results are −27.9% in SC1, −19.2% in SC2, and −45.6% in SC3. Regarding biodiversity loss, where SC0 has 7.54 E^{-06} $species.yr\cdot m^{-2}$, the impacts are −30.9% in SC1, −32.6% in SC2, and −58.6% in SC3. HH damage in SC0 being 3.37 E^{-03} DALY, was reduced in SC1 −44.2%, in SC2 −39.2%, and in SC3 −67.1%. Existing solutions can reduce GWP in −81%, Ecotocicity in −46%, biodiversity loss in −59% and HH in −67%. Spanish SFHs built in timber, earth or straw-bale are real alternatives to conventional building.

KEY WORDS
Life Cycle Assessment, Biodiversity, Human health, Ecotoxicity, Land use, Fine particulate matter, Embodied carbon, Single-Family House

HIGHLIGHTS

Damage of single-family houses on biodiversity and human health is assessed in a 50 year lifecycle.

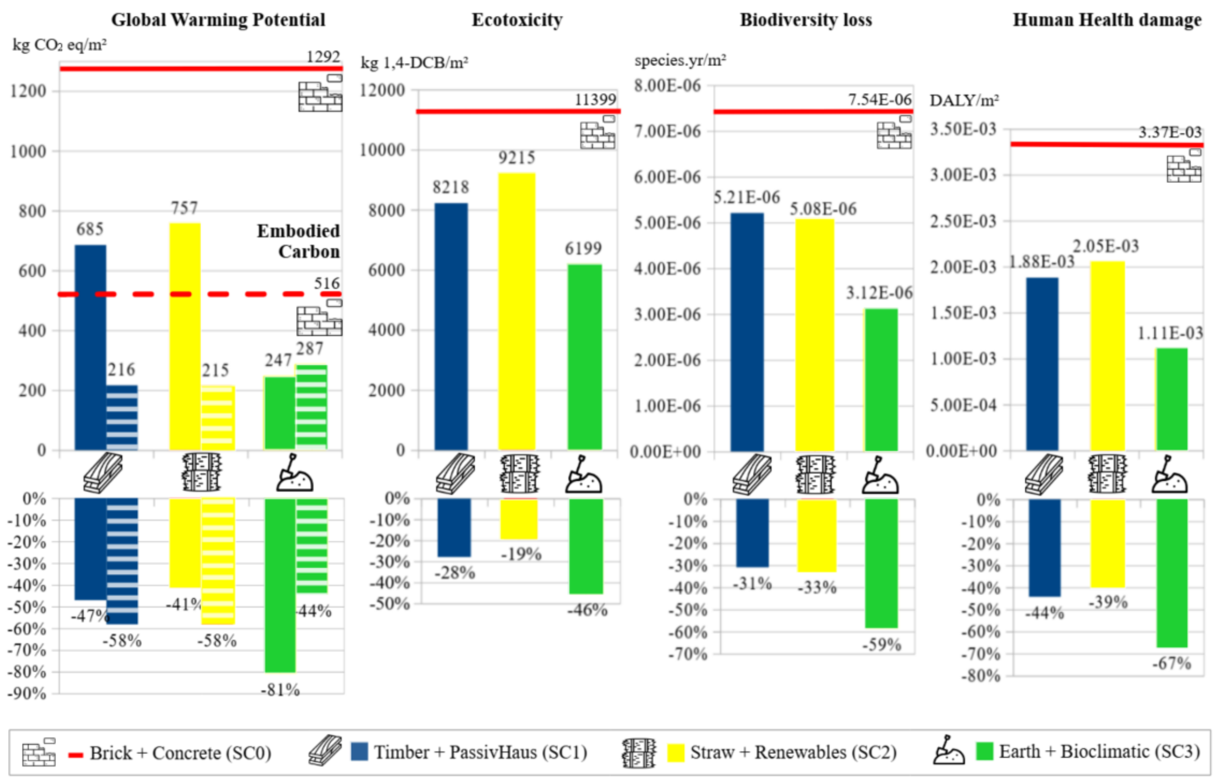
Terrestrial ecotoxicity midpoint impacts weight more than CO2eq emissions to the atmosphere.

Timber, straw, or rammed earth constructions cut impacts of conventional brick houses by half.
The Spanish stock of single-family houses drives yearly 6.052 species extinct in a 50 year lifecycle.

GRAPHICAL ABSTRACT

Biodiversity burdens of different Single Family Homes (SFH). Average Functional Unit: 180 m² built surface

Life-Cycle Assessment on ReCiPe 2016 (H) method, over a 50-year lifecycle, without Replacement nor Refurbishment (EN15978 B4, B5)



INTRODUCTION

The Kunming-Montreal Global Biodiversity Framework, agreed at the United Nations Biodiversity Conference COP15 on Biological Diversity, on the establishment of 4 goals and 23 targets to be achieved by 2050. These include the restoration of the integrity, connectivity and resilience of all ecosystems, the reduction to one-tenth of the extinction rate and risk of all species, the safeguard of genetic diversity, the sustainable use of biodiversity and ecosystem functions and services, and the progressive and universal closing of the biodiversity finance gap of $700 billion per year. Its target 12 specifies the need to ensure biodiversity-inclusive urban planning and buildings. Its target 19/f calls for "Mother Earth Centric" actions to restore ecosystems at every human activity, including buildings (CBD, 2022). The EU's Biodiversity Strategy for 2030 plans to protect nature, and reverse ecosystems' degradation. It aims at putting Europe's biodiversity on a path to recovery by 2030 and is a core part of the European Green Deal. It builds resilience to threats such as the impacts of climate change, forest fires, food insecurity or disease outbreaks. It extends Natura 2000 areas and launches an EU Nature Restoration Plan to better respect nature in public and business decision-making (DG Env EC, 2021a). Target 14 of the EU Biodiversity Strategy urges cities with at least 20,000 inhabitants to have an ambitious Urban Greening Plan following a guidance document (CIRCABC, 2022) and an online Urban Greening Platform (DG Env EC, 2021b). Some countries, as Spain, have already transposed it into their own regulations (MITERD, 2021), identifying 23 ecosystem services in green urban infrastructures, relating actions to regulations on building refurbishment and urban regeneration, prompting ecological landscaping in building and urban design, limiting construction works in sensitive areas and avoiding nature fragmentation.

However, according to the United Nations Organization, (DESA, 2018) estimations on population growth speak of 9,700 M people by 2050, 68% of them living in cities, of which 43 megacities will host more than 10 M. The construction of new 25 M km of roads (60% more than in 2010) and 335,000 km of railroads are expected in 2050, 90% of which on greenfield. Also, related Sustainable Development Goals (SDG) 14 "Marine life" and 15 "Terrestrial ecosystems" experience direct threats, and SDG 2 "Nutrition" and 6 "Clean water", indirect. Insufficient integration of SDG 13 "Climate change" and those containing ecotoxicity and overexploitation issues, SDG 6 and 12, deter the Goals from reaching expected results (CBD, 2020). The "State of nature in the EU" report, based on the Birds (2009/147/EC) and the Habitats (92/43/EEC) directives, the Natura 2000 network and the targets 1 and 3 of the previous EU 2020 Biodiversity Strategy, confirm continuous worsening of species status, from 32% in 2012, to 39% in 2018, and 9% fewer wintering birds in the same period. Habitat conservation worsened too (75% in 2012, 81% in 2018), with only 15% of the 233 European habitats well preserved. The Natura 2000 network, despite some positive impacts, has not achieved its potential effectiveness. As a result, there is a 12 % conservation gap for habitats, 20 % for bird species, and 2% for non-bird species. Also 31 % of forest habitats have a bad conservation status. (EEA, 2020) concludes that biodiversity in the EU continues to decline and faces deteriorating trends from changes in land and sea use, overexploitation and unsustainable management practices, as well as water regime modification, pollution, invasive alien species and climate change.

The Intergovernmental Platform on Biodiversity and Ecosystem Services focuses on strengthening the science-policy interface for the conservation of biodiversity and ecosystem services, long-term human well-being and sustainable development. Its European region Assessment Report (IPBES, 2018a) admits that nature's contributions to people are under threat due to the continuing loss of biodiversity, that European biodiversity is in continuous strong decline, and that progress towards healthy ecosystems is insufficient. Land use change is the major direct driver of the loss of both biodiversity and ecosystem services. Trends in natural resource extraction, pollution and invasive alien species lead to biodiversity decline. Economic growth is not decoupled from environmental degradation, preventing widespread achievement of goals similar to and including the SDG. Its Assessment Report on Land Degradation and Restoration (IPBES, 2018b) warns that combating land degradation and restoring it is an urgent priority to protect biodiversity and ecosystem services vital to all life on Earth, and to ensure human health. Human-induced Earth's land degradation negatively impacts the health of at least 3.2 Bn people, pushes the planet towards a 6th mass extinction, and costs more than 10% of annual global GDP. Land degradation and climate change are likely to force up to 700 M people to migrate by 2050. 97% of land (excluding Antarctica) and 87% of oceans have been modified by human activities. 83% of wild mammal biomass and 50% of plants have been lost. Livestock and humans now account for nearly 96% of all mammal biomass. Climate change increasingly interacts with these processes (IPBES, 2021). Moreover, the Workshop Report on Biodiversity and Pandemics concludes that 70% of emerging diseases like Ebola or Zika, and all known pandemics like AIDS or COVID-19, jump from microbes of animal origin. It is believed that there are 1.7 M viruses yet to be discovered in animal hosts, 52% of which could have the capacity to infect humans. Land use change is a global driver of pandemics and caused the emergence of over 30% of the new diseases since 1960 (IPBES, 2020).

The world's global built-up area is projected to double by 2060; an extra 230 Bn m2, equivalent to the size of New York City every month (Adams et al., 2019). In 2021, the building industry global emissions reached 13.6 Gt CO2eq and its energy consumption 37,500 GWh (UNEP, 2022). Housing is responsible for 22% of the industry's energy demand and 17% of the related CO2eq emissions. In Europe, an estimated 97% of the building stock is not efficient enough to comply with the Paris Agreement. To limit carbon emissions, Europe is leading the way in terms of carbon regulations and building benchmarks (Izaola et al., 2022), but the importance of liveable and biodiverse cities is still underestimated (Botzat et al., 2016). European limits on energy-related emissions (European Commission, 2021) for Spain, aim for a Class A of 6.8 kg CO^2-eq·m^{-2}·y^{-1}, although current averages are Class E, between 26.4 and 59.1 kg kg CO^2-eq·m^{-2}·y^{-1}. Current average Global Warming Potential (GWP) baselines for residential buildings of 1,298 kg kg CO^2-eq·m^{-2} over a 50-year life cycle have been suggested for Europe, and of 1,240 for Spain (Izaola et al., 2023).

The goal of this research is to propose impact metrics on biodiversity loss (1) and human health (2) of the average Spanish Single-Family House (SFH) and its low-impact variations. The average Spanish SFH has been characterized by a 180 m^2 home on a 800 m^2 plot in Madrid. This base building has been compared to three other SFH within the same climate zone (D3): a Cross-Laminated Timber (CLT) house, a straw bale house, and a rammed earth SFH. This research suggests that midpoint terrestrial ecotoxicity impacts create more damage than global warming emissions. Recognizing the importance and contribution of midpoint GWP data to understand climate change, the authors suggest looking at endpoint areas as well, in order to understand ecosystem quality loss affecting both humans and all other species. The overall habitability of the planet is at stake, but humans might not realize this if they only look at greenhouse gas emissions to the atmosphere, or the building industry by limiting only GWP. Instead, this article gives figures of how many species disappear and how much a human life is shortened due to buildings. The industry's increasing responsibility to comply with the Paris Agreement by implementing specific GWP reduction measures could prompt other biodiversity protection agreements by specifically reducing harm to humans and other species. This article quantifies the extent to which this reduction is achieved by choosing known low-impact building materials and techniques. It is structured with an initial literature review and a subsequent section to describe the methodological approach. The results section shows detailed figures on the proposed metrics. At the end, the discussion and conclusions comment on these results in the light of the studies reviewed, including some recommendations for interpreting results, raising awareness, clarifying limitations and suggesting further research.

LITERATURE REVIEW

The scientific study of biodiversity loss as proxy for Ecosystem Damage (ED) (1) and human life expectancy reduction (2), caused by buildings is a new field of analysis following the GWP of the industry (Bahramian and Yetilmezsoy, 2020). Initial impacts within the construction site (in-situ) and off-site (ex-situ) in building components such as roofs are analyzed, showing that an extensive green roof loses 35% less biodiversity (9.34E−07 against 1.43E−06 species.yr) than a conventional one, and that ex-situ biodiversity impacts are 10 times higher than in-situ (Brachet et al., 2019). Building materials have also been compared in terms of their impact on Human Health (HH). For instance, timber has 95% less effects on HH (1.26E−06 vs. 2.98E−05 DALY) than ceramic tiles (Shi et al., 2022). Technological innovation in the industry offers some positive results, as is the case with the latest generation of photovoltaics (PV). For instance, Perovskite panels cause 68% less HH damage (4.56E−07 vs. 1.43E−06 DALY) than polycrystalline (Zahedi et al., 2022). HH damage and ecotoxicity of rooftop PV is also analysed throughout Europe with big differences due to location (Martinopoulos, 2020). Another study compares HH and ED impacts of a renovated building and new ones in timber frame, CLT and conventional concrete. Although renovation is clearly the best option (39.4% HH and 36.3% ED impacts than that of the concrete building), both timber solutions have 15% less HH impacts than the concrete one. However, it is inconclusive in terms of ED impacts (Ryberg et al., 2021).

Although the damage pathways between Midpoint impacts and Endpoint protection areas are well defined and interconnected in methods such as ReCiPe 2016 (Huijbregts et al., 2017), sciences still address climate, biodiversity and social impacts separately, despite scientists claiming for an integrated approach to overcome the multiple crises (Pörtner et al., 2023). ReCiPe points to damage to terrestrial species with 6 pathways, followed by damage to freshwater species and to HH with 4 pathways. These three damages share GWP as main precursor. However, their dependencies are not sufficiently studied. For instance, only two studies were found that concomitantly quantify aspects of pollinator health and HH (Garibaldi et al., 2022), although their nutritional and medicinal contribution is indisputable. It is necessary to dive deeper into the pollutants emitted by building materials (Park et al., 2016), (Bhoonah et al., 2023), their life cycle eutrophication (Kobetičová and Černý, 2019) and toxicity effects (Rey-Álvarez et al., 2022), to find the connections between human and ecosystem health. ReCiPe clarifies this by defining Endpoints related to three critical areas of protection. Human health is represented by the years that are lost or that a person is disabled due to a disease or accident, with the metric “DALY” (disability-adjusted life years). Ecosystem damage is measured by the time-integrated loss of local species, “species year”. The third one, out of the scope of this article is resource scarcity, accounted in dollars (US$), which represents the additional costs involved in future mineral and fossil resource extraction (Huijbregts et al., 2017).

As already exemplified, insect decline is a proxy indicator of biodiversity loss or ED. Insects constitute the world's most abundant animal group and provide critical ecosystem services. The current proportion of insect species in decline (41%) doubles that of vertebrates (20%). Every year, 1% of all insect species are lost, and the decline in biodiversity accounts for an annual loss of 2.5% of the world's biomass. Decline is similar in tropical (45%) and temperate regions of the world (continental Europe, 44%). Causes of insect decline include habitat change as the main driver (49.7%), followed by pollution (25.8%). Habitat change derives from land transformation to provide housing, mobility, industry, or agriculture. Agriculture causes 24% of insect decline, urbanization 11%, and deforestation 9%. In terms of pollution, herbicides, insecticides and fungicides cause 13% of the decline, fertilizer inputs 10%, and urban and industrial sewage and landfill leachates 3%. Fertilizers and sewage also cause eutrophication and acidification with direct toxic effects and indirect support of biological factors as parasites and pathogens. Likewise, invasive species are favored by climate change and urbanization (Sánchez-Bayo and Wyckhuys, 2019). There are, however, studies arguing that low-density urbanization with integrated landscaping has less impact on pollinators than intensive agriculture (Wenzel et al., 2020).

At ecosystem level, building impacts change over the years, depending on factors such as location, building type, and species’ specificity. In terms of bird deaths, it is estimated that 988 M birds die annually in the USA by collision with buildings (Loss et al., 2012). Regarding habitat loss and fragmentation, several studies assess the negative effects of urbanization on forests (Zhou et al., 2017) and ecosystems (Liu et al., 2016). Buildings and infrastructures can generate light pollution, disrupting the behavior and migratory patterns of flying and swimming species. It drives moth (Boyes et al., 2021) or bat decline (Haddock et al., 2019), turtle disorientation (Silva et al., 2017), and in general, reduces fish abundance (Bolton et al., 2017). Likewise, noise pollution from buildings above 40dBA can disrupt the communication and breeding behavior of mammals, birds and amphibians (Shannon et al., 2016). Overall, studies highlight the importance of considering biodiversity and ecological impacts in the design, construction and management of buildings.

At urban level, there are numerous calls for defining urban biodiversity, and connecting it to urban planning, but few examples like the Rotterdamm “Green Metamorphosis Plan”, the Edmonton network of biodiversity corridors, or the more recent planning actions in Montreal and Melbourne explicitly address and deliver on biodiversity conservation (Oke et al., 2021). However, approaches for cities to play a relevant role in addressing global extinction are on the agendas and include citizen participation, shared use of urban gardens, strengthening ecosystem communities, creating refugia for species, and broadening the geographic and taxonomic focus. Again, some pioneers like the 260 German municipalities network “Kommbio”, the 11 Southafrican cities under a wetland protection program, the GUBIC consortium or the UWIN partnership (Knapp et al., 2021) should be highlighted. 34 specific attributes that a biodiverse city should have, according to (Nilon et al., 2017), include baselining and monitoring goals on local species protection, habitat management, constructing bio-swales, green roofs, green streets, rain gardens, yards and other green infrastructures using nature-based solutions, more taxa and ecosystem space, improvement of water quality and flood retention, removing air, light and noise pollution; improvement of urban heat islands and authorization of urban agriculture.

Despite cities hardly occupy 3% of global land area, they host 5 Bn people who exploit 82% of the land and oceans. However, cities can provide habitat and ecosystem services to a much wider community of species. For instance, 25% of unfragmented urban area dedicated to Atlantic forest in the proper climate zones for 65 years can achieve 80% of the biodiversity found in mature forests, albeit they require more than a thousand years to reach endemic levels (40% of species) (Pedersen Zari, 2019). A built environment incorporating biodiversity would improve the planet's ability to adapt to climate change, air quality, flood mitigation and the overall health and well-being of people, thus contributing to reach the SDGs (Opoku, 2019).

At building level, typology, occupancy and climate zone are relevant factors to take into account when considering environmental impacts of SFH. (Lavagna et al., 2018) provide figures for the total annual (related to 2010) EU-27 LCA impacts in relation to housing on 15 EN15978 impact categories, for a 100-year life cycle. SFH cause greater impacts than apartments in multifamily buildings, as they have larger floor area, but on a per m^2 and per capita basis, metrics are comparable. According to this study, there were 16,233,830 people living in 4,960,716 SFH in 2010 in Spain (and 30 M more living in 11 M apartments), or 3.27 occupants per SFH (2.56 per apartment). Of the 15 Midpoint impact categories identified, the study expresses 10 with metrics that need conversion to be compared with the methods used in our article. (Dong et al., 2021) has developed conversion factors to solve this problem. But still, three Midpoint impact categories relevant for our article, and all Endpoint, are missing at (Lavagna et al., 2018). In order to find comparable studies, (Dong et al., 2021) conversion factors have been applied where possible at (Lavagna et al., 2018) results, giving per m^2 a 50-year life cycle adjusted GWP of 1,078 kg CO_2eq·m_{-2}, Fine particulate matter of 0.51 kg PM2.5eq, Water resource depletion of 9.69 m^3, and Land use of 1,415 m^2y^{-1} crop·eq.

Other attempts have been made to benchmark impacts of residential buildings per m^2, as in the case of typical Spanish multifamily buildings, with an average of 73.10 m^2 NFA apartments, for a 50-year life cycle, including 19 impact categories assessed with the same Midpoint methodology as in our article, but without Endpoint analysis (Izaola et al., 2023). That study gives per m^2, among other less relevant data, a GWP of 1,913.8 kg CO_2eq, Fine particulate matter of 3.6 kg PM2.5eq, Water consumption of 64.7 m^3, Land use of 35.8 m2y-1 crop·eq, Human carcinogenic toxicity of 230.5 kg 1,4-DCB, and Freshwater ecotoxicity of 179.6 kg 1,4-DCB. That study separates GWP in Operational and Embodied carbon to highlight energy and material issues. Building techniques and materials’ choice also influence LCA results of buildings. Four examples from Slovakia (Moňoková and

Vilčeková, 2020) show that the best results come from their Straw house, except in the Renewable Energy and Water Footprint impact categories. Some comparable metrics include a GWP of 1,700 kg CO_2eq for the brick house, 330 for the Straw SFH, 1,400 for the earth house, and 970 kg CO_2eq for the timber one. Eight other impact categories are compared in the four scenarios. Similar results can be found at (Muñoz et al., 2023), where straw and adobe buildings reduce respectively 40, 30 and 20% the HH, resource depletion and ED average impacts of a conventional concrete and brick house.

At material level, comparative studies between cement and lime as mortar base indicate that the latter performs better in terms of biodiversity. Lime, being more flexible and porous, has better hygroscopic control, which attracts insects and rodents, which in turn attract birds, improving the surrounding ecosystem. As it has lower emissions than cement, it also lowers GWP (Mukherjee and Roy, 2020). Another study comparing steel structures with diversely managed timber gives a 1000:1 ED ratio of steel versus selectively logged native forest timber, with intermediate ratios of 100:1 versus international plantation timber and 500:1 versus clear fell native forest timber (Nolan et al., 2009). When comparing wood- and concrete-based frame buildings, LCA gives a carbon footprint of 219 kg $CO_2eq \cdot m^{-2}$ for concrete and 87 kg $CO_2eq \cdot m^{-2}$ for wood (40% that of concrete). The concrete building consumed 850 liters of fresh water per m², the wooden one 230 l/m^{-2} (27%); and 1,519 $MJ \cdot m^{-2}$ of energy, compared to 510 (33%). It also consumed a ton of non-renewable material per m², compared to 327 $kg \cdot m^{-2}$ for wood (32%). Social LCA data are also relevant as the concrete building causes 855 occupational accidents for every million m² and the wooden one 11 (1%) (Linkevičius et al., 2023). Another Cradle-to-Gate analysis (Arduin et al., 2022) of five earth-based techniques comparing the Embodied Carbon and Embodied Energy per kg of 2-storey bearing walls made of these techniques, found the best results in the Cob technique, except the Embodied energy of compressed earth blocks, which was 77% that of Cob. More environmental details on Compressed earth block and Rammed earth techniques are presented in another study from (Fernandes et al., 2019), with 9 impact categories. On average, Rammed earth has −7.5% impact.

The circular economy model has entered the urban, building and material realms aiming at enlarging the life cycle of products and reducing waste. The decarbonization potential of this model has been assessed (Nußholz et al., 2023). Slowing resource solutions could bring up to 99% savings in GHG emissions per functional unit, and closing resource solutions by 30–50%, although a case-by-case quantification is crucial (Gallego-Schmid et al., 2020). At a city level, participatory approaches and decission making science are largely missing but necessary (Rios et al., 2022). However, when local materials, techniques and agents are included in the circular economy case, the model can mitigate pressures on biodiversity. It so happens in a Finnish case on quarrying, forest management and the Real Estate sector identifying seven critical factors, of which cascading the reuse of wood materials shows the highest potential (Ruokamo et al., 2023). Retrofitting is the clearest circular economy approach for buildings. It has been assessed that through an optimal retrofitting plan, 39% life-time cost-saving, 55% life-time energy reduction and 59% life-time carbon reduction can be achieved at an investment cost of £1.32 × 106 (Luo and Oyedele, 2021). Moreover, retrofitting makes the energy required for building conditioning affordable for 84% of households (Ma'bdeh et al., 2023). However, in Spain the ratio of building refurbishment is only 0.8% of residential buidings per year (Marmolejo-Duarte et al., 2022).

According to official Spanish data, average yearly operational energy consumption of SFH is 15,514 kWh (14,991 in the Atlantic, 19,654 in central Spain and 13,246 in the Mediterranean) and that of apartments, 7,547 (IDAE, 2022). Of the 19,654 kWh for central Spain, and in particular for climate zone D3, 75% (14,838 kWh) comes from the combustion of fuels to provide HVAC+Hot Water, 6% (1,136 kWh) from electrical HVAC+Hot Water, 3% (557 kWh) from lighting, and the remaining 16% (3,003 kWh) from electrical appliances. Official statistics give an average SFH floor area of 144 m^2 (INE, 2011), recently updated to 152 m^2 (INE, 2023). With these figures, the average energy-related emissions of a Spanish SFH in the period 2011-2020 were 26.92 kg CO_2 eq·$m^{-2}y^{-1}$. Moreover, the 2020 Carbon Cartography Report, following Scope 3 Carbon Footprint, gives an average 5.5 t CO^2eq·y^{-1} per capita in Spain (Clean Planet, 2021). This footprint is distributed in Lifestyle (14%), Food (34%), Transport (42%) and Home (10%). These results are lower than the European Carbon Footprint Map (Ivanova et al., 2017), giving EU and Spanish averages of 11 t CO2 eq·y−1 per capita, with a distribution in products and Services (42%), Food (21%), Mobility (25%) and Shelter (11%). Income strongly influences results, which in Spain means inequalities such as the richest 5% being responsible for 33% of the domestic carbon footprint, while the poorest 45%, of the 23% (López et al., 2020). Another Spanish projection from 2018 to 2030 on the effects of decarbonization policies to meet thermal demands leads to reductions in the HH (64.5%), GWP (62.0%) and Resource Consumption (59.5%) categories. However, ED increases 16.5%. Damages due to the 2030 electricity generation scenario on HH, GWP and Resource Consumption decrease by 45%, 43% and 39%, respectively; but on ED increase 70% (González-Prieto et al., 2020).

The above state of the art was searched in Sciencedirect, Nature and Google Scholar, using the keywords "building" OR "single-family house" AND "biodiversity" AND "ecotoxicity", filtering articles from 2013 on, and with more than 50 citations. Initially, 39 were obtained. The search was extended to articles from 2001 onwards, regardless of their citations, finding 147, of which 18 were repeated. 129 articles were grouped into the following impact levels: General (14), Ecosystem (21), Urban (27), Building (34) and Material (17). Of these, 22 are reviews or systematic reviews; 13 at impact, 6 at Urban and 3 at Building level, and were discarded. A final quality and timely filter discarded articles older than ten years and with less than ten citations, finding 61 articles grouped as General (10), Ecosystem (8), Urban (11), Building (18) and Material (8). A final group of 6 articles contextualizing the situation in Spain was added. This article tries to fill the research gap on biodiversity impacts of buildings in Spain.

METHODS, DATA AND TOOLS

The methodology used for this research is Life-cycle Assessment (LCA) using the ReCiPe 2016 LCIA Hierarchical (H) method at Midpoint and Endpoint, where midpoints help to understand the cause-impact pathway and endpoints reflect damage to HH, ED and resource scarcity. The two approaches are complementary in that Midpoint has a stronger relation to environmental flows and a relatively low uncertainty, while Endpoint provides better information on the relevance of the environmental flows, but is also more uncertain (Huijbregts et al., 2017). OpenLCA software with data from Ecoinvent 3.9 has been used for their acceptance in the scientific community, their wide inclusion of impact categories, the clarity along the cause-effect pathways, and the specific biodiversity metrics, including ecosystems, land use and an eight-group species taxonomy. In a review of the applicability of 64 methods in biodiversity impact assessment, ReCiPe is also recommended (Damiani et al., 2023). However, it only includes biodiversity community composition and not ecosystem functions or structure, which, on the other hand is only provided by the too specific "Habitat Change Potential" method.

Model parameters include choosing the cut-off criteria of allocation of environmental burdens of materials, applying EU regionalization wherever possible, and defining as scope the whole building construction, use and end-of-life processes in terms of NFA; reduced to m2 as functional unit. The system boundary is a cradle-to-grave LCA from stage A to stage C. EN15978 modules B4 (Replacement) and B5 (Refurbishment) have not been considered in the 50-year life-cycle period due to lack of data and in accordance with a building culture which does not favour any of both (Val, 2011). For the inventory of the scenarios, in average, 33 input flows and 16 output flows have been introduced at the OpenLCA model of the four buildings (see tables S3 to S6 of the Supporting information file). An estimation of 98% of the average 160 measured items from the original bill of materials of the studied buildings were grouped in average 44 streams and included with few adjustments as inputs. 18 impact categories at Midpoint, with Global Warming Potential (GWP) separated in embodied and operational carbon, and 22 at Endpoint, with aggregated metrics per species.yr, DALY and USD2013, are presented.

Four specific metrics highlight the purpose of this article: the two Midpoint metrics are kg CO2eq, as it provides context to buildings' LCA, and kg 1,4-DCB (dichlorobenzene), a chemical compound commonly used as a solvent, deodorizer, and insect repellent. Because of its characteristics and wide use in toxicity testing, it is often chosen in LCA as an ecotoxicity reference substance. Dichlorobenzene appears in the building industry for wood preservation, as a concrete formwork release agent and in adhesives, sealants, paints and coatings. The two endpoint metrics are species extinction per year "species.yr" and Disability-Adjusted Life Years "DALY". Species extinction quantifies the potential impact of activities on species' richness over a specified period. It considers both the number of species locally extinct and the duration of the impact. DALY is a measure of overall disease burden considering the years of life lost due to premature death for humans, plus the years of healthy life lived with a disability (Huijbregts et al., 2017). Both metrics allow for a quantitative comparison of processes or products in terms of their biodiversity impact.

Full LCA at Mid- and End-point of the four scenarios have been calculated, using a conventional brick house as base scenario, on which to compare three low-impact scenarios. Brick masonry is the standard building system in Spain, with 98% of SFH. The optimized scenarios are less common, but current 1% timber buildings are growing, and earth-based buildings remain present in older buildings all over the country, except on the north coast (Arriaga, 2020). While the newest national statistic (INE, 2023) reports 152 m2 as average area of SFH, 27.5% of the SFH have an average surface above 180 m2, which is the largest statistical category by area. A real case with this size has been considered representative for central Spain. Also, plot area definition is determined by local urban codes, with a wide spectrum between 160 m2 for row houses and 2500 m2 for detached homes. However, in the region of the chosen case, average plot area is 804 m2 (Santos Preciado and García Lázaro, 2012), which fits to the 800 m2 of the case representing the base scenario.

For all 18 Mid- and 22 End-point impacts, comparisons are made per m^2. GWP Midpoint impact is divided into Operational Carbon (OC) and Embodied Carbon (EC). OC has been calculated from the energy certification. The five Midpoint impacts related to ecotoxicity are aggregated under the same metric (kg 1,4-DCB) and their relative weights considered to find the most influential one. The processes that contribute most to each indicator are then presented. This allows to draw conclusions to diminish biodiversity impacts. A similar approach is applied to the two mentioned Endpoint metrics. 12 impacts sharing the "species.yr" metric and the DALY metric are aggregated, their relative weights compared to find the most influential, and finally the most relevant contributing processes are explained. A study on recommendations for communicating aggregated buildings LCA results includes this proposal and encourages practitioners to transparently experience on this to help convey LCA messages (Gomes et al., 2022). Table S1 of the Supporting information file presents the categories that are aggregated at each impact method.

Description of Scenarios

Four scenarios have been created to measure the impact of conventional 98% of Spanish SFH, (Arriaga, 2020) and three low-impact SFH to reach virtually all Spanish SFH. All scenarios fall within the same climate zone (D3 according to spanish building regulation) to facilitate energy usage comparison. For all four scenarios, the functional unit is a square meter of the built area of the SFH, the system boundary is a cradle-to-grave LCA from stage A to stage C according to EN15978, excluding replacement and refurbishment, in a 50-year life cycle after which the building is demolished and sent to landfill. .

Scenario 0 (SC0: Brick + Concrete): The Base Scenario represents 98% of Spanish SFH (Arriaga, 2020). It is a detached (three members) home in the south of Madrid (Getafe, 630 m above sea level (a.s.l.)), built in 2016 on a previously urbanised flat 800 m^2 plot surrounded by planted pine trees. It has a Net Floor Area (NFA) of 151 m^2 (main floor 120 m^2, mezzanine 31 m^2; total built 181 m^2). An envelope surface of 768.6 m^2 confines a volume of 488.7 m^3, giving a shape factor of 1.57 (Shape factor (SF) = envelope surface / volume). Foundations and structure are made of reinforced concrete, and facades of cavity brick walls insulated with 5 cm of mineral wool and finished inside and outside with cement mortar and painting. The gable roof slab (also insulated with 5 cm of mineral wool) and the floor slab are bidirectional reinforced concrete sheds with an axes distance of 82 cm. Roofing is finished with ceramic tile. Inside floorings are laid with ceramic tile on the wet rooms and hard wood on the rest. It weights 443 t, of which foundations and structure 403 t and ceramics 27 t. Windows are thermal brake aluminium framed with double glazing. It has an energy certification Class B (15.12 kg $CO_2eq \cdot m^{-2}y^{-1}$ emissions and 66.72 $kWh \cdot m^{-2}y^{-1}$·non-renewable energy demand). Heating is provided by a Natural gas 4 kW heater. Lay-out and main elevation can be found in the supporting information file, as figures S1 and S2.

Scenario 1 (SC1: Timber + Passivhaus): Semi-detached (four members) SFH in the outskirts of Madrid (770 m a.s.l.), built in 2020 on a semi-arid flat 250 m^2 sprawl-type plot with 2 pine trees, one palm and one fig tree, with NFA 157 m^2 (built 216 m^2). The other adjacent semi-detached SFH is structurally and thermally isolated by a party wall. An envelope surface of 441.2 m^2 confines a volume of 691 m^3, giving a SF of 0.64. It is built under standard Passivhaus (Moreno-Rangel, 2020) with an energy certification Class A (7.42 kg $CO_2eq \cdot m^{-2}y^{-1}$ emissions and 40.82 $kWh \cdot m^{-2}y^{-1}$·non-renewable energy demand). It has no underground floor and the outer structure, inner partitions, floors and roof are made of Cross Laminated Timber (CLT) (balloon frame technique). Foundations are superficial (0.8 m below ground) strip footing concrete blocks suitable for a light building. It has a 8.7*9.5 (82.6 m^2) lay-out on two full floors plus half floor under a N-S gable roof. It weights 84 tons, of which foundations 40 t and timber 35 t. It has a heat-recovery ventilation system solved with an 8 kW heat pump. Peak electricity demand is 9.9 kW, supported by a 2.6 peak kW PV installation on the south facing slope of the roof. Envelope insulation is made of 40 cm wood fibre except ground floor 10 cm cork. Windows are wood-framed with double low-emissive glazing. This house has automated devices for sun shading, HVAC, PV, artificial lighting, door opening, fire safety, air ventilation and air quality systems. Painting and surface finishes are VOC-free ecological products. Lay-out and main elevation can be found in the supporting information file, as figures S3 and S4.

Scenario 2 (SC2: Straw + Renewables): Detached (four members) SFH in the north mountains of Madrid (Robledo de Chavela, 900 m a.s.l.), built in 2019 on a south-facing 15% slope mixed with granit rock outcrops and local wild shrubs: rockrose, heather, broom, rosemary, thyme and medium size broom, rosemary, thyme and holm oak. The plot has 10,215 m^2, is not fenced and the nearest home is 260 m down the gravel road. It is built with a very light hybrid timber-and-straw-bale modular bearing wall system. Three 7*6 m modules with a total NFA of 90 m^2 (built 123 m^2) are laid on one floor over a levelling cyclopean concrete slab filled with the local granit rock. It weights 69 t, of which the concrete slab 51 t and the straw-bales, 1.1 t. An envelope surface of 386.8 m^2 confines a volume of 362.9 m^3, giving a SF of 1.07. It has an energy certification B (12.59 kg $CO_2eq \cdot m^{-2}y^{-1}$ emissions and 65.09 $kWh \cdot m^{-2}y^{-1}$·non-renewable energy demand). The lower part of the single south facing roof slope made of I-Joist and OSB boards insulated with straw, is covered with greenroof (5 cm substrate) while the upper part hosts 4 m^2 of solar thermal panels (300 l tank) and 6.65 m^2 of photovoltaic panels (1.3 peak kW). In the living room there is a 7 kW logwood fireplace with stove. Windows are wood-framed with double glazing. Waste water is bio-depurated on-site. Lay-out and main elevation can be found in the supporting information file, as figures S5 and S6.

Scenario 3 (SC3: Earth + Bioclimatic): Detached (six members) two floor SFH in Catalonia, Lleida (Balager, 266 m a.s.l.), built in 2019 on a flat urban plot of an agricultural village at the crossing of two rivers. The two adults work at home. The site contains radon gas and a filtering membrane is laid between the foundation and the ground floor to avoid it entering the house. It has a NFA of 224 m^2 (total built 276 m^2). An envelope surface of 560.1 m^2 confines a volume of 828 m^3, giving a SF of 0.68. It is built with structural walls of rammed earth extracted from the site. The foundation is made with cyclopean bastard concrete from the site boulders and pebbles, found below 1 m of sand and clay. It weights 580 t, of which 157 t to rammed earth. The strip footing below the bearing walls are the same type, but reinforced with corrugated steel. The floors and roof structure are made of local pine tree timber (Pyrenees, 150 km) with 2/3 of flat greenroof finish and 1/3 of wooden pinned slates. The roof insulation is 20 cm of cotton while North and East external walls' cotton insulation is 14 cm thick, and at South and West, 7 cm. It is a bioclimatic Energy+ building (Kumar and Cao, 2021) under a non-ventilated rammed earth thermal wall behind a greenhouse, with energy certification A (2.4 kg $CO_2eq \cdot m^{-2}y^{-1}$ emissions and 14.1 $kWh \cdot m^{-2}y^{-1}$·non-renewable energy demand). In the upper floor, sleeping rooms partition walls are 5 cm earth mortar radiant walls on the timber structure, operated with a 1.2 kW heat pump with a 200 l tank. These rooms also have a skylight going through the greenroof. Windows are wood-framed with triple low-emissive glazing. For occasional heating there is an extra pellet 17 kW furnace. It also has a 4.5 kW peak PV installation producing more energy than demanded. Lay-out and main elevation can be found in the supporting information file, as figures S7 and S8. Table 3.1 presents a general comparison of building metrics of the four scenarios.

Table 3.1. Comparison of building metrics of the four scenarios

SC3 Earth	**SC2 Straw**	**SC1 Timber**	**SC0 Brick**	**Unit**	
580,931	68,817	84,008	433,353	kg	Total weight
276	123	216	181	m^2	Built surface
2,104.8	559.5	388.9	2,394.2	kg/m^2	Weight/m2
560.1	386.8	441.2	768.6	m^2	Envelope surface
828	362.9	691	488.7	m^3	Confined volume
0.68	1.07	0.64	1.57	m^{-1}	Shape factor
14.1	65.09	40.82	66.72	$kWh \cdot m^{-2}y^{-1}$	Non-Renewable Energy demand

RESULTS

Table 3.2 summarizes the four biodiversity impact categories studied at the four scenarios, and estimates the overall impacts of the Spanish 4,960,716 (Lavagna et al., 2018) SFH stock represented by our base scenario. Spanish SFH emit 1.16 Gt CO2eq to the atmosphere in a 50-year life cycle, of which 39.9% is embodied in the building materials. They also pollute land, water and human health with 10.2 Gt 1,4-DCB. They drive 6,052 species extinct, and lose 3.03 M years of human life. Divided by the 16 M people living in the Spanish SFH stock, each inhabitant lost 0.19 DALY; or 68.1 days of their lives. The Earth house gives the best results, in average 63% below the Brick SFH. Its energy+ solution effectively cuts GWP to 19% that of SC0. The initial graphical abstract illustrates these data.

Table 3.2. Summary of biodiversity impacts of the scenarios per m², and the Spanish SFH stock on absolute values.

SFH stock	SC3 Earth	SC2 Straw	SC1 Timber	SC0 Brick	Unit	Impact category
1,160,857 M	247	757	685	1,292	kg CO2 eq/m²	Global Warming Potential (GWP)
463,718 M	287	215	216	516	kg CO2 eq/m²	of which Embodied Carbon (EC)
10,235,357 M	6199	9215	8218	11399	kg 1,4-DCB/m²	5 aggregated ecotoxicity metrics
6,052	3.12E-06	5.08E-06	5.21E-06	7.54E-06	species.yr/m²	12 aggregated species.yr metrics (ED)
3,029,387	1.11E-03	2.05E-03	1.88E-03	3.37E-03	DALY/m²	8 aggregated DALY metrics (HH)
						Compared to Base scenario (Brick)
	19.1%	58.6%	53.0%	100 %	% kg CO2 eq/m²	Global Warming Potential (GWP)
	54.4%	80.8%	72.1%	100 %	% kg 1,4-DCB/m²	5 aggregated ecotoxicity metrics
	41.4%	67.4%	69.1%	100 %	% species.yr/m²	12 aggregated species.yr metrics (ED)
	32.9%	60.8%	55.8%	100 %	% DALY/m²	8 aggregated DALY metrics (HH)

Table 3.3 details all the impact categories of the scenarios at Mid- and Endpoint, per m². At Midpoint, GWP is decomposed in Operational and Embodied Carbon, and Ecotoxicity metrics are aggregated and appear underlined for clarification. At Endpoint, "species.yr", "DALY" and "USD2013" metrics are also aggregated. Red cells highlight the worst results, and green ones, the best.

Table 3.3. Impact categories of the studied houses at Mid- and End-point per m². Best in green, worst in red.

SC3 Earth	SC2 Straw	SC1 Timber	SC0 Brick	Unit	Midpoint Impact category
0.59	1.21	1.13	1.78	kg PM2.5 eq/m²	Fine particulate matter formation
23.60	6.24	23.16	57.52	m3/m²	Water consumption
2.14E-04	2.91E-04	3.25E-04	3.81E-04	kg CFC11 eq/m²	Stratospheric ozone depletion
4,566.63	7,325.83	6,497.92	8,351.44	kg 1,4-DCB/m²	Terrestrial ecotoxicity
1,175.54	1,493.65	1,391.30	1,898.69	kg 1,4-DCB/m²	Human non-carcinogenic toxicity
49.89	225.28	204.81	446.33	kg oil eq/m²	Fossil resource scarcity
1.24	2.77	2.56	3.99	kg SO2 eq/m²	Terrestrial acidification
1.12	1.78	1.74	3.16	kg NOx eq/m²	Ozone formation, Terrestrial ecosystems
159.93	192.74	249.52	134.72	m2a crop eq/m²	Land use
219.93	182.10	155.16	549.78	kg 1,4-DCB/m²	Marine ecotoxicity
0.25	0.04	0.06	0.04	kg N eq/m²	Marine eutrophication
10.00	6.15	5.05	8.45	kg Cu eq/m²	Mineral resource scarcity
58.05	68.50	50.26	148.11	kg 1,4-DCB/m²	Human carcinogenic toxicity
0.98	1.68	1.65	2.99	kg NOx eq/m²	Ozone formation, Human health
0.14	0.23	0.21	0.33	kg P eq/m²	Freshwater eutrophication
178.92	145.01	123.16	451.33	kg 1,4-DCB/m²	Freshwater ecotoxicity
16.76	18.71	18.71	18.80	kBq Co-60 eq/m²	Ionizing radiation
246.99	756.54	684.58	1,292.87	kg CO2 eq/m²	Global warming potential (GWP)
-40.15	541.11	469.06	776.42	kg CO2 eq/m²	- Operational carbon
287.14	215.43	215.52	516.45	kg CO2 eq/m²	- Embodied carbon
6,199.08	9,215.09	8,217.80	11,399.35	kg 1,4-DCB/m²	**total**

SC3 Earth	SC2 Straw	SC1 Timber	SC0 Brick	Unit	Endpoint Impact category
1.42E-07	1.59E-07	1.74E-07	1.59E-07	DALY/m²	Ionizing radiation
5.21E-08	8.36E-08	7.42E-08	9.54E-08	species.yr/m²	Terrestrial ecotoxicity
1.41E+01	7.25E+01	6.58E+01	1.46E+02	USD2013/m²	Fossil resource scarcity
6.88E-07	2.11E-06	1.90E-06	3.65E-06	species.yr/m²	Global warming, Terrestrial ecosystems
1.93E-04	2.27E-04	1.67E-04	4.92E-04	DALY/m²	Human carcinogenic toxicity
1.41E-06	1.71E-06	1.90E-06	1.20E-06	species.yr/m²	Land use
1.45E-07	2.30E-07	2.25E-07	4.07E-07	species.yr/m²	Ozone formation, Terrestrial ecosystems
1.24E-07	1.00E-07	8.52E-08	3.12E-07	species.yr/m²	Freshwater ecotoxicity
3.19E-07	8.43E-08	3.13E-07	7.73E-07	species.yr/m²	Water consumption, Terrestrial ecosystem
1.43E-11	3.77E-12	1.40E-11	3.47E-11	species.yr/m²	Water consumption, Aquatic ecosystems
1.14E-07	1.54E-07	1.73E-07	2.02E-07	DALY/m²	Stratospheric ozone depletion
2.68E-04	3.41E-04	3.17E-04	4.33E-04	DALY/m²	Human non-carcinogenic toxicity
2.31E+00	1.42E+00	1.17E+00	1.96E+00	USD2013/m²	Mineral resource scarcity
2.62E-07	5.88E-07	5.56E-07	8.29E-07	species.yr/m²	Terrestrial acidification
4.32E-10	5.83E-11	1.07E-10	6.16E-11	species.yr/m²	Marine eutrophication
1.89E-11	5.79E-11	5.24E-11	9.89E-11	species.yr/m²	Global warming, Freshwater ecosystems
5.24E-05	1.38E-05	5.14E-05	1.28E-04	DALY/m²	Water consumption, Human health
9.29E-08	1.55E-07	1.43E-07	2.20E-07	species.yr/m²	Freshwater eutrophication
2.31E-08	1.91E-08	1.63E-08	5.78E-08	species.yr/m²	Marine ecotoxicity
3.69E-04	7.61E-04	7.10E-04	1.12E-03	DALY/m²	Fine particulate matter formation
9.06E-07	1.54E-06	1.48E-06	2.71E-06	DALY/m²	Ozone formation, Human health
2.29E-04	7.02E-04	6.35E-04	1.20E-03	DALY/m²	Global warming, Human health
3.121.14E-06	5.08E-06	5.21E-06	7.54E-06	species.yr/m²	**total**
1.11E-03	2.05E-0.3	1.88E-03	3.37E-03	DALY/m²	**total**
16.38	73.90	66.93	148.33	USD2013/m²	**total**

Taking Scenario 0 as base for comparison (100% green line), the following logarithmic scales present the relative impacts at Mid- and Endpoint methods of the previous Table 3.3 results (metrics per m^2). Figure 7 shows the Midpoint impacts comparison, while Figure 8, the Endpoint's. Land use impacts are worse than SC0 in scenarios 1-3 and Marine eutrophication impact of the Earth house exceeds averages (701% at Midpoint and 700 % at Endpoint). Average impact of the Timber house is 71% at Midpoint, and 66% at Endpoint of the Brick home. The Straw SFH averages are 67% and 61% respectively, and the Earth house's, 87% and 76%. The Earth house has the lowest results in 26 of the 40 indicators and 12 highest results. The Timber home, 8 lowest and 5 highest. The Straw SFH has 6 lowest and 23 highest results.

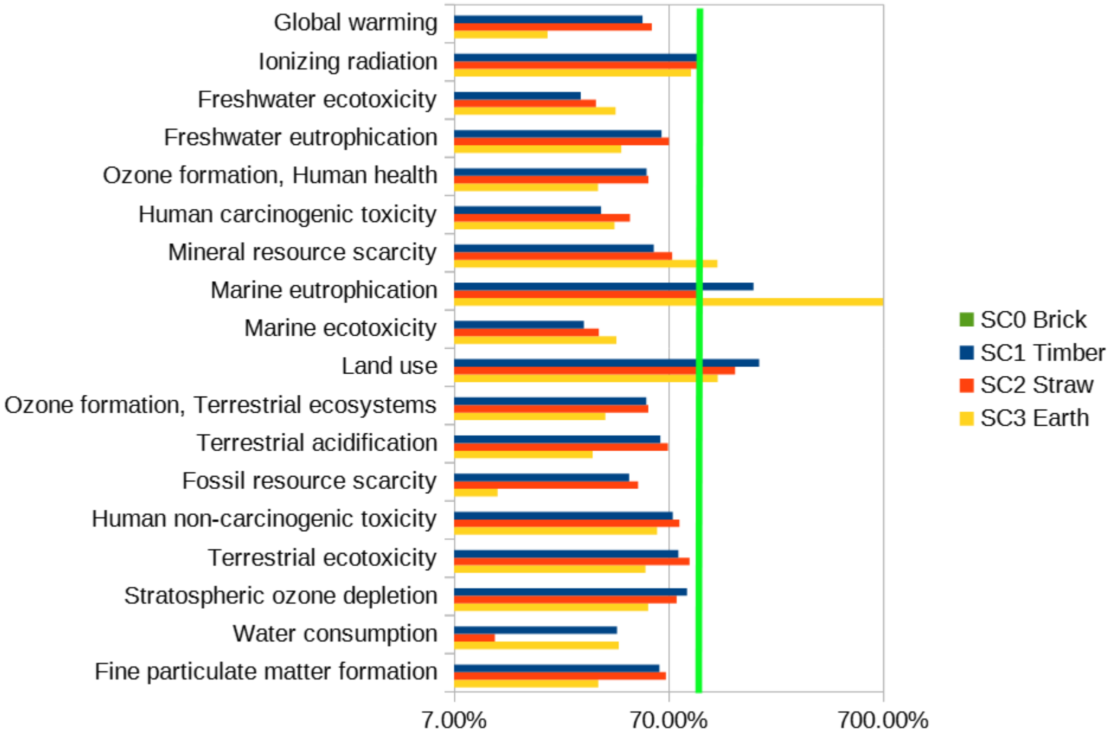


Figure 7. *Midpoint impact category comparison (Brick house 100%, as green line)*

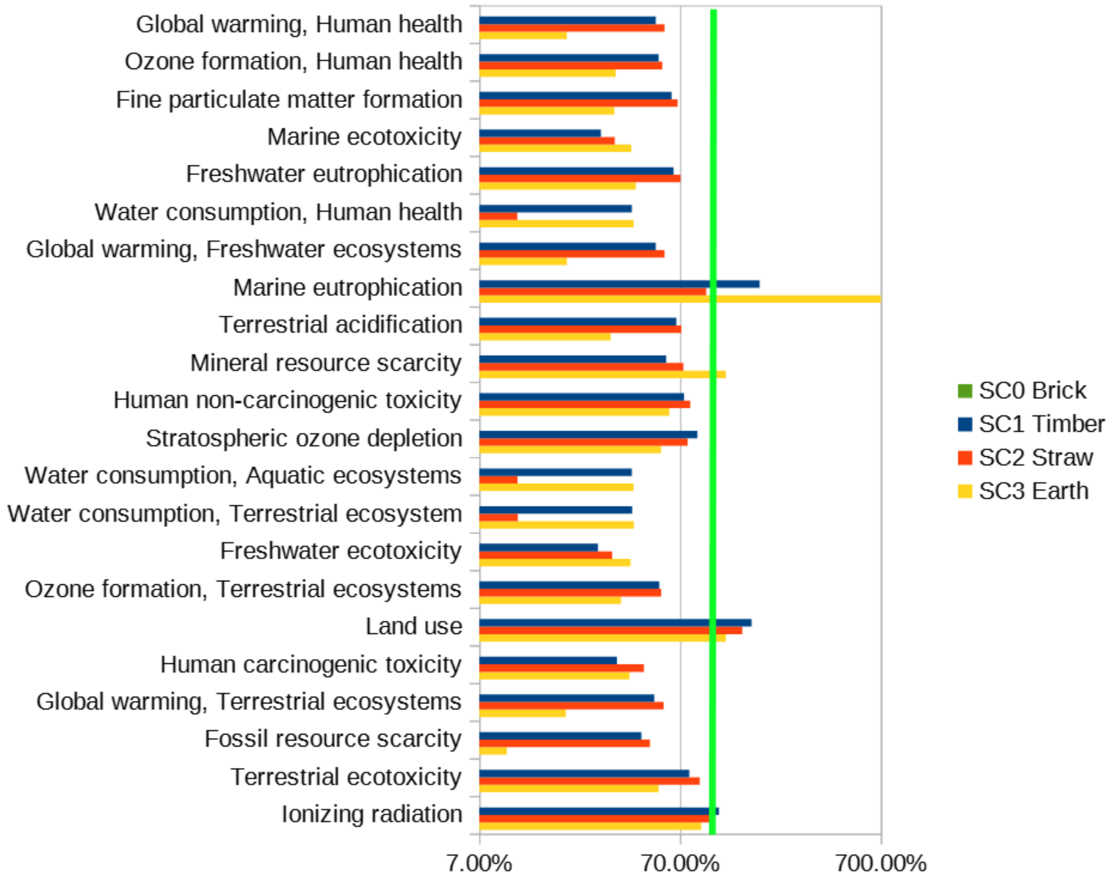


Figure 8. *Endpoint impact category comparison (Brick house 100%, as green line)*

Table 3.4 presents the contribution of the main LCA processes on GWP. The Operational Carbon has an average weight of 64.4%, except in the Earth house, which, as mentioned, is an Energy+ house. Where there is a photovoltaic installation, it ranks second. Cement presents strong differences in the four scenarios, and their specific processes are commented at the discussion section. The only characteristic material of any scenario that appears as high contributor is CLT in the Timber house.

Table 3.4. Main contributing LCA flows on Global Warming Potential (GWP)

SC3 Earth	SC2 Straw	SC1 Timber	SC0 Brick	Global warming potential, % contribution kg CO2 eq
	71.31%	68.52%	60.05%	market for electricity, low voltage | electricity, low voltage | Cutoff, U - BD
15.04%	3.21%	4.04%		market for PV slanted-roof installation, 3kWp, multi-Si panel | Cutoff, U - GLO
		3.23%		market for cross-laminated timber | cross-laminated timber (CLT) | Cutoff, U - RER
26.65%	3.40%	3.22%	13.78%	cement production, Portland | cement, Portland | Cutoff, U - IN
4.09%	1.99%	2.96%		window frame production, wood, U=1.5 W/m2K | Cutoff, U - RER
4.59%	2.20%			alkyd paint production, solvent-based, in 60% solution state| Cutoff, U - RoW
3.28%				structural timber production | structural timber | Cutoff, U - RER
3.64%				market for fibre, cotton | fibre, cotton | Cutoff, U - GLO
5.66%				treatment of waste rubber,municipal incineration | Cutoff, U - EU without CH
3.88%				market for seal, natural rubber based | seal, natural rubber based | Cutoff, U - GLO
4.41%			2.69%	reinforcing steel production | reinforcing steel | Cutoff, U - AT
6.04%				market for furnace, pellet, 15kW | furnace, pellet, 15kW | Cutoff, U - GLO
3.19%	0.96%	1.18%		glazing production, triple, U<0.5 W/m2K | Cutoff, U - RER
			5.49%	market for natural gas, low pressure | natural gas, low pressure | Cutoff, U - MX
80.47%	83.07%	83.15%	82.01%	**Total**

Table 3.5 presents the contribution of the main LCA processes on Terrestrial ecotoxicity, at Midpoint. Terrestrial ecotoxicity carries 76% of the 5 ecotoxicity indicators, as seen in Table S2 of the Supporting Information file. Copper-containing items rank high on this indicator. Electric wiring appears as the main toxic building component with an average contribution of 49%. Four processes (from average 55), are enough to account for an average weight of 86% of the indicator.

Table 3.5. Main contributing LCA flows on Terrestrial ecotoxicity.

SC3 Earth	SC2 Straw	SC1 Timber	SC0 Brick	Terrestrial ecotoxicity, % contribution kg 1,4-DCB
52.77%	48.19%	51.16%	43.21%	market for cable, three-conductor cable | cable, three-conductor cable | Cutoff, U - GLO
	21.63%	21.21%	27.31%	market for electricity, low voltage | electricity, low voltage | Cutoff, U - BD
28.87%	11.67%	14.99%		market for photovoltaic slanted-roof installation, 3kWp, multi-Si panel| Cutoff, U - GLO
	9.08%		13.12%	market for solar collector system, Cu flat plate collector, one-family house, hot water | solar collector system | Cutoff, U - GLO
81.64%	90.57%	87.36%	83.64%	**Total**

Table 3.6 presents the contribution of the main LCA processes on Land use, at Endpoint. Land use carries 39% of the 12 ED indicators except in SC0, as seen in Table S2 of the Supporting Information file. Each building has a different behaviour in this realm, and it is strongly tied to its main structural system. The characteristic material of the Timber house clearly bears with most of its impacts. In the case of the Straw home, the straw-bales are framed within glued timber bearings, as also happens with the floors of the Brick SFH. Also in the Earth house, structural timber is present at the greenhouse, roof structure and cladding, with high contribution. The cotton insulation here appears as another crop, next to forestry and cereal straw, showing their impact on land use.

Table 3.6. Main contributing LCA flows on Land use.

SC3 Earth	SC2 Straw	SC1 Timber	SC0 Brick	**Land use,% contribution species.yr**
		48.41%		market for cross-laminated timber | cross-laminated timber (CLT) | Cutoff, U - RER
		19.65%		oriented strand board production | oriented strand board | Cutoff, U - RoW
7.06	8.72%	9.09%		window frame production, wood, U=1.5 W/m2K | Cutoff, U - RER
		9.07%		market for sawnwood, lath, hardwood, dried (u=10%), planed | Cutoff, U - RoW
	69.58%		42.25%	glued solid timber production | glued solid timber | Cutoff, U - RER
	9.91%			straw production, stand-alone production | straw, stand-alone production | Cutoff, U - RoW
45.80%				structural timber production | structural timber | Cutoff, U - RER
28.89%				wood cladding production, softwood | wood cladding, softwood | Cutoff, U - CA-QC
6.88%				market for fibre, cotton | fibre, cotton | Cutoff, U - GLO
			14.35%	cement production, Portland | cement, Portland | Cutoff, U - IN
			7.46%	market for electricity, low voltage | electricity, low voltage | Cutoff, U - BD
			7.41%	door production, inner, wood | door, inner, wood | Cutoff, U - RoW
			4.46%	sand quarry operation, open pit mine | sand | Cutoff, U - BR
			3.50%	treatment of waste reinforced concrete, for final disposal | Cutoff, U – EU without CH
88.63%	88.21%	86.22%	79.43%	**Total**

Table 3.7 presents the contribution of the main LCA processes on fine particulate matter formation, at Endpoint. This indicator carries 35% of the 8 HH indicators, as seen in Table S2 of the Supporting Information file. The Operational energy contributes an average 49%, except in the energy + Earth house. Electric wiring ranks second in all scenarios, and where there is a photovoltaic installation, third. Also, the ceramic tile production appears high in all houses. Diverse processes related to the structural system of each scenario appear, as CLT in SC1 and cotton in SC3.

Table 3.7. Main contributing LCA flows on Fine particulate matter formation.

SC3 Earth	SC2 Straw	SC1 Timber	SC0 Brick	**Fine particulate matter formation, % contribution DALY**
	50.26%	46.81%	49.21%	market for electricity, low voltage | electricity, low voltage | Cutoff, U - BD
16.77%	11.90%	12.00%	8.27%	market for cable, three-conductor cable | cable, three-conductor cable | Cutoff, U - GLO
15.19%	4.82%	5.89%		market for photovoltaic slanted-roof installation, 3kWp, multi-Si panel, | Cutoff, U - GLO
		4.85%		market for cross-laminated timber | cross-laminated timber (CLT) | Cutoff, U - RER
15.89%	4.98%	4.24%	5.14%	ceramic tile production | ceramic tile | Cutoff, U - CH
3.62%		3.77%		window frame production, wood, U=1.5 W/m2K | Cutoff, U - RER
		3.43%		oriented strand board production | oriented strand board | Cutoff, U - RoW
	4.22%			glued solid timber production | glued solid timber | Cutoff, U - RER
	3.97%			market for solar collector system, Cu flat plate, one-family home hot water | Cutoff, U - GLO
3.91%				market for fibre, cotton | fibre, cotton | Cutoff, U - GLO
9.44%			8.42%	cement production, Portland | cement, Portland | Cutoff, U - IN
4.57%				structural timber production | structural timber | Cutoff, U - RER
4.50%				market for furnace, pellet, 15kW | furnace, pellet, 15kW | Cutoff, U - GLO
3.18%				alkyd paint production, solvent-based in 60% solution state | | Cutoff, U - RoW
			7.04%	window frame production, aluminium, U=1.6 W/m2K | Cutoff, U - RoW
2.67%			2.81%	reinforcing steel production | reinforcing steel | Cutoff, U - AT
79.74%	80.15%	80.99%	80.89%	**Total**

Due to the outstanding impact of the Marine eutrophication Endpoint indicator on the Earth house seen at Figure 3.2, the related contribution tree was also calculated to find out that 61% of the weight comes from the wastewater treatment, and 32% comes from the market for fibre cotton process. The uncertainty of this process, and other limitations of this study are discussed below.

DISCUSSION

This article provides new biodiversity-related data on the impacts of housing in Spain. It updates Midpoint and Endpoint impact categories by applying the ReCiPe 2016 (H) method in a 50-year life cycle full LCA, with exception of replaceable components or building refurbishment. A longer timespan might have allowed the inclusion of these two modules, but still data was missing and complying with international standards of 50 years lifecycle was concidered a priority. Comparing results with other reviewed studies was difficult due to different metrics and LCA approaches. But it has been possible to compare 15 Midpoint impact categories between a Spanish average apartment (Izaola et al., 2023) mentioned in the literature review and the conventional SFH of our article.

Table 3.8 presents indicators per built m^2 and their variation. On average, the SFH impacts are 77% that of the apartment, except four categories that present higher impacts, Stratospheric ozone depletion (114.4%), Freshwater ecotoxicity (251.3%), Human non-carcinogenic toxicity (103%) and Land use (125.4%). If we are right and a built square meter of SFH impacts half of the Fossile resource scarcity (50.2%), Fine particulate matter formation (49.5%), Mineral resource scarcity (54.2%) or Terrestrial acidification (45.8%) than that of an apartment in a multifamily building, widely accepted urban policies that defend the idea of a dense, compact city versus scattered SFH are at least challenged. A similar conclusion was reached at a study (Muñiz et al., 2012) using the ecological footprint methodology, including mobility. Concerning Land use and Freshwater ecotoxicity, it is consistent among all scenarios of this paper that use of timber pays its toll at these impact categories. Extracting minerals from quarries (for bricks or concrete) spoils less land and water, in accordance with findings from (Ruokamo et al., 2023). What is efficient for logistics and economy of scale, may not be optimal for biodiversity protection but also exploitation of timber has a scale limit just as not any reforestation sequesters carbon. Some golden rules must be followed to mitigate global warming, recover biodiversity and enhance habitats for all (Di Sacco et al., 2021). Single-family homes studied here suggest better human and ecosystem health than multifamily flats, specially scenarios 1 to 3. The discussion is nevertheless open. However, the standard SFH considered as scenario 0 does not include an underground garage, which is common in the Spanish SFH, as well as in the multifamily building stock. To make the four researched scenarios more comparable, the chosen SC0 also lacked basement, although, when there is one, in average it yields 15% of the results (Hartmann et al., 2022).

Table 3.8. Midpoint impacts comparison between (Izaola et al, 2023) and our research, per square meter of built area.

% variation of Scenario 0, from Izaola et al, 2023	SC 0: Brick	Izaola et al, 2023	Unit	Impact Category
50.2%	446.33	889.30	kg oil eq	Fossil resource scarcity
114.4%	0.00	0.00	kg CFC11 eq	Stratospheric ozone depletion
67.6%	1,292.87	1,913.80	kg CO2 eq	Global warming potential
49.5%	1.78	3.60	kg PM2.5 eq	Fine particulate matter formation
64.3%	148.11	230.50	kg 1,4-DCB	Human carcinogenic toxicity
251.3%	451.33	179.60	kg 1,4-DCB	Freshwater ecotoxicity
88.9%	57.52	64.70	m3	Water consumption
55.3%	2.99	5.40	kg NOx eq	Ozone formation, Human health
54.2%	8.45	15.60	kg Cu eq	Mineral resource scarcity
103.0%	1,898.69	1,842.70	kg 1,4-DCB	Human non-carcinogenic toxicity
54.8%	0.33	0.60	kg P eq	Freshwater eutrophication
2.7%	18.80	703.70	kBq Co-60 eq	Ionizing radiation
36.3%	0.04	0.10	kg N eq	Marine eutrophication
125.4%	44.91	35.80	m2a crop eq	Land use
45.8%	3.99	8.70	kg SO2 eq	Terrestrial acidification

A comparison on scenarios is also possible thanks to (Moňoková and Vilčeková, 2020). The Timber and Brick buildings in this research reduce impacts of the three comparable categories as can be seen in Table S7 of the Supporting information file. However, the Straw and Earth buildings present too large variations due to different approaches to the technique and main material. Comparability is difficult due to differing research conditions.

One limitation of this article is that ReCiPe (and other methods such as Impact2002+) do not take social preferences into account when calculating DALY. In contrast, Eco-indicator 99 and other methods do consider them, although they are culturally influenced. Also, the DALY compound of "years lived with disability" has very different implications in Europe or other parts of the world. Further research could integrate Social LCA with HH impacts such as DALY. This reinforces the idea that biodiversity studies should enter and reframe environmental impacts of buildings. This is aligned with (Frischknecht et al., 2016) in suggesting to explore the sensitivity of LCA results to metrics other than GWP. GWP can act as spearhead for other indicators. This article has aggregated common metrics (5 ecotoxicity-related at Midpoint, and 12 species.yr-related and 8 DALY-related, at Endpoint) that present different weights. It can be seen that Terrestrial ecotoxicity (average 76%), Land use (average 39%) and Fine particulate matter (average 35%) carry the heaviest loads at Ecotoxicity, Species lost and DALY, respectively. In the case of Land use, the importance of forestry (Timber house), cereal crop (Straw house) and cotton crop for the insulation of the Earth house can be seen in scenarios 1-3. The global warming impact on HH at Endpoint has a high average weight (31%) showing the connection of GWP with biodiversity and health. More details appear in Table S2 of the Supporting Information file. All IPBES data mentioned in the introduction of this research are confirmed here. Authors expect these results to support IPBES and IPCC interactions.

Research on the links between LCA and biodiversity at buildings lacks both baselines and Reference Situations (RS), and this article advances on this. Baselines are used in LCA for specific purposes, whereas RS reflect, often at an aggregated level, social preferences related to biodiversity. We agree with (Vrasdonk et al., 2019) that RS for biodiversity in LCA, based on biodiversity targets which are aligned with society's conservation frameworks, could give decision-makers tools to reduce the impacts of buildings. However, we disagree with (Curran et al., 2010) about the value of the shortcomings of these models, and consider that metrics such as those provided here give meaningful Mid- and End-point indicators on biodiversity impacts. We aim to raise awareness, such as the popular image of the orangutan habitat destroyed by the palm oil industry. Average citizens may not know the figures of 0.0035 species.yr lost and 0.0302 DALY (11 days) of 1 ha of palm trees (Obaideen et al, 2019), but if possible, choose food without palm oil. Taking this as an example, we can figure out that an equivalent built surface (1 ha or 55 conventional SFH) impacts with 0.0067 species.yr and 33.756 DALY, almost twice as much ED and more than one thousand times HH damage than palm oil. Will knowing this drive low-impact building decisions?

This research understands that housing is just one of many areas of impact of human activity, with a limited share, even in Europe, representing only 26% of EU consumption (Sanyé-Mengual et al., 2023), including appliances and household goods; the main share being food (58%) and not forgetting mobility (16%). Awareness of biodiversity damage should include all consumption areas, not only those of Europeans, and be done per capita. In fact, we should include hidden energy flows from other world regions (Akizu-Gardoki et al., 2021). Moreover, direct electricity consumption in houses only accounts for 3.6% of the total national energy footprint, so indirect energy consumption and their respective environmental impacts need to be taken into account. Global impacts such as GHG emissions or marine acidification and eutrophication should not distract us from very unequal local differences (Andersen et al., 2022).

There is a particular penalization on the rammed earth house that is fair to describe. It is unlikely that Ecoinvent's inclusion of cotton fiber flows in the LCA bill of materials comes as a first-hand product from the global market, but rather as a local reused by-product. If this were the case, burdens would actually become negative, and calculated impacts such as water consumption, marine and freshwater eutrophication, land use and fine particulate matter formation would be reduced. In addition, because the site contained radon gas, extra membranes were laid, something that the other scenarios lacked. Other studies on earthen materials (Ben-Alon et al., 2019), (Ben-Alon and Rempel, 2023), (Ajabi Naeini et al., 2021) suggest that their impacts are significantly smaller than those calculated here. However, the energy performance of this scenario as energy positive is confirmed by other studies (De Masi et al., 2021), (Lamnatou et al., 2019).

Although earth-based buildings in Spain have a long tradition, straw-bale ones were introduced in the second half of last century. However, they are gaining attention, both from the market and from scientists. There are several techniques to implement straw as structural and insulation material, and Scenario 2 cannot represent all techniques, but still, it shows results in line with other studies in Spain (Revuelta-Aramburu et al., 2020), and far beyond (Li et al., 2021). However, 75% of the total weight of Scenario 2 is the concrete slab. Cement is still very present in all scenarios, showing its highly relevant impacts. The importance of specific materials can be seen in Tables 3.5, 3.7 and 3.8 above, but a substitute of cement is still largely missing. The cement industry is optimistic in relation to its challenges, but its transformation still needs to happen if it means to continue (Cembureau, 2021).

CONCLUSIONS AND POLICY IMPLICATIONS

This article shows that biodiversity impact indicators deserve greater understanding and attention in the building industry. The industry has studied its contribution to Global warming, but other Mid- and End-point impacts found in the literature review are minor. However, Terrestrial ecotoxicity, Land use and Fine particulate matter formation seem highly relevant, and are studied here. Spanish Single-Family Homes (SFH) emit 1.16 Gt CO2eq to the atmosphere in a 50-year life cycle, of which 39.9% is embodied in the building materials. They also impact land, water and human health with 10.2 Gt 1,4-DCB, 8.8 times more than the GHG emissions. In addition, they drive 6,052 species extinct, and are responsible for 3.03 M years of life lost due to premature death or living with a disability. Divided by the 16 M people living in the Spanish SFH stock, each inhabitant lost 0.19 DALY; or 68.1 days of their lives lost. We authors are concerned that health policies disconnect human health from ecosystem health, and propose including biodiversity metrics alongside climate metrics in buildings and other industries. Overarching policies would address the habitability of all species.

When compared to the base scenario on a per m2 basis, we found that the Earth house emitted 19,10% GHG, the Straw home had 41.71% embodied carbon, and the Timber SFH depleted 59.73% mineral resources of that of the Brick house. Comparing Endpoint indicators with Scenario 0, the Earth SFH depleted 9.61%, the Straw house three water consumption impacts averaged 10.86%, and the Timber home carcinogenic effect was 33.93% than that of the Brick SFH. However, on average, the three low-impact scenarios are 140% worse in land use and 323% in marine eutrophication impacts on species than the Brick home. On average per m2, the Timber scenario impacts, excluding these two, are 57%, the Straw scenario 60%, and the Earth scenario 44%, that of the base scenario. Concerning only ecotoxicity, the results are 48.11%, 55.58% and 47.09%, respectively. Regarding biodiversity loss the impacts are 69.10%, 67.42% and 41.38%, those of the Brick house. Human Health damages of the Timber home are 64.17%, of the Straw SFH 61.96%, and of the Earth house 46.63% that of the Brick Scenario. But if the best solutions of the three low-impact scenarios are chosen, Midpoint impacts can be reduced by 43% and Endpoint impacts by 40% that of the Brick scenario. Species lost would be reduced by 56% and DALY by 47%. This means that biodiversity impacts of buildings can be reduced by half. We authors recommend policy makers to develop building benchmarks in this direction.

ACKNOWLEDGMENTS

The authors are grateful for the support provided by Life Cycle Thinking Group (LCTG) with the grant funded by the University of the Basque Country (GIU21/010).

9. Resultados

9. RESULTADOS

Los resultados logrados por esta tesis se pueden agrupar en tres ámbitos:

1. La contribución de los sistemas de certificación de la sostenibilidad de edificios en la descarbonización se ha corroborado en dos sentidos. Por un lado, hay una contribución directa, a pequeña escala, gracias a un número limitado (<1% anual de la obra nueva) pero significativo de edificios de bajo impacto ambiental. Por otro lado, indirectamente, los gestores de certificaciones ejercen un liderazgo en sus respectivos sectores nacionales, y a escala Europea, apoyando, por ejemplo el Marco Level(s). También en su papel consultivo en la elaboración y testeo de normativas, herramientas, estándares y marcos de reporte, como Level(s). Este conjunto de buenas prácticas, recomendaciones y directivas tracciona al sector en los estados miembros, por ejemplo, redactando hojas de ruta de la descarbonización. La tesis analiza cómo cinco certificaciones contribuyen para descarbonizar el sector, implementando ACV cumpliendo entre otros el indicador 1.2 del Marco Level(s) sobre potencial de calentamiento global. Su grado de cumplimiento es: HPI 19%, VERDE 30%, NF HQE 62%, DGNB 69% y BREEAM NL 100%.

2. Se han analizado diferentes aplicaciones de ACV en la edificación y se ha encontrado que cuando se aplica a escala parque edificado, se generan datos como el promedio de emisiones de los edificios residenciales colectivos, en el caso español, de 1.944 kg CO2eq/m^2. Estos datos resultan útiles en la generación de políticas. Así, se han estudiado las características del parque español de edificación residencial colectiva, se ha identificado una tipología representativa del parque, se ha conseguido un proyecto arquitectónico real, se ha modelado en ACV y se han calculado sus emisiones de carbono equivalente. Basado en buenas prácticas, recomendaciones y disponibilidad de mercado, se ha modelado el mismo edificio con elementos de menor huella de carbono y se han comparado las reducciones. Con ambos conjuntos de datos, los del edificio representativo y los de los escenarios mejorados, se han propuesto valores de referencia y valores límite del potencial de calentamiento global de un apartamento medio. Como resultado principal, se constata que los apartamentos españoles pueden reducir a un tercio su huella de carbono, hasta un valor de 543 kg CO_2eq·m^{-2} embebido y 202 kg CO_2eq·m^{-2} operativo.

3. Se ha aplicado igualmente ACV al parque español de viviendas unifamiliares. Se ha ampliado el foco de atención en las categorías y puntos de la cadena causa-efecto de impactos que evalúa el ACV. Si el ámbito de los apartamentos se focalizaba en la huella de carbono y el consumo energético, en el de las unifamiliares se amplía para incluir la ecotoxicidad, la pérdida de biodiversidad y el daño a la salud humana. Esta ampliación de foco resulta novedosa en los estudios de los impactos de la edificación con ACV. Como resultado principal, eligiendo técnicas y materiales locales y naturales, se constata que es posible construir viviendas unifamiliares con 76% menos emisiones de carbono, 59% menos pérdida de biodiversidad y 67% menos daño a la salud humana que la edificación convencional, con el caso de la vivienda de tierra apisonada.

Ahondando en el primer ámbito, se ha comprobado aplicando ACV a edificios con diferente sistema estructural y material principal que el carbono incorporado en la etapa de construcción del edificio varía hasta un 1044% dependiendo de la estructura (Pomponi and Moncaster, 2018). Solo 2 de los 15 estudios de ACV sobre edificios analizados con respecto a edificios de apartamentos incluyen todas las etapas reconocidas en el estándar EN15978. Todos ellos analizan sólo los indicadores de potencial de calentamiento global y recogen solo la parte calefactada o los elementos estructurales y cerramientos del edificio. Aunque el estándar es indiscutible, la disponibilidad de datos y los intereses previos limitan la aplicabilidad del ACV. Por otro lado, el enfoque progresivo de los sistemas de certificación, que reconoce por medio de puntos o calificaciones ser un poco, algo o muy sostenible, oscurece la efectividad del propio sistema, que resulta tanto más útil cuanto mejor calificación obtiene el edificio, o en el caso de quienes atienden por primera vez a los asuntos de sostenibilidad en la edificación, como puerta de entrada en el asunto. Esto no excluye que sistemas como BREEAM cumplieran al 100% ya en 2020 los requisitos para el indicador de GWP, o DGNB o NF HQE al 60%. Pero de 9 criterios que aparecen en la Tabla 1.6 sobre el cumplimiento de los sistemas de certificación con Level(s) y por tanto con la EN15978, el irlandés HPI y el español VERDE incumplían 7 en 2021. El *gap-analysis* realizado y las propuestas de resolución incluyen estandarizar el periodo de referencia de ACV a 50 años, incluir las etapas A, B y C, así como todos los materiales del edificio, calcular los indicadores de acidificación, ozonificación, agotamiento de recursos y huella hídrica, y extender el de GWP más allá de lo relacionado con el consumo energético, a los cambios de uso de la tierra. De todo esto lo que más efecto tiene es que se complete el ciclo de vida (etapas, A, B y C). Así sucede en el caso de los apartamentos estudiados aquí, aunque falta el módulo B4 o se deja fuera el 1% de los materiales. Sin embargo, no incluir la etapa de uso, por ejemplo, deja fuera más de la mitad de los impactos y resta valor a la aplicación de ACV.

Con una penetración de los edificios certificados menor al 1% del total construido (más de 7.000 edificios en 2020, como se observa en la Tabla 1.1), aunque en crecimiento, los sistemas de certificación, salvo en sus calificaciones óptimas, tienen una contribución baja, pero significativa, en la reducción de los impactos de la edificación. Ocurre algo similar con la política de las clases energéticas en la EPBD, que admite la clase E con un valor de emisiones de 42 kg CO_2-eq·m^{-2}·y^{-1} (2.100 kg CO_2-eq·m^{-2}·en un ciclo de 50 años) muy por encima del valor de referencia estudiado en los apartamentos de esta tesis. También, una reciente publicación (Capeluto, 2022) critica la eficacia real de las certificaciones y argumenta que la unidad funcional por m^2 es menos sostenible en términos de equidad que la per cápita. Esto se ha realizado en las viviendas unifamiliares, y concuerda con esta crítica, pero se ha dejado para una posterior publicación. En cualquier caso, los edificios de los escenarios menos contaminantes analizados en esta tesis cuentan con certificaciones VERDE, PassivHaus o de Edificio de Energía Positiva, y efectivamente contribuyen de manera significativa en la reducción de sus impactos cuando se comparan con su correspondiente escenario base, como se detalla para los resultados en vivienda unifamiliar.

Por otro lado, para analizar las contribuciones indirectas de las certificaciones en la descarbonización del sector, se han aplicado métodos cualitativos, singularmente el de la Perspectiva Multinivel. La adaptación del tema al método produjo las tablas 1.2 y 1.5, y las figuras 3 y 3. La figura 3, adaptada de (Rip and Kemp, 2000) identifica cómo las innovaciones a gran escala se reproducen a lo largo del tiempo en escalas menores pero de mayor eficacia transformadora. Así, artefactos de escala intermedia como el ACV, con el tiempo definen estándares que terminan caracterizando un sector como ocurre con la EN15978. O marcos como Level(s), de alcance intermedio entre las certificaciones y las estrategias políticas, con el tiempo definen patrones estructurales, como está sucediendo con el New European Bauhaus. La perspectiva multinivel aplicada aquí da como resultado proponer a los sistemas de certificación un camino de transición hacia la plena incorporación del marco Level(s) en seis pasos:

1. Las certificaciones evalúan la sostenibilidad de los edificios pioneros;
2. Los agentes pioneros en sostenibilidad dentro del sector se fusionan bajo políticas energéticas, de cambio climático y economía circular aplicada al sector;
3. Los avances energéticos, climáticos y de circularidad del sector de la construcción en Europa interactúan entre sí;
4. Aumenta la demanda de materiales de construcción fabricados en el mercado europeo bajo los citados avances;

5. Las inercias sectoriales nacionales (pero también los avances) mantienen (y también inspiran) objetivos más importantes a nivel político de la UE;

6. El resultado son sistemas de evaluación de la sostenibilidad de los edificios más ambiciosos y generalizables, con el marco Level(s) y el enfoque de ciclo de vida plenamente integrados.

Con respecto a los resultados en apartamentos, la búsqueda de valores de referencia (baselines) y valores límite (benchmarks) de diversos indicadores de impacto ambiental es objeto de investigación y desarrollo normativo. Además de los estudios revisados referidos a edificios residenciales colectivos, otro más reciente concreta valores para diversas tecnologías energéticas en la ruta de la descarbonización (Vallejos et al., 2023). El debate sobre la amplitud de estos valores continúa abierto, y la opción de esta tesis es aportar el mayor grado de segregación de datos, expresando el incorporado en los materiales (EC), el operativo derivado del consumo energético (OC) y la suma de ambos (WLC). En la edificación convencional el OC representa el 67% del WLC, pero si las políticas de descarbonización de la energía se cumplen, el EC cobraría mayor relevancia. Así, se pasaría de un GWP actual del apartamento medio español con EC 528 kg CO_2-eq·m^{-2}, OC 1.386 kg CO_2-eq·m^{-2} y WLC 1.914 kg CO_2-eq·m^{-2}, a un apartamento descarbonizado energéticamente, con EC 543 kg CO_2-eq·m^{-2}, OC 202 kg CO_2-eq·m^{-2} y WLC 745 kg CO_2-eq·m^{-2}. Se observa que el incorporado crece un 3% y el operativo se reduce un −86%. Esto es debido a que la eficiencia energética cuesta emisiones en forma de una envolvente del edificio con mejores prestaciones. Pero con medidas más ambiciosas, principalmente aumentando el uso de la madera y reduciendo el del hormigón armado, es factible limitar la EC a 500 kg CO_2-eq·m^{-2}. El consumo energético puede bajar gracias a la reducción de la demanda, por medio de medidas de eficiencia y renovables, pero resulta complicado alcanzar el edificio de cero energía en residenciales colectivos. No así en viviendas unifamiliares, como se demuestra en el siguiente ámbito, en el escenario de la casa de tierra y madera, que sigue el modelo de los Edificios de Energía Positiva, produciendo más energía renovable local que la que consume.

Puesto que herramientas de cálculo de ACV como OpenLCA proporcionan el árbol de contribuciones de cada flujo de materiales de entrada y salida de cada indicador, el GWP resultante se puede caracterizar en más detalle, como aparece en la tabla 2.6. Se ve que la electricidad contribuye entre el 55% y el 24% del GWP de los escenarios propuestos. El gas natural llega a contribuir otro 24%. El cemento se sitúa entre el 16% y 6% y el acero de refuerzo entre el 15% y el 6%. El ladrillo entre el 11% y el 4%. La instalación fotovoltaica contribuye con otro 6%. Las tablas S9 a S12 del material suplementario muestran otra división de resultados útil para la toma de decisiones, aportada por OERCO2, una herramienta mucho más sencilla, online, pero de menor alcance. Como media modelar y obtener resultados del mismo edificio requirió 4 horas en OpenLCA y apenas 15 minutos en OERCO2. Esta aplicación específica del sector español detalla el GWP, además de por familias de materiales, asimilable a los flujos de OpenLCA, por capítulos de obra. El 30% del GWP se lo lleva el capítulo de estructura, el 21% los muros y particiones de ladrillo, el 11% la cimentación, el 8% la nivelación del terreno, el 7% el abastecimiento de agua y el 6% la instalación eléctrica.

La Tabla 2.7 muestra 19 indicadores ambientales, permitiendo ponderar el de GWP respecto a los demás de impacto intermedio, y ver sus respectivas variaciones a lo largo de escenarios progresivamente más sostenibles. En la Figura 9 se observan estas variaciones porcentuales respecto al escenario base, un edificio de 14 apartamentos del año 2013, con superficie total 1700 m^2, superficie media por apartamento 73,1 m^2, y características constructivas convencionales. El comportamiento es muy desigual por indicadores. Por escenarios se reconoce un patrón tanto más extremo cuanto más sostenible es el escenario (la línea granate con ventana de madera en vez de aluminio, suelo de madera en vez de gres, aislamiento de corcho en vez de lana de roca y además cumpliendo el estándar de edificio de energía casi nula según la EPBD en la zona climática B). Por indicadores sólo aumenta (14.9%) el potencial de toxicidad de agua potable (Freshwater ecotoxicity) debido a la instalación fotovoltaica del Escenario con las tres mejoras de material y estandar NZEB. Este escenario reduce los impactos una media de −50% respecto a los del Escenario base; el Escenario con las tres mejoras de material pero sin estándar de energía casi nulo reduce los impactos un −33% y el Escenario 1 un −25%. La reducción provista cuando sólo se cambia el suelo es despreciable. Hay tres categorías de impacto con reducciones por encima de −80% en el mejor escenario. Otras siete causan reducciones de entre el −60% y el −80%. Entre estas categorías se encuentra la de GWP, que respecto a los Escenarios con ventana de madera, con suelo de madera, con aislamiento de corcho y combinando esas tres mejoras, reduce un −26%, 0%, −15% y −46%, respectivamente. Las medidas que caracterizan los escenarios, inicialmente pensadas para reducir la huella de carbono, resulta que tienen mayor efecto en otras categorías.

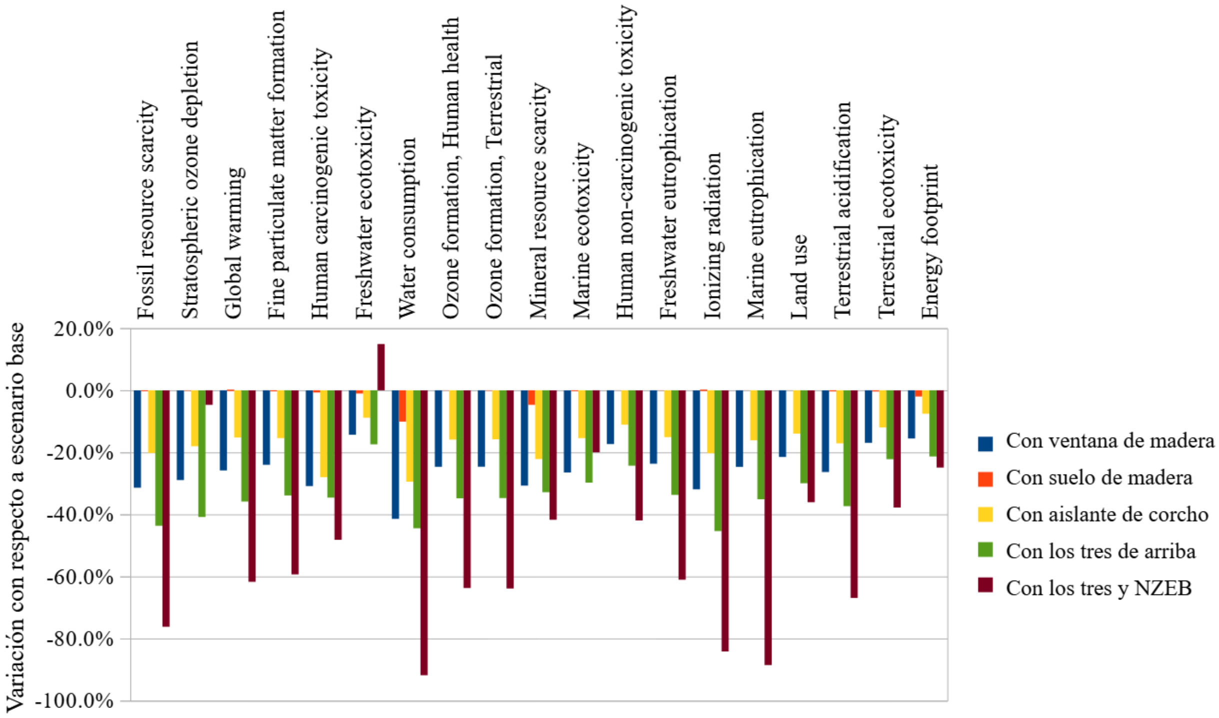


Figura 9. *Reducción de los impactos respecto al Escenario base de apartamentos, en las 19 categorías de impacto ambiental analizadas para los escenarios de mejora.*

El tercer grupo de resultados analiza los edificios con la metodología ReCiPe 2016 (h) en puntos intermedios y finales. Esto entrega en los puntos intermedios de impacto ambiental 18 categorías (la energy footprint de la figura 0.3 proviene de su método específico), de las cuales 15 están medidas en kg de diversos elementos químicos. Las cinco relacionadas con ecotoxicidad (carcinogénica y no carcinogénica, del agua dulce y marina, y terrestre) tienen la misma métrica en kg 1,4-DCB (diclorobenceno), un compuesto químico habitual en disolventes, desodorantes e insecticidas, que también aparece en la industria de la construcción para la conservación de la madera, para desencofrar hormigón, y en adhesivos, selladores, pinturas y revestimientos. En todos los escenarios de apartamentos y unifamiliares hay más kg 1,4-DCB de ecotoxicidad terrestre que kg CO_2-eq de potencial de calentamiento, un 287% más de media. Sumadas las cinco ecotoxicidades, un 429% más que el GWP. Un kg de 1,4-DCB pesa lo mismo que un kg de CO_2-eq, pero la interpretación sobre el valor ponderado de estos pesos queda abierta para futuras investigaciones.

Esta tesis ha innovado en el uso de ReCiPe en los 22 puntos finales de la cadena causa-efecto, allí donde se producen los daños reales, sobre el ser humano, sobre otras especies, o sobre el coste del agotamiento de recursos. Esto no se había encontrado en la revisión bibliográfica, con la excepción de (Brachet et al., 2019) aplicado a tejados, con el único indicador de pérdida de biodiversidad. A nivel de materiales (madera, tejas cerámicas) y componentes (paneles fotovoltaicos) también se han encontrado impactos finales sobre la salud humana. Pero no se han encontrado más estudios sobre impactos en punto final de edificios con ACV y foco en biodiversidad y salud. OpenLCA incluye un método ReCiPe a este nivel, que devuelve 22 categorías de impacto expresadas con tres métricas.

Se trata de la extinción de especies por año «species.yr», de los años de vida ajustados por discapacidad «DALY» y del coste en dólares ajustados al valor de los recursos en 2013, «USD2013», que representa los costes adicionales necesarios para la futura extracción de recursos minerales y fósiles. La extinción de especies cuantifica el impacto potencial de la actividad humana sobre la abundancia de especies durante un período específico. Se usa en 12 de las 22 categorías de impacto. DALY es una medida de enfermedad que considera los años de vida perdidos debido a la muerte prematura de los seres humanos por enfermedad, más los años de vida sana vividos con una discapacidad. Tanto la enfermedad como la discapacidad son consecuencia de las eco-toxicidades, acidificaciones, eutrofizaciones, ozonizaciones, producción de partículas en suspensión, radiaciones ionizantes y también del calentamiento global trazados desde los puntos intermedios con otras métricas. DALY se usa en 8 de las 22 categorías de impacto. Ambas métricas permiten una comparación cuantitativa de procesos o productos en términos de su impacto en la biodiversidad. La métrica en dólares (2 de 22 categorías) caía fuera del ámbito de esta investigación.

La Tabla 3.2 compara la variación de impactos en viviendas unifamiliares de paja, madera y tierra apisonada con una vivienda unifamiliar ejecutada en hormigón armado y ladrillo, la misma solución constructiva que en los edificios de apartamentos, aunque con diferencias debidas a la escala. Hay procesos y técnicas auxiliares de construcción no equiparables entre un edificio de 1700 m^2 con 14 apartamentos y en una zona urbana de alta densidad como el considerado representativo para el parque residencial colectivo español, con un chalet de 151 m^2 en la periferia suburbana, como el considerado representativo para la vivienda unifamiliar española. Esta tabla 3.2 compara el GWP y las cinco ecotoxicidades que operan en los puntos intermedios, y las métricas agregadas de «species.yr» y DALY que operan en los puntos finales de impacto ambiental. La Figura 0.4 muestra la reducción de impactos en estas cuatro categorías, a lo largo de los tres escenarios de vivienda unifamiliar, en comparación con su escenario base, un chalet construido con estructura de hormigón armado y cerramientos de ladrillo. La línea amarilla representa el chalet de tierra apisonada, que reduce un −81% el GWP del escenario base, un −46% las ecotoxicidades, un 59% la extinción de especies y un 67% el daño a la salud humana. La media de reducción del chalet de paja (línea roja) es de −33% y la del unifamiliar de madera (línea azul), de −37%, ambos respecto al escenario base.

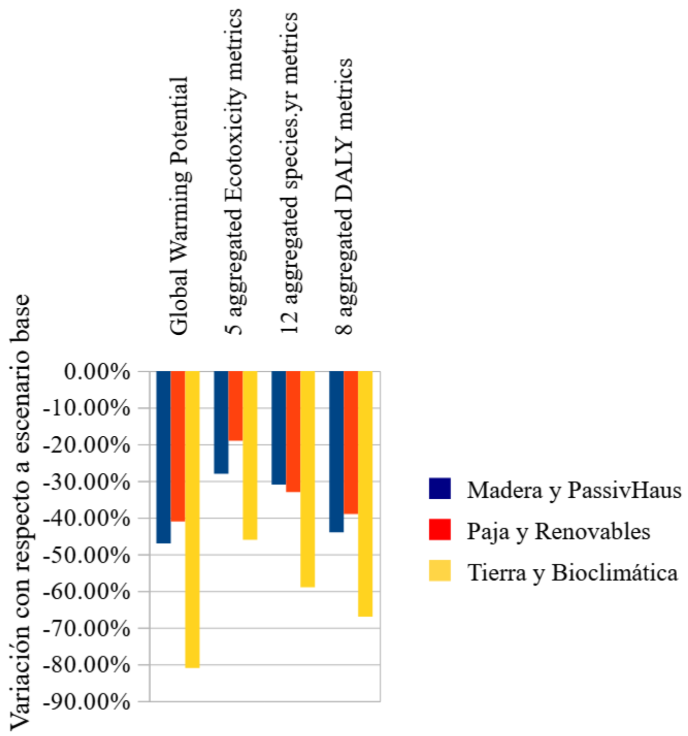


Figura 10 Reducción de los impactos respecto al escenario base de vivienda unifamiliar, en las 4 categorías de impacto ambiental analizadas para los escenarios de mejora.

Pero el objetivo de clarificar cuáles son los impactos ambientales más relevantes de la edificación, y cuál es la posición de la huella de carbono entre éstos, permanece sin responder sólo con la comparativa entre escenarios. Es necesario profundizar en los valores absolutos de cada caso para comprender dónde están los impactos y para priorizar posteriormente, de manera coherente, las decisiones más respetuosas con el medio ambiente. Así, las Tablas 3.4, 3.5, 3.6 y 3.7 recogen los árboles de contribución de los flujos principales de cada indicador, GWP, ecotoxicidad terrestre, cambios de uso del suelo y producción de partículas finas (PM2.5) en suspensión, estudiado en las viviendas unifamiliares.

El carbono operativo contribuye de media con el 64% del GWP de las viviendas unifamiliares convencional, de madera y de paja. Como se ha dicho, el chalet construido en tierra apisonada tiene un comportamiento distinto en este ámbito debido a que sigue el modelo de edificio de energía positiva. Pero se ve en la mencionada Tabla 3.4 que el siguiente mayor contribuyente es el cemento, con una media del 12%, seguido por la instalación fotovoltaica donde la hay, con un 7% (15% en el chalet de tierra apisonada para conseguir el excedente de producción requerida por el modelo). Ningún material tiene cero impacto, ni siquiera los marcos de madera de las ventanas, con una contribución media del 3%. Pero comparados con un marco de aluminio con las mismas prestaciones, el de aluminio tiene un GWP 395% mayor que el de madera.

La ecotoxicidad terrestre supone el 76% de las cinco ecotoxicidades. Los productos que contienen cobre ocupan un lugar destacado en este indicador como se ven la Tabla 3.5. El cableado eléctrico aparece como el principal componente tóxico de la construcción con una contribución media del 49%. Cuatro procesos (de un promedio de 55 en su árbol de contribuciones) suman un peso medio del 86% del indicador, a saber, el mencionado cableado, la producción de electricidad (23%), la instalación fotovoltaica donde la hay (18%) y los colectores termosolares donde los hay (11%).

Los cambios de uso del suelo suponen el 39% del peso conjunto de los 12 indicadores relacionados con la pérdida de biodiversidad, medidos en «*species.yr*». La característica constructiva de cada escenario se lleva la mayor parte de este indicador, porque la madera contralaminada, sólida, estructural o en paneles, presente en todos los edificios unifamiliares, ocupó durante el crecimiento del árbol un suelo forestal, desnaturalizado aunque boscoso. Siguiendo la Tabla 3.6, en la unifamiliar de madera contralaminada, los paneles de fibra orientada, los marcos de las ventanas y el parquet del suelo, todo de madera, suman el 86% de este indicador, aunque su valor absoluto de extinción de especies reduzca un −31% el del Escenario base. En la unifamiliar de paja, la cosecha de paja también contribuye con un 10% en este indicador, y en la vivienda de tierra apisonada el aislamiento de algodón contribuye con un 7%. En el Escenario base de ladrillo y hormigón, estos materiales, proviniendo de canteras y minas también suman un 30% en la pérdida de biodiversidad por cambios de uso del suelo.

La producción de partículas finas en suspensión pesa el 35% de los 8 indicadores con métrica DALY. Las PM2.5 entran en los pulmones y en el torrente sanguíneo, se consideran carcinogénicas y no carcinogénicas, y se estima que son causa de la muerte de 7 millones de personas al año y de graves pérdidas en especies vegetales y animales (Rajpoot & Lego, 2018). Son una de las principales características del aire contaminado y proceden de la combustión, de la industria química y siderúrgica y del machacado de roca para la producción de áridos y cemento. En la Tabla 3.7 se ve que están presentes en todos los procesos de elaboración de materiales de construcción, cuanto más elaborados, más. Pero hay mucho margen de mejora de la construcción convencional, como demuestran las reducciones de DALY del −44% de la unifamiliar de madera, de −39% de la de paja y de −67% de la de tierra apisonada.

9.1 Discusión

Con una penetración de los edificios certificados inferior al 1% del total construido, aunque en crecimiento, los sistemas de certificación, salvo en sus calificaciones óptimas, tienen una contribución baja, pero significativa, en la reducción de los impactos de la edificación. (Capeluto, 2022) critica la eficacia real de las certificaciones y argumenta que la unidad funcional por m^2 es menos sostenible en términos de equidad que la per cápita. Los edificios de los escenarios menos contaminantes analizados en esta tesis cuentan con certificaciones VERDE, PassivHaus o de Edificio de Energía Positiva, y efectivamente contribuyen de manera significativa en la reducción de sus impactos cuando se comparan con su correspondiente edificio de referencia.

En la primera parte de esta tesis se observa que las transiciones ecosociales son largas y suponen cambios de régimen y de paisaje conceptual, pero también se indican los nichos que están impulsando esa transición, aunque las rutas no sean claras, y las certificaciones parecen ejercer un papel en este sentido. Precisamente la profusión de hojas de ruta para la descarbonización del sector es el intento corporativo, profesional y científico de avanzar en la transición, liderado por los gestores de sistemas de certificación. El análisis del cumplimiento de los cinco principales sistemas de certificación europeos respecto a Level(s), en las tablas 1.6, 1.7 y 1.8 muestra que las exigencias mínimas de los sistemas de certificación están muy por debajo de los valores de referencia resultantes del ACV aplicado a edificios de apartamentos.

El sistema de certificación francés no exige directamente un valor de referencia, pero se remite desde 2022 a la legislación francesa RE2020 (Décret no. 2021-1004, 2021). El sistema irlandés exige que los edificios tengan una huella de carbono por debajo de 300 kg $CO_2eq \cdot m^{-2} \cdot yr^{-1}$, lo que en un ciclo de vida de 50 años equivale a 15.000 kg $CO_2eq \cdot m^{-2}$, muy por encima de los 1.298 kg $CO_2eq \cdot m^{-2}$ homogeneizados para Europa en la tabla 2.1. En el caso de la certificación española, sus 2.000 kg $CO_2eq \cdot m^{-2}$ se encuentran ligeramente por encima de los 1.944 kg $CO_2eq \cdot m^{-2}$ calculados para la edificación residencial colectiva nacional. El sistema alemán, con 900 kg $CO_2eq \cdot m^{-2}$, se encuentra dentro de las buenas prácticas, y el holandés, con una horquilla entre 750 y 1.750 kg $CO_2eq \cdot m^{-2}$, valida tanto el mejor escenario de apartamentos como el valor de referencia de la edificación convencional española. Esta variedad de resultados en la primera parte de la tesis alimentó la decisión de continuar desarrollando una propuesta de valores límite de Potencial de Calentamiento Global de la edificación residencial española.

Gracias a la aplicación de la metodología de la Perspectiva Multinivel se han identificado vectores clave de la transición hacia la sostenibilidad del sector en la escala política, sectorial y social. Los edificios son factor de cambio climático y tienen potencial de mitigación y adaptación. Un dato clave que hay que tener muy en cuenta es el 8% de contribución de la fabricación mundial de cemento en las emisiones mundiales de GEI (Sverdrup & Olafsdottir, 2023). Limitando la obra nueva en favor de la rehabilitación, diseñando en clave bioclimática, reduciendo la demanda energética de los edificios mediante una envolvente de altas prestaciones, favoreciendo el uso de materiales locales, de baja transformación y de origen natural, y educando en el uso eficiente de las instalaciones se puede eliminar el 60% del daño ambiental provocado por los edificios. Pero es necesario mejorar la calidad de los datos aumentando el número de productos de construcción con declaración ambiental (ecoetiqueta 3), la formación de profesionales expertos, la valoración de la descarbonización dentro de la sostenibilidad y las incoherencias del sector.

Los resultados por caso y característicos del parque edificado o de los edificios convencionales han aportado un conocimiento de mayor calidad al de los estudios de referencia en esta tesis (Röck et al., 2021), (Lavagna et al., 2018), (Oneclick LCA, 2021), (Moňoková & Vilčeková, 2020), (Arduin et al., 2022), (Fernandes et al., 2019), (Muñoz et al., 2023), gracias a la inclusión de todos los módulos de la EN15978 excepto el B4 (rehabilitación). Esta investigación se alinea con estudios transdisciplinares muy recientes que conectan el sector de la construcción con las ciencias de ecología y biodiversidad (Brachet et al., 2019), (Bahramian & Yetilmezsoy, 2020), (Ryberg et al., 2021), (Pörtner et al., 2023), (Bhoonah et al., 2023). Los resultados de impacto en punto intermedio y final abren futuras vías de investigación para profundizar más en campos poco explorados como la eutrofización provocada por el saneamiento de los edificios (Kobetičová & Černý, 2019) o los efectos tóxicos para el medio ambiente de materiales de construcción como pinturas, adhesivos y barnices (Rey-Álvarez et al., 2022). Esta tesis está siendo utilizada por el Green Building Council español en su labor de impulsar la sostenibilidad en el sector, en su hoja de ruta para la descarbonización del sector y en el desarrollo de proyectos europeos, como referencia de valores límite para la edificación residencial española

En esta Tesis se han expresado los impactos en una unidad funcional por metro cuadrado (m^2) construido. Pero hay un debate en torno a la idoneidad de referirse a los m^2 construidos, o útiles o calefactados, y el Marco Level(s) se inclina por la superficie útil, que considera también calefactada, al asociar a esta las emisiones operativas derivadas de la calefacción. Para incluir otros impactos además del relacionado con la energía, en esta Tesis se considera la superficie construida, incluyendo espacios no calefactados como garajes, locales técnicos o trasteros, y espacios comunes de paso como escaleras y portales de entrada. Pero más allá de la superficie, las personas habitamos espacios tridimensionales, por lo cual tendría más sentido hablar de m^3, aunque a un volumen no ocupado no se le pueden exigir responsabilidades, y a la persona que lo habita, sí. En las viviendas unifamiliares se han tenido en cuenta los habitantes reales de los chalets analizados y se han realizado los cálculos teniendo como unidad funcional a la persona habitante (per cápita), responsable del uso, desgaste y justificación del espacio construido, edificio con unas funcionalidades para la persona, descansar, trabajar, relacionarse y satisfacer sus necesidades.

Aunque esta métrica per cápita no se ha incluido finalmente en la tesis, estamos de acuerdo con (Capeluto, 2022) que su inclusión hace posible un indicador más justo y relevante para la equidad. En el futuro los autores trazarán una línea convergente con estudios recientes como el de (Vélez-Henao & Pauliuk, 2023) que, partiendo del marco de los «niveles de vida dignos» (DLS por sus siglas en inglés) elabora valores límite de consumo de materiales y energía, y emisiones, requeridos para eliminar la pobreza, per cápita y año. Según este estudio, del umbral de pobreza en huella material calculado en 6 toneladas por persona y año, los edificios son responsables del 98% del peso directo y el sector de la construcción es responsable del 61% del peso indirecto. Queda mucho por investigar sobre el impacto social y per cápita de la edificación, y para ello el ACV social es una herramienta fundamental.

También, en retrospectiva, se ha considerado insuficiente el planteamiento de un periodo de referencia de 50 años para el cálculo del ACV, aunque se ha realizado así a lo largo de la tesis, en consonancia con las recomendaciones del Marco Level(s) y del estándar EN15978. Si bien este periodo es correcto en la asignación de una generación de habitantes al edificio habitado, la realidad, particularmente en España, debido a la pobre cultura de rehabilitación y mantenimiento que tenemos con nuestros edificios, es que resulta improbable encontrar edificios rehabilitados dentro de ese período, lo cual supuso anular el módulo B4 (rehabilitación) de la EN15978 de nuestros cálculos. Pero también, la inclusión de materiales de origen biológico como la madera, el corcho y otras fibras vegetales que han fijado CO_2 en su crecimiento, sugieren períodos de 80 o 100 para el GWP y otras categorías de impacto ambiental. Cuando se contabilizan conjuntamente el CO_2 atmosférico y el CO_2 biogénico, los ritmos de plantación, extracción, uso y desmantelamiento de recursos forestales resultan muy distintos de los ritmos de permanencia del CO_2 y de los otros gases con efecto invernadero relacionados, como el metano y el vapor de agua. Un pinar para hacer paneles de fibra puede completar su ciclo en menos de 30 años, pero una viga de roble ejerce su función perfectamente durante 500.

Si las piezas de madera desechadas se sustituyen en otros edificios o al menos se reciclan dentro del sector maderero para la producción de fibra, pueden persistir durante varios ciclos de vida, restando impactos cuando se aplica el módulo D de la EN15978. Pero si los materiales biogénicos terminan en vertederos, lejos de conservar inerte el carbono, se lixivia o emite en procesos de putrefacción derivados de la compactación, falta de oxígeno y presencia de otras sustancias en los vertederos, cuando no se transforma en metano u otros derivados más contaminantes, sino para la atmósfera, sí para el agua y la tierra, como el amoníaco. Además, la prevalencia media del CO_2 en la atmósfera durante 100 años, que le aporta utilidad como unidad de calentamiento global, está sujeta a ajustes de observaciones científicas y a las interacciones con otros gases a diversas alturas de la atmósfera y condiciones de radiación. Puede estar causando efecto invernadero más o menos tiempo que esos 100 años, y ser demandado antes o después por organismos fijadores de CO_2 a través de la fotosíntesis. Está todo relacionado, pero no depende de los ritmos generacionales de uso de una vivienda. Todo esto sugiere ampliar el periodo de análisis del ACV de 50 a 80 o 100 años, que aseguran una o varias rehabilitaciones y una trazabilidad completa de los materiales biogénicos.

El vínculo entre la edificación y la biodiversidad requiere mayor investigación. Los resultados relacionados con la pérdida de biodiversidad provienen de múltiples e insuficientemente comprendidas interacciones negativas de la ocupación de suelo, la energía y agua requerida para extraer, manufacturar, transportar, colocar y mantener los materiales del edificio, los propios compuestos químicos tóxicos incluidos en estos o necesarios para su elaboración y mantenimiento, así como las emisiones al aire, agua y tierra provocadas por la erección, uso y final de vida de los edificios. La metodología del ACV construye el daño final ejecutado sobre la biodiversidad por las actividades relacionadas con la edificación a través de 12 indicadores con métrica común *species.yr*. El resultado de la extinción de 6.052 especies como consecuencia de la edificación del parque español de viviendas unifamiliares (1,22 especies en los mil adosados que hay en el barrio donde se sitúa la vivienda unifamiliar convencional estudiada) puede resultar difícil de comprender. La multiplicidad de causantes asociados a construir y habitar este tipo de edificación se supone, pero ¿cómo se entiende que una vivienda unifamiliar extinga 0,00121998 species.yr a lo largo de sus 50 años de ciclo de vida? Se cifra en 73 los géneros completos, incluidas 10 familias (6 de mamíferos y 4 de aves) y 2 órdenes (ambos de aves), de vertebrados terrestres extinguidos por la acción humana en los últimos 500 años. Las 34.600 especies (y millones de individuos) que forman estos géneros habrían tardado 18.000 años en desaparecer por causas naturales, sin la presión humana. La tasa de extinción de estos últimos cinco siglos es 35 veces mayor que la media del millón de años anterior. Si la tendencia actual se mantiene, esta tasa podría acelerarse hasta 511 veces para final de siglo, lo que habría requerido 153.000 años en ausencia humana (Ceballos & Ehrlich, 2023). Obviamente todas las actividades humanas además de la construcción deben contribuir en la reducción de esta tasa, pero en esta Tesis hemos visto que podemos elegir construir en tierra apisonada reduciendo el 59% el daño a la biodiversidad de la vivienda unifamiliar de referencia construida con ladrillo y hormigón.

En cualquier caso, resulta evidente que no es suficiente caracterizar la sostenibilidad con un único indicador, y que la tarea de simplificar y estandarizar los modelos de cálculo debe incluir factores relacionados con el objetivo o ámbito de estudio principal. Aunque la complejidad aumente, la identificación de sinergias y rutas de dependencia, como se reconoce en la Perspectiva Multinivel, supera en beneficio a las demás dificultades, y sugiere una mejor comprensión de los fenómenos ambientales estudiados. Solo así es posible tomar las decisiones más apropiadas para este reto. Las futuras áreas de investigación que marca esta Tesis invitan a comparar los impactos sobre la biodiversidad del sector con los de otros sectores, y buscar sinergias. Algunas ya se han señalado, por ejemplo, con el sector de movilidad, el de agricultura y el de consumo, a través de estilos de vida de menor huella ecológica, así como a través de la identificación y asunción de los flujos escondidos por el comercio internacional. La propuesta de valores de referencia y de valores límite acometida para los objetivos de descarbonización marca una metodología a seguir para los objetivos de protección de la biodiversidad, los de cuidado de la salud humana y los de conservación de los ecosistemas.

10. Conclusiones

10. CONCLUSIONES

La primera hipótesis de esta investigación reconocía una falta de referencias sobre las emisiones de CO_2 del sector de la edificación. Aludía a los sistemas de certificación de sostenibilidad de edificios y a sus prácticas ejemplarizantes, que demuestran al sector que es posible edificar reduciendo significativamente las emisiones de carbono y otros impactos. Sin embargo, la descarbonización del sector no partía de unos valores de referencia. Se ha analizado la presencia de estas métricas en cinco sistemas de certificación y la adopción de estándares y metodologías al respecto. El marco Level(s) está impulsando la estructuración de las certificaciones desde el enfoque de ciclo de vida, otorgando centralidad a la norma EN15978 y relacionando resultados de huella de carbono con políticas sectoriales y otras iniciativas reglamentarias o recomendaciones como las que se han resumido gráficamente en la figura 1.

Los Sistemas de certificación conectan Level(s), el mercado, la contratación pública y la sociedad. Adoptan mejores prácticas para proporcionar, junto con la calificación de sostenibilidad, un impulso en la armonización de los datos y del ACV. Sin embargo, su papel dentro de un marco voluntario podría verse cuestionado si aparecieran normas obligando al uso del ACV, como parece querer indicar la Comisión Europea. De momento, estos sistemas están explotando sus nichos nacionales dentro de un ratio limitado pero en constante crecimiento. Para cambiar la trayectoria del sector, además de su papel, sería necesaria una acción sociopolítica como la interpreta la metodología multinivel. Son los habitantes y usuarios de edificios quienes deben exigir un espacio construido sano, sostenible, descarbonizado y protector de la biodiversidad.

Una visión integral de la sostenibilidad de los edificios, incluyendo aspectos sociales, como aparecen en los sistemas de certificación de la sostenibilidad de edificios y en políticas como el Marco Level(s), además de tener un enfoque de ciclo de vida, deberían ponderar de manera trazable sus distintos indicadores como lo hacen los sistemas de certificación. Pero a diferencia de las certificaciones, parece adecuado priorizar diseños bioclimáticos y vernáculos, pues son los que reconocen el valor de los materiales y técnicas naturales y locales. También se debería superar la calificación de las certificaciones, marcar límites claros por encima de los cuales no se permita construir. En este sentido, los valores de referencia son un paso intermedio antes de marcar valores límite, susceptibles de ser adoptados por las políticas sectoriales. Así lo han realizado varios países europeos, y con el objetivo de aportar en esa dirección se ha hecho la propuesta de *benchmark* de 500 kg $CO_2eq \cdot m^{-2}$ para el carbono incorporado en los materiales de construcción de un apartamento medio en un edificio residencial colectivo en España, muy en línea con los *benchmark* de otros países europeos como Dinamarca, Finlandia, Alemania o Francia. Además del uso de valores de referencia y valores límite, esta tesis aprovecha otras metodologías como la aplicación integral de estándares, la comparativa de escenarios y tipologías o el estudio del parque edificado.

Se requieren datos de calidad y armonizados sobre los productos de construcción para que el ACV de resultados agregados y transformadores. Estos son necesarios para cumplir con los requisitos legales y voluntarios actuales y futuros y para fomentar el desacoplamiento del sector de la construcción del consumo actual de recursos y de generación de impactos. El autor de esta tesis sugiere a los proveedores de datos y software que colaboren y faciliten el acceso. Se necesitan expertos y esto requiere políticas de formación acordes con el reto. Según la norma, el ACV de edificios debe seguir un enfoque modular, informando sobre el conjunto completo de impactos y las etapas en las que estos ocurren, para evitar una transferencia de cargas. El ACV debe incluir todos los elementos de construcción. Los demás impactos pueden seguir el indicador de GWP como el más conocido y relevante para el sector en la actualidad. Los impactos de pérdida de biodiversidad, daño sobre la salud humana, ocupación de suelo y uso del agua requieren atención urgente.

El marco Level(s), en su debida conformidad con las políticas europeas, es un poderoso agente de cambio, capaz de afrontar el *greenwashing*, la financiación engañosa y la opacidad de la información, los tres, factores puestos en práctica por parte del sector. Level(s) puede y el autor de esta tesis recomienda que debe, convertirse en herramientas, datos, puntos de referencia y criterios de interpretación generalizados y completos para la transición del sector. Igualmente importante es la transparencia con respecto a los supuestos adoptados al modelar el edificio en el ACV. Para cumplir con la norma EN15978, las herramientas y las bases de datos de ACV de construcción específicas son más útiles para el sector que las herramientas generales. Sin embargo, para profundizar en categorías de impacto, etapas y formulación de políticas más integrales, las herramientas generales como OpenLCA son cruciales, ya que las específicas capan parte de esta información.

La segunda hipótesis de esta investigación sugería que existen materiales y técnicas constructivas disponibles en el mercado capaces de reducir las emisiones de la edificación. Aunque, por razones de mercado, la construcción convencional sigue sin abandonar el ladrillo y el hormigón armado, la tradición preindustrial, los nuevos materiales industrializados y el cálculo con ACV de esta tesis demuestran que introducir fibras vegetales en la edificación reduce las emisiones de carbono. Por otro lado, aplicar la normativa de eficiencia energética, reduce las emisiones aún más.

Esta tesis muestra una reducción del −63% del Potencial de Calentamiento Global (GWP) de un edificio residencial colectivo representativo del parque español, comparado con uno similar equipado con soluciones biogénicas, disponibles en el mercado y que cumplen con la Directiva Europea sobre energía en los edificios (EPBD). El carbono operativo se reduce así en un −85%. Pero el carbono incorporado crece por efecto de las tecnologías de eficiencia y generación de renovables, salvo que se substituyan materiales de alto impacto como el cemento por los de muy bajo impacto, como la madera. La metodología de Análisis de Ciclo de Vida (ACV) aplicada demuestra factible reducir la huella de carbono de la edificación hasta un valor de referencia de 745 kg CO_2eq/m^2 para una vivienda de esta tipología, a 50 años, con suelos y ventanas de madera. Con materiales como la madera estructural, el carbono incorporado se reduce por debajo de 500 kg CO_2eq/m^2. Al descarbonizar el mix eléctrico, se reduce aún más el carbono operativo respecto a la media actual de 1.386 kg CO_2eq/m^2.

Los estándares de edificios de energía casi nula son factibles, viables y pueden reducir el impacto de las viviendas hasta en un −85%. Los mercados y la normativa europea están liderando el camino con medidas para 2030 y 2050, como lo demuestran los casos analizados en esta tesis de los países nórdicos y Francia. En este sentido, las estrategias de rehabilitación son fundamentales. Cualquier reforma o sustitución de materiales que no suponga una renovación profunda (energética y ambiental) del edificio sería una oportunidad perdida para empezar a solucionar la emergencia climática y de biodiversidad. Emplear materiales locales naturales y energías renovables es crucial y urgente. Establecer una cadena de valor para reciclar y reutilizar componentes de construcción al fin de su vida útil es tan necesario como crear estándares de mantenimiento para extender la vida de los productos de construcción. La nueva construcción debería justificarse cuidadosamente, o si no, los nuevos usos requeridos podrían ubicarse en un edificio rehabilitado.

La tercera hipótesis apuntaba a los materiales y técnicas disponibles no convencionales existentes que pueden reducir no sólo las emisiones, sino también otros impactos ambientales importantes de las viviendas unifamiliares. Las técnicas constructivas sostenibles pueden reducir los impactos de emisiones de calentamiento global de la edificaación y otros impactos ambientales como la ecotoxicidad, la pérdida de biodiversidad y el daño a la salud humana. En la construcción de vivienda unifamiliar es factible ir más allá de mejoras en ventanas, suelos y aislamiento, construyendo con paja, madera estructural o tierra apisonada, y atajar los impactos.

Si bien el GWP es un indicador ambiental reconocido, esta tesis también señala otros impactos ambientales de los edificios. El análisis de impactos de ecotoxicidad en el mar, el agua dulce, la superficie terrestre y la salud humana muestran un fuerte envenenamiento de los ecosistemas provocado por los edificios. Construyendo edificios residenciales colectivos con mejores ventanas, aislamiento y suelos no solo se reduce el GWP en un −63% o la pérdida de biodiversidad un -59%, sino también el consumo de agua en un −91%, la eutrofización marina en un −88% o el agotamiento de recursos fósiles en un −76%. El ACV puede establecer valores de referencia para estas y las demás categorías de impacto. Utilizando materiales locales de baja transformación como la tierra apisonada, el carbono incorporado se puede reducir un -44%, la ecotoxicidad un -46%, la pérdida de biodiversidad un -59% y el daño a la salud humana un -67% comparado con una vivienda unifamiliar convencional. El ACV también puede proporcionar datos para otras soluciones ideadas para avanzar en la descarbonización del sector, como la minería urbana, la creación de un banco de materiales y el diseño para el desensamblado. Sin embargo, las diferentes herramientas y bases de datos del ACV necesitan armonización antes de comparar resultados.

Cuando se categoriza al sector de la construcción como un sector difuso, además de reconocer la multiplicidad de procesos, agentes y ámbitos de actuación, se reconoce que también falta una herramienta de análisis de aplicación universal en el sector. Esta herramienta podría ser el ACV. Por ejemplo, del análisis de ciclo de vida de los impactos ambientales de una instalación fotovoltaica dimensionada para llevar un edificio al estándar de energía positiva se desprende que la electrificación renovable y local reduce el indicador de GWP incluso hasta compensar parte del carbono incorporado en los materiales, pero no el de ecotoxicidad terrestre, que requeriría una gran reducción en el uso del cobre, hasta ahora imposible en los sistemas eléctricos. Se contemplan así aspectos arquitectónicos, energéticos, climáticos, de salud e industriales. El enfoque de ciclo de vida puede acompañar al sector a lo largo de sus procesos mejor que el análisis de la cadena de valor.

Del estudio de los impactos sobre la salud en las viviendas unifamiliares se desprende que, además de filtrar el aire interior mediante una ventilación forzada, y vivir lejos de carreteras e industrias, lo cual es difícil generalizar en una población eminentemente urbana como la europea, lo sostenible en este ámbito es utilizar materiales naturales y locales poco transformados. Tres módulos de la EN15978, el A2, el A4 y el C2 recogen los impactos asociados al transporte de materiales en fase de producción, de erección del edificio y de retirada de residuos, respectivamente. Además del impacto asociado a los combustibles consumidos, el desgaste de neumáticos es causa mayor de producción de partículas en suspensión (Järlskog et al., 2022). Por tanto, cuanto menos transporte, mejor.

Las emisiones de gases de efecto invernadero, reconociendo sus graves efectos en las precipitaciones, variaciones térmicas, subida del nivel del mar, y demás riesgos climáticos, no pueden representar por sí solas la complejidad de la sostenibilidad. Tomar decisiones exclusivas de descarbonización puede ignorar otras categorías relevantes de impacto ambiental. Así, electrificar la calefacción y refrigeración de edificios incide negativamente por ejemplo en la ecotoxicidad terrestre por efecto del alto contenido en cobre del material eléctrico, superando en todos los casos estudiados el 80% del peso del indicador. Sin embargo, el reconocimiento público del problema de los GEI debe servir para dar paso a problemáticas insuficientemente consideradas a nivel social, industrial y político, como las relacionadas con la pérdida de biodiversidad. Los fabricantes y constructoras cuidan también su contribución al calentamiento global, pero los otros impactos de punto medio y final de la edificación requieren mayor atención. La ecotoxicidad terrestre, el uso de la tierra y la formación de partículas finas parecen focos de análisis muy relevantes para caracterizar ambientalmente los productos de construcción además de su huella de carbono. Se invita a hacer de la descarbonización la punta de lanza de las medidas de mitigación de los daños de origen antropogénico en la biodiversidad, la ecotoxicidad y la salud de las especies.

10.1 Futuras líneas de investigación

El parque español de viviendas unifamiliares emite a la atmósfera 1,16 Gt de CO_2eq en un ciclo de vida de 50 años, de los cuales el 39,9% está incorporado en los materiales de construcción. Este conjunto de edificios también impacta en la tierra, el agua y la salud humana con 10,2 Gt 1,4-DCB, provocando la extinción de 6052 especies y causando la pérdida de 3,03 millones de años de vida humana por muerte prematura o por discapacidad. Dividido entre los 16 millones de personas que viven en el parque español de unifamiliares, cada habitante perdió 0,19 años; o 68,1 días de sus vidas. Pero si se eligen las mejores soluciones, los impactos se pueden reducir en un −43% de media. La pérdida de biodiversidad se reduciría en un −56% y el daño a la salud humana en un −47%. Pero en los ecosistemas todo está relacionado. Aunque ampliar las categorías de impacto enriquece los puntos de vista, no integra el peso de estos impactos en el medio. Está previsto continuar en esta línea de investigación para comprender mejor el impacto de la edificación en los ecosistemas. La ponderación de indicadores en los sistemas de certificación parte de conocimiento experto, pero el ACV podría aportar otra forma de integrar los impactos en los ecosistemas.

Del análisis de los materiales naturales como los elegidos para los chalets de madera, paja y tierra apisonada se desprende que todo material, por muy natural que sea, impacta en el medio ambiente, y que la sostenibilidad tiene que transitar hacia el diseño regenerativo, recuperando las cubiertas como suelo, en forma de techos verdes, y por utilizar la tierra o la piedra misma del suelo, en forma de muros de carga, pensando en edificios de transporte casi nulo y de mínima transformación material. Esto ya lo desarrolla el diseño bioclimático, presente en los edificios que obtienen la mejor certificación, aunque al traspasar estas mejores prácticas a la normativa y al mercado se pierde su enfoque integrador y se termina exigiendo a un aspecto aislado, como por ejemplo la reducción de la demanda energética, que cargue con todo el esfuerzo de la descarbonización. Está previsto seguir aplicando ACV a edificios diseñados con criterios regenerativos y bioclimáticos para identificar las sinergias y retroalimentaciones positivas de las decisiones de diseño en la reducción final de impactos.

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Anexos sobre información complementaria a los artículos

Artículo 1:

Life Cycle Analysis Challenges through Building Rating Schemes within the European Framework
Autores: Borja Izaola, Ortzi Akizu-Gardoki y Xabat Oregi
Nombre de la revista científica y fecha de publicación:
MDPI, Sustainability, Abril de 2022
Doi: https://doi.org/10.3390/su14095009

No incluía información complementaria

Artículo 2:

SETTING BASELINES OF THE EMBODIED, OPERATIONAL AND WHOLE LIFE CARBON EMISSIONS OF THE AVERAGE SPANISH RESIDENTIAL BUILDING

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Nombre de la revista científica y fecha de publicación:
ELSEVIER, Sustainable Production and Consumption, Julio de 2023
Doi: https://doi.org/10.1016/j.spc.2023.07.001

Article 2 Supporting information contains 11 tables and 2 figures further detailing the main article. Tables 1 and 2 show respectively the homogenized weight and final values of reference and reviewed studies. Tables 3 and 4 elaborate data from official sources to portrait the Spanish residential stock. Table 5 lists the bill of quantities of the building project chosen as representative case study. Tables 6 to 9 contain original results from OERCO2 software, while tables 10 and 11 present Input and Output flows of the building model using OpenLCA software. Figures 1 and 2 outline the selected building floor and main elevation. This building is representative of 20% of the Spanish residential stock. It is an apartments' multifamily building of the years 1980-2010 in Cartagena (Spain).

Table S1. Homogenised average values of the relative weight of stages of EN15978, excluding B5.

Global Warming Potential (GWP) per by Life Cycle Stage (%, percentage)	**A1-3**	**A4**	**A5**	**B1-3**	**B4**	**B6**	**B7**	**C1**	**C2**	**C3-4**
(LETI, 2020)	21.00	2.00	0.50		9.00	66.50		0.33	0.34	0.33
(Lavagna et al., 2018)	21.29	1.00	0.71	1.57		70.41	4.40			0.62
(Hart et al., 2021)	21.93	4.23	3.20			66.67		2.05	1.91	0.01
(World Business Council for Sustainable Development, 2021)		11.95			7.14	80.59			0.32	
Scenario 0	22.24	3.12	1.56	4.40		65.85	1.01	0.75	0.76	0.31
homogenised average	**19.57**	**2.34**	**1.35**	**2.70**	**8.45**	**60.99**	**2.45**	**0.94**	**0.91**	**0.29**
Standard Dev.	0.57	1.40	1.23	2.00	3.88	2.07	2.40	0.90	0.81	0.25

This homogenization process is not the main focus of the article. However, it is a key initial process, solely leading to compare the scenarios modeled in the article against referenced studies. The average percentages deduced in Table S1 are applied to assumptions from the reviewed studies in lines 231-321 of the main text, adding missing EN15078 stages where due. The uncertainty from reviewed studies using different databases is considerably lower than the effect of stages A4, A5, B4, B7 or the whole Module C, which in some cases was not fully considered. Nevertheless, as mentioned and cited from Feng et al.,2022, the range of uncertainty falls within accepted and useful.

Table S2. Whole Life Carbon (WLC) and Embodied Carbon (EC) values per stage of the homogenised reviewed studies in kg CO_2-eq·m^{-2}.

Author	A1-3	A4	A5	B1-3	B4	B6	B7	C1	C2	C3-4	Whole Life Carbon	Embodied Carbon
(Röck, Martin et al., 2022)	400.00	47.88	27.62	55.24	166.55	300.00	7.93	19.31	18.57	−10.55	1.032.55	724.62
(Zimmermann et al., 2021)	359.71	43.06	24.84	49.68	149.78	1.135.88	50.06	17.36	16.70	−9.49	1.837.57	651.63
(Suomen Ympäristöministeriö, 2021)	282.00	10.20	27.30	2.16	98.00	321.00	12.72	18.10	12.24	0.00	783.72	450.00
	361.51	43.28	24.96	49.92	150.52	1.141.55	31.09	17.45	16.78	−9.53	1.827.52	654.89
(Oneclick LCA, 2021)	330.34	39.54	22.81	45.62	137.55	1.043.14	45.24	15.95	15.33	−8.71	1.686.81	598.43
	218.15	26.11	15.06	30.13	90.83	688.86	41.34	10.53	10.13	−5.75	1.125.39	395.19
(Décret n° 2021-1004, 2021)	290.91	34.82	20.09	40.17	121.13	918.63	23.63	14.04	13.50	0.00	1.476.93	534.67
(Rietz et al., 2019)	259.45	31.06	17.91	35.83	108.03	819.27	36.41	12.52	12.04	−6.84	1.325.68	470.00
(DGNB, 2021)	240.13	28.75	16.58	33.16	99.98	758.26	32.47	11.59	11.15	−6.33	1.225.73	435.00
(Heeren et al., 2009)	286.82	34.34	19.80	39.61	119.43	500.00	19.82	13.84	13.31	−7.56	1.039.41	519.59
(UK Parliament Post, 2021), (LETI, 2020)	271.59	32.51	18.75	37.51	113.08	212.50	8.42	13.11	12.61	−7.16	712.92	492.00
(World Business Council for Sustainable Development, 2021)	257.79	30.86	17.80	35.60	107.34	993.62	39.38	12.44	11.97	0.00	1.506.80	473.80
homogenised average	**296.53**	**33.53**	**21.13**	**37.89**	**121.85**	**736.06**	**29.04**	**14.69**	**13.69**	**−5.99**	**1.298.42**	**533.32**
Standard dev	54.96	9.85	4.25	13.56	24.01	333.05	14.41	2.85	2.58	3.88	378.78	102.14

Table S3. Totals (number) and percentage (%) of Spanish dwellings per year of construction and floor area. Elaborated by the authors based on ERESEE (MITMA, 2020).

Number of dwellings according to floor area and year of construction [*1000]	**total**	**<60m²**	**61-75m²**	**76-90**	**91-120**	**121-150**	**>150m²**
<1940	1,311.9	243.6	183.2	225.9	303.4	134.6	221.2

1941-1960	1,777.1	377.5	382.9	390.3	365.2	127.2	134
1961-1980	6,370.2	930.2	1,469.2	1,827.8	1,424.9	369.1	349
1981-2010	8852	781.2	1,203.1	2,666.6	2,210.8	845.8	1,144.5
2010-2018	225.1	28.6	31.5	56.4	44.8	23.2	40.6
Total	**18,536.3**	**2,361.1**	**3,269.9**	**5,167**	**4,349.1**	**1.499.9**	**1,889.3**
Share of dwellings according to floor area and year of construction [%]	**total**	**<60m^2**	**61-75m^2**	**76-90**	**91-120**	**121-150**	**>150m^2**
<1940	7.08%	1.31%	0.99%	1.22%	1.64%	0.73%	1.19%
1941-1960	9.59%	2.04%	2.07%	2.11%	1.97%	0.69%	0.72%
1961-1980	34.37%	5.02%	7.93%	9.86%	7.69%	1.99%	1.88%
1981-2010	47.75%	4.21%	6.49%	14.39%	11.93%	4.56%	6.17%
2010-2018	1.21%	0.15%	0.17%	0.30%	0.24%	0.13%	0.22%
Total	**100.00%**	**12.74%**	**17.64%**	**27.88%**	**23.46%**	**8.09%**	**10.19%**

Table S4. Totals and % of Spanish dwelling per year of construction and type of building. Elaborated by the authors based on ERESEE (MITMA, 2020).

Number of dwellings according to typology and year of construction [*1000]	**total**	**detached**	**paired**	**double**	**3-9 storeys**	**>10 storeys**
<1940	1,307.2	359.4	405	94.8	197.7	250.3
1941-1960	1,771.6	269.9	362.2	67.8	365	706.7
1961-1980	6,356.3	636.5	657.9	192.8	1,168.6	3,700.5
1981-2010	8,835.3	1,265.7	1,850.2	236.9	1,493.0	3,989.5
2010-2018	224.9	44.7	50.6	4.2	18.4	107.0
Total	18,495.3	2,576.2	3,325.9	596.5	3,242.7	8,754.0
Share of dwellings according to typology and year of construction [%]	**total**	**detached**	**paired**	**double**	**3-9 storeys**	**>10 storeys**
<1940	7.07%	1.94%	2.19%	0.51%	1.07%	1.35%
1941-1960	9.58%	1.46%	1.96%	0.37%	1.97%	3.82%
1961-1980	34.37%	3.44%	3.56%	1.04%	6.32%	20.01%
1981-2010	47.77%	6.84%	10.00%	1.28%	8.07%	21.57%
2010-2018	1.22%	0.24%	0.27%	0.02%	0.10%	0.58%
total	100.00%	**13.93%**	**17.98%**	**3.23%**	**17.53%**	**47.33%**

Table S5. Bill of quantities of the building project chosen as representative case study. Elaborated by the authors based on the Executive Project Chapters of the case study building project.

Category	**Executive Project Chapter**	**Unit**	**Amount**
Ground works	1,1,1-5	m^3	1,856.0
PVC drainage eq ϴ110	1,2,1-4	m	11.0
Leveling gravel	1,3,1-2,2,1,1	m^3	322.0
Concrete foundations	2,1,1-2,5,1	kg	782,400.0
Steel foundations	2,2,1-2,5,1	kg	23,141.0
Concrete staircase slab	3,1,1	kg	21,504.0
Steel staircase slab	3,1,1	kg	1,344.0
Concrete flat beams	3,1,2	kg	25,804.8
Steel flat beams	3,1,2	kg	16,979.2
Concrete floor slabs	3,1,3	kg	30,240.0
Steel floor slabs	3,1,3	kg	1,916.2
Concrete structures	3,1,4	kg	791,827.2
Steel structures	3,1,4	kg	47,904.8
Concrete core	3,1,5	kg	82,080.0
Steel cre	3,1,5	kg	4902
Light brick facade	4,1,1	kg	52,020.0
Brick 1 facade	4,1,2	kg	91,290.0
Brick 2 facade	4,1,3	kg	62,220.0
Fix alu windowframe 100x100	4,2,1	Item	10.0
Alu windowframe120x120	4,2,2	Item	14.0
Alu windowframe120x120 with blinds	4,2,3	Item	440
Alu doorframe 120x210	4,2,4	Item	14.0
Brick windowsill	4,3,1	kg	31,280.0
Stainless Steel railing	4,3,2	kg	2,654.4
8mm glass railing	4,3,2	kg	1,400.0
Marble finishes	4,4,1,9,3,1	kg	1,612.8
Limestone flashing	4,4,2	Kg	653.6
Glass 4/6/4	4,5,1-2	kg	2,142.0
Inner stainless Steel railing	5,2,1	kg	1,319.6
Inner 8mm glass railing	5,2,1	kg	696.0
Armored inner doors	5,3,1	Item	14.0
Steel inner doors	5,4,1	Item	16.0
Blind Wood inner doors	5,4,2	Item	57.0
Glassed inner doors	5,4,3-4	Item	28.0
Firewall doors	5,4,5	Item	7.0
7 Brick party wall	5,5,1	kg	157,998.0
11 Brick party wall	5,5,2-3	kg	39,780.0
NG heater	6,1,1	Item	14.0
Insulated copper duct 10-16	6,1,2-4	m	1550
Insulated copper duct 20-33	6,1,5-6	m	47.0
Pipe PEX ACS 16	6,1,7	m	896.0

Category	Executive Project Chapter	Unit	Amount
Steel collector vitro 80l	6,1,10-11	Item	14.0
Radiant Element alu h425	6,1,13-15	Item	764.0
Solar termal panel 2'1m2	6,1,16	Item	3.0
Conditioned air duct alu+wool+mesh	6,1,18	m	157.0
Vent alu grill	6,19-21	Item	116.0
Duct refrigerant 3/8"	6,1,22	m	117.0
Corrugated pipe for cable 16mm	6,1,23	m	117.0
Cable RZ1K 4G1,5mm	6,1,24	m	117.0
Tube PVC condensation 16mm	6,1,25	m	117.0
Cable RZ1K 4G2,4mm	6,2,4	m	40.0
Cable ES07Z1K 3G13	6,2,7-10	m	237.0
Water pipe PE 20mm	6,3,1-2	m	14.0
Water tank 200l	6,3,5	Item	4.0
Vertical wáter pipe PEX20mm	6,3,6-9	m	182.0
Fluorescent light 36W	6,4,1-3	Item	80.0
Drainage PVC 110mm	6,6,1-3	m	147.0
Steel vent duct 200mm	6,6,10-11	m	200.0
Elevator 453kg 6p	6,7,1	Item	1.0
Rockwool insulation 40mm	7,1,1-2, 8,1,1	m^2	1,335.0
Waterproofing sheet PE ISO604	7,2,1-2,8,1,1-2	m^2	713.0
Roof slab trans morter eq	8,1,1	kg	7,927.5
Pitched roof tile	8,2,1	kg	54,162.0
Kitchen and toilet tiling	9,1,1	m^2	933.0
Anchored limestone cladding 2cm	9,2,1	kg	23,294.0
White plastic paint	9,4,1-2	l	1,314.7
Cement render M5	9,5,1-3,9,6,1	kg	80,280.0
Plaster trim	9,5,4-5	kg	431.3
Stoneware tile floors	9,8,2-6	kg	95,500.0
Hanging ceiling plaster plates	9,9,1-2	kg	8,616.0

Table S6. Results obtained from OERCO2 software for Scenario 0 (in kg CO_2-eq·m^{-2}). Output data grouped as materials' families.

Embodied Carbon (EC), A1-A5 tper materials family	Concrete and cement	Ceramics and bricks	Wood	Metals	Plastics	Water	Gravel and sand	Gypsum	Others
EC Total (kg CO_2-eq/building)	324.13	187.62	−21.82	147.98	22.64	0.8	4.24	1.43	106.52
EC/m^2 (kg CO_2-eq·m^{-2})	0.19	0.11	−0.01	0.09	0.01	0.00	0.00	0.00	0.06

Table S7. Results obtained from OERCO2 software for Scenario 0. Figures in kg CO_2-eq·m^{-2}. Output data grouped as main Project Chapters.

Embodied Carbon (EC) A1-A5 per Project Chapter	EC Total (kg CO_2-eq/building)	EC/m^2 (kg CO_2-eq·m^{-2})	%
C02.: Plot leveling	70.256	0.041	8.35%
C03.: Foundations	93.072	0.055	11.06%
C04.: Drainage	4.116	0.002	0.49%
C05.: Structure	252.12	0.148	29.96%
C06.: Masonry	176.905	0.104	21.02%
C07.: Roof	14.644	0.009	1.74%
C08.1: HVAC.	9.907	0.006	1.18%
C08.2: Electricity	46.894	0.028	5.57%
C08.3: Water installations	60.732	0.036	7.22%
C08.4: Domestic hot water	6.766	0.004	0.80%
C08.5: Accesibility	0	0.000	0.00%
C09. Insulation	13.948	0.008	1.66%
C10. Finishes	42.702	0.025	5.07%
C11. Carpentry works	29.844	0.018	3.55%
C12. Glass	1.626	0.001	0.19%
C13. Paints	17.907	0.011	2.13%

Table S8. Results obtained from OERCO2 software for Scenario 4 (in kg CO_2-eq·m^{-2}). Output data grouped as Materials' families.

Embodied Carbon (EC) A1-A5 per materials family	Concrete and cement	Ceramics and bricks	Wood	Metals	Plastics	Water	Gravel and sand	Gypsum	Others
EC Total (kg CO_2-eq/building)	315.83	183.57	−39.85	130.13	23.29	0.72	3.21	1.43	87.96
EC/m^2 (kg CO_2-	0.19	0.11	−0.02	0.08	0.01	0.00	0.00	0.00	0.05

eq·m^{-2})

Table S9. Results obtained from OERCO2 software for Scenario 4. Figures in kg CO_2-eq·m^{-2}. Output data grouped as main Project Chapters**.**

Embodied CArbon (EC) A1-A5 per Project Chapter	EC Total (kg CO_2-eq/building)	EC/m2 (kg CO_2-eq·m^{-2})	%
C02.: Plot leveling	70,256	0.041	9.07%
C03.: Foundations	93,072	0.055	12.02%
C04.: Drainage	4,116	0.002	0.53%
C05.: Structure	252,12	0.148	32.57%
C06.: Masonry	176,905	0.104	22.85%
C07.: Roof	14,644	0.009	1.89%
C08.1: HVAC.	9,907	0.006	1.28%
C08.2: Electricity	46,894	0.028	6.06%
C08.3: Water installations	60,732	0.036	7.84%
C08.4: Domestic hot water	6,766	0.004	0.87%
C08.5: Accesibility	0	0.000	0.00%
C09. Insulation	-4,528	-0.003	-0.58%
C10. Finishes	13,865	0.008	1.79%
C11. Carpentry works	9,913	0.006	1.28%
C12. Glass	1,626	0.001	0.21%
C13. Paints	17,907	0.011	2.31%

Table S10. Input flows of the building model at OpenLCA.

Input flows	Ecoinvent Category	Amount	Unit
Ventilation, decentralized, 6 x 120 m^3/h	F:Construction/43:Specialized construction activities/432: Electrical, plumbing and other construction installation activities/4322:Plumbing, heat and air-conditioning	4.9	$m^2 \cdot y^{-1}$
Heat, district or industrial, natural gas	D:Electricity, gas, steam and air conditioning supply/35: Electricity, gas, steam and air conditioning supply/351: Electric power generation, transmission and distribution	13,773.6	MJ
Tap water	E:Water supply; sewerage, waste management and remediation activities/36:Water collection, treatment and supply/360:Water collection, treatment and supply	83,160,474.3	kg
Wastewater, from residence	E:Water supply; sewerage, waste management and remediation activities/37:Sewerage/370:Sewerage	83,037.5	m^3
Cement, Portland	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products./2394:Manufacture of cement, lime and plaster	234,769.2	kg
Plaster mixing	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products./2394:Manufacture of cement, lime and plaster	9,047.3	kg
Ceramic tile	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products./2392:Manufacture of clay building materials	14,928.0	kg
Roof tile	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products./2392:Manufacture of clay building materials	54,162.0	kg
Natural stone plate, polished	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2396:Cutting, shaping and finishing of stone	25,560.4	kg
Glasswool mat uncoated, Saint-Gobain ISOVER	C:Manufacturing/23:Manufacture of other non-metallic mineral products/EPD	1,335.0	kg
BitumenSealAlu80	C:Manufacturing/23:Manufacture of other non-metallic mineral products/EPD	2,852.0	kg
Reinforcing steel	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel	91,775.4	kg
Chromium steel 18/8, hot rolled	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel	3,974.0	kg
Expansion vessel, 80l	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251: Structural metal products, tanks, reservoirs and steam generators	35.0	Item
Input flows	**Ecoinvent Category**	**Amount**	**Unit**
Hot water tank, 600l	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251: Structural metal products, tanks, reservoirs and steam generators	1.3	Item
Window frame,	C:Manufacturing/25:Manufacture of fabricated metal	128.8	m^2

aluminium, U=1.6 W/m^{2}K	products, except machinery and equipment/251: Manufacture of structural metal products, tanks, reservoirs and steam generators/ 2511:Structural metal products		
Cable, three-conductor cable	C:Manufacturing/27:Manufacture of electrical equipment/ 273:Manufacture of wiring and wiring devices/2732 Manufacture of other electronic and electric wires and cables	394.0	m
Compact fluorescent lamp	C:Manufacturing/27:Manufacture of electrical equipment/274:Manufacture of electric lighting equipment/2740:Manufacture of electric lighting equipment	288.0	Item
Gravel, crushed	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	1,222,400.6	kg
Glazing, double, U<1.1 W/m^{2}K	C:Manufacturing/23:Manufacture of other non-metallic mineral products/231:Manufacture of glass and glass products/2310:Manufacture of glass and glass products	2,142.0	m^2
Flat glass uncoated	C:Manufacturing/23:Manufacture of other non-metallic mineral products/231:Manufacture of glass and glass products/2310:Manufacture of glass and glass products	2,096.0	kg
Clay brick	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:Manufacture of clay building materials	434,588.0	kg
Elevator, hydraulic	C:Manufacturing/28:Manufacture of machinery and equipment./281:Manufacture of general-purpose machinery /2816: Manufacture of lifting and handling equipment	0.5	Item
Cement tile	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products 2395:Articles of concrete, cement and plaster	95,500.0	kg
Sand	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay	821,519.4	kg
Extrusion, plastic pipes	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products	742.0	kg
Metal, average for copper product manufacturing	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/259:Manufacture of other fabricated metal products; metalworking service	1,276.0	kg
Input flows	**Ecoinvent Category**	**Amount**	**Unit**
Metal, average for aluminium product manufacturing	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/259:Manufacture of other fabricated metal products; metalworking service	1,268.5	kg
Gas boiler	C:Manufacturing/28:Manufacture of machinery and equipment./281:Manufacture of general-purpose machinery/2815: Ovens, furnaces and furnace burners	14.0	Item
Door, inner, glass-wood	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	95.5	m^2

Door, inner, wood	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	46.9	m^2
Door, outer, wood-aluminium	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2511:Manufacture of structural metal products	59.8	m^2
Acrylic varnish, without water, in 87.5% solution state	C:Manufacturing/20:Manufacture of chemicals and chemical products/202:Manufacture of other chemical products/2022: Manufacture of paints, varnishes and similar coatings and ink	1,840.6	kg
Solar collector system, Cu flat plate collector, multifamily, hot water	F:Construction/43:Specialized construction activities/432: Electrical, plumbing and other construction installation activities/4322:Plumbing, heat and air-conditioning installation	0.1	Item
Occupation, urban	Elementary flows/Resource/unspecified	1,856.0	$m^2 \cdot y^{-1}$
Ventilation duct, steel, 100x50 mm	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Ggeneral-purpose machinery	357.0	m

Table S11. Output flows of the building model at OpenLCA.

Output Flows	**Ecoinvent Category**	**Amount**	**Unit**
waste brick	E:Water supply; sewerage, waste management & remediation activities/38:Waste collection, treatment & disposal activities; materials recovery/383:Materials recovery	503,678.0	kg
waste mineral wool	E:Water supply; sewerage, waste management & remediation activities/38:Waste collection, treatment & disposal activities; materials recovery/383:Materials recovery	1,335.0	kg
waste reinforced concrete	E:Water supply; sewerage, waste management & remediation activities/38:Waste collection, treatment & disposal activities; materials recovery/383:Materials recovery	1,913,839.0	kg
scrap copper	E:Water supply; sewerage, waste management & remediation activities/38:Waste collection, treatment & disposal activities; materials recovery/382:Waste treatment & disposal/ 3821:Treatment and disposal of non-hazardous waste	1,370.5	kg
waste glass sheet		2,096.0	kg
used door, inner, glass-wood		95.5	m^2
used door, inner, wood	E:Water supply; sewerage, waste management & remediation activities/38:Waste collection, treatment & disposal activities; materials recovery/382:Waste treatment & disposal/ 3821:Treatment and disposal of non-hazardous waste	46.9	m^2
used door, outer, wood-aluminium		59.,8	m^2
used double glazing U<1.1W/m^2K		2,142.0	m^2
waste aluminium	S E:Water supply; sewerage, waste management & remediation activities/38:Waste collection, treatment & disposal activities; materials recovery/382:Waste treatment & disposal/ 3821:Treatment and disposal of non-hazardous waste	1,268.5	kg
waste bitumen sheet		2,852.0	kg
waste electric wiring		157.6	kg
waste emulsion paint	E:Water supply; sewerage, waste management & remediation activities/38:Waste collection, treatment & disposal activities; materials recovery/382:Waste treatment & disposal/ 3821:Treatment and disposal of non-hazardous waste	1,840.6	kg
waste plastic, mixture		742.0	kg
waste gypsum		9,047.3	kg
used window frame, wood-metal	E:Water supply; sewerage, waste management & remediation activities/38:Waste collection, treatment & disposal activities; materials recovery/382:Waste treatment & disposal/ 3821:Treatment and disposal of non-hazardous waste	128.8	m^2
scrap steel		4,010.3	kg
waste concrete		121,060.4	kg

Figure S1. *Top view of the 3rd floor of the analyses 4 stories residential building designed in year 2013. Representing an average building of 1981-2010, 20% of current Spanish stock.*

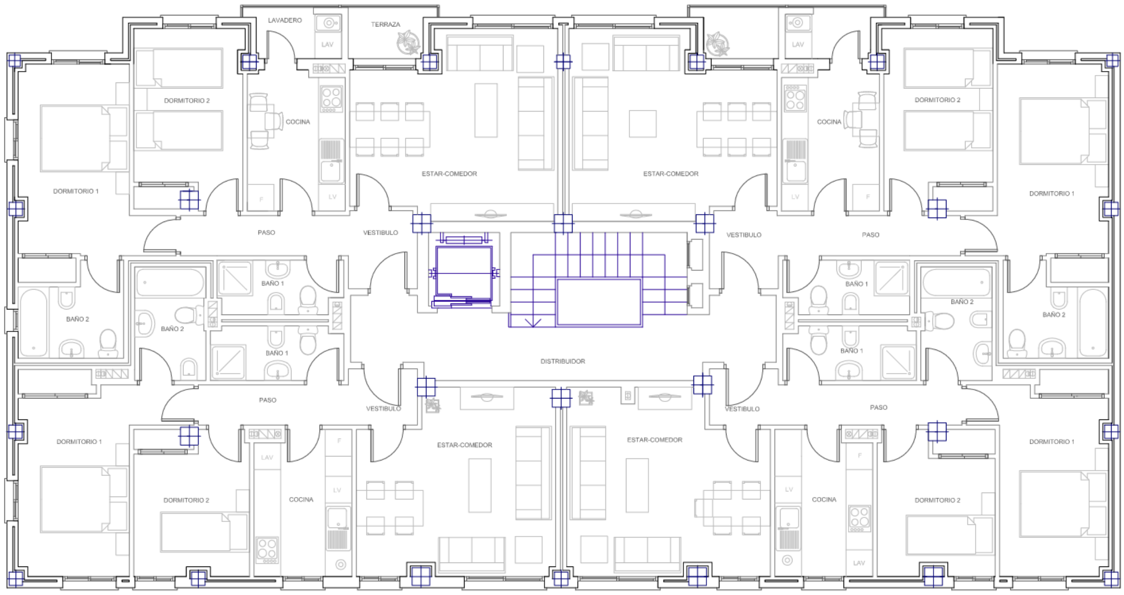
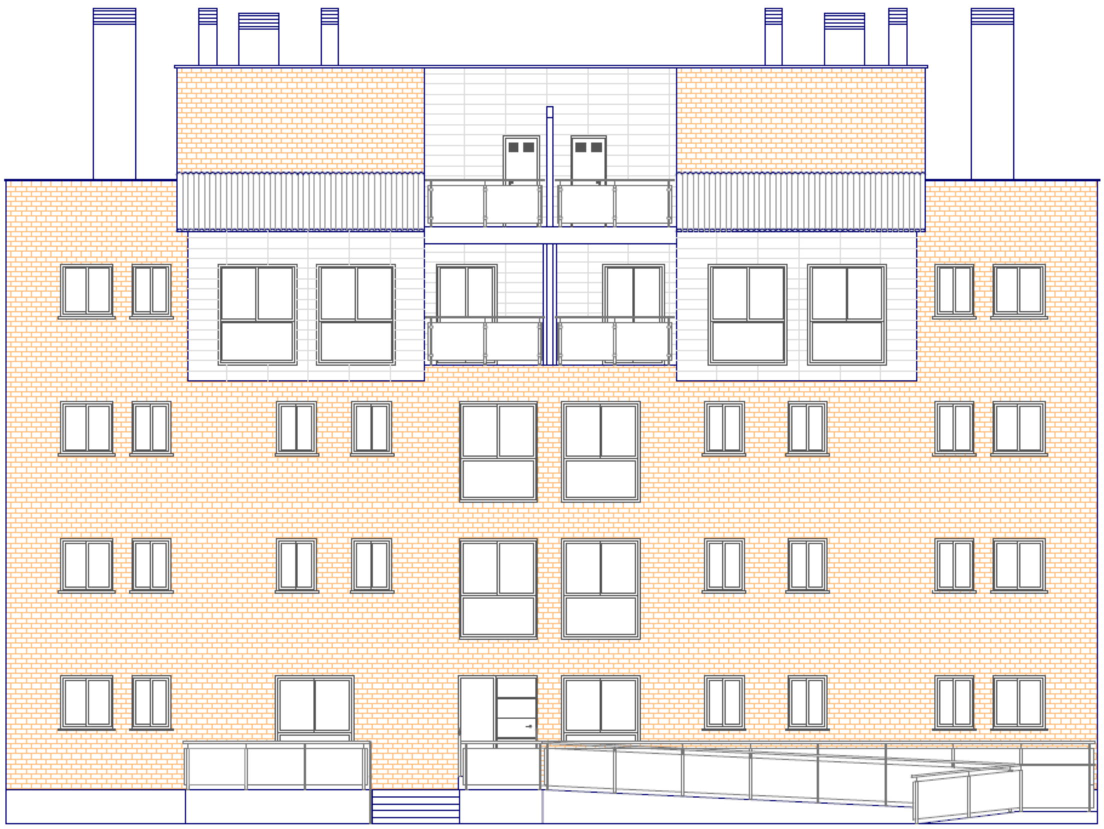


Figure S2. *Main elevation of the analysed project with 14 flats of an average of 73.1 m^2 Net Floor Area (NFA) per apartment (minimum NFA of 51 m^2, maximum NFA of 96 m^2)*



Artículo 3:

BIODIVERSITY BURDENS IN SPANISH CONVENTIONAL AND LOW-IMPACT SINGLE FAMILY HOMES

Autores: Borja Izaola y Ortzi Akizu-Gardoki
Nombre de la revista científica y fecha de publicación:
ELSEVIER, Science of the Total Environment, Noviembre de 2023
Doi: https://doi.org/10.1016/j.scitotenv.2023.168371

Article 3 Supporting information contains 7 tables and 8 figures that complete information from the main article. Table S1 lists impact categories of the studied houses at Mid- and End-point per capita. Table S2 details the relative weight of the aggregated impact metrics. Tables S3 to S6 list the Input and Output flows used per Scenario on the LCA calculations. Table S7 compares results between a revised article and this research. Figures S1 to S8 present the lay-out and main elevation of the four studied houses, respectively the Brick and Concrete (Scenario 0), Timber PassivHaus (Scenario 1), Straw with Renewables (Scenario 2) and Earth Bioclimatic (Scenario 3) single family houses.

Table S12. Aggregated categories at each impact method.

Midpoint ecotoxicity Impacts	**Endpoint species.yr-related Impacts**	**Endpoint DALY-related Impacts**
Terrestrial ecotoxicity	Land use	Fine particulate matter formation
Freshwater ecotoxicity	Terrestrial ecotoxicity	Ionizing radiation
Marine ecotoxicity	Global warming, Terrestrial ecosystems	Human carcinogenic toxicity
Human non-carcinogenic toxicity	Ozone formation, Terrestrial ecosystems	Human non-carcinogenic toxicity
Human carcinogenic toxicity	Freshwater ecotoxicity	Stratospheric ozone depletion
	Water consumption, Terrestrial ecosystem	Water consumption, Human health
	Water consumption, Aquatic ecosystems	Ozone formation, Human health
	Terrestrial acidification	Global warming, Human health
	Marine eutrophication	
	Global warming, Freshwater ecosystems	
	Freshwater eutrophication	
	Marine ecotoxicity	

Table S13. Relative weight of the aggregated impact metrics.

Midpoint Ecotoxicities relative weight	**Timber**	**Straw**	**Earth**	**Brick**
Terrestrial ecotoxicity	79.1%	79.5%	73.7%	73.3%
Human non-carcinogenic toxicity	16.9%	16.2%	19.0%	16.7%
Marine ecotoxicity	1.9%	2.0%	3.5%	4.8%
Human carcinogenic toxicity	0.6%	0.7%	0.9%	1.3%
Freshwater ecotoxicity	1.5%	1.6%	2.9%	4.0%

Endpoint species.yr-related relative weight	**Timber**	**Straw**	**Earth**	**Brick**
Terrestrial ecotoxicity	1.4%	1.6%	1.7%	1.3%
Global warming, Terrestrial ecosystems	36.4%	33.6%	45.3%	15.9%
Land use	4.3%	4.5%	4.6%	5.4%
Ozone formation, Terrestrial ecosystems	1.6%	2.0%	4.0%	4.1%
Freshwater ecotoxicity	6.0%	1.7%	10.2%	10.3%
Water consumption, Terrestrial ecosystem	0.0%	0.0%	0.0%	0.0%
Water consumption, Aquatic ecosystems	0.0%	0.0%	0.0%	0.0%
Terrestrial acidification	10.7%	11.6%	8.4%	11.0%
Marine eutrophication	0.0%	0.0%	0.0%	0.0%
Global warming, Freshwater ecosystems	0.0%	0.0%	0.0%	0.0%
Freshwater eutrophication	2.7%	3.0%	3.0%	2.9%
Marine ecotoxicity	0.3%	0.4%	0.7%	0.8%

Endpoint DALY-related relative weight	**Timber**	**Straw**	**Earth**	**Brick**
Ionizing radiation	0.0%	0.0%	0.0%	0.0%
Human carcinogenic toxicity	8.9%	11.1%	17.3%	14.6%
Stratospheric ozone depletion	0.0%	0.0%	0.0%	0.0%
Human non-carcinogenic toxicity	16.8%	16.6%	24.1%	12.8%
Water consumption, Human health	2.7%	0.7%	4.7%	3.8%
Fine particulate matter formation	37.7%	37.2%	33.1%	33.2%
Ozone formation, Human health	0.1%	0.1%	0.1%	0.1%
Global warming, Human health	33.7%	34.3%	20.6%	35.6%

Table S14. Input and Output flows of Scenario 0, Brick and Concrete house.

Input Flows	Category	Amount	Unit
electricity, low voltage	D:Electricity, gas, steam and air conditioning supply/35:Electricity, gas, steam and air conditioning supply/351:Electric power generation, transmission and distribution/3510:Electric power generation, transmission and distribution	551448	MJ
ventilation of dwellings	F:Construction/43:Specialized construction activities/432:Electrical, plumbing and other construction installation activities/4322:Plumbing, heat and air-conditioning installation	0.81018518 5185185	m2*a
heat, district or industrial, nat gas	D:Electricity, gas, steam and air conditioning supply/35:Electricity, gas, steam and air conditioning supply/351:Electric power generation, transmission and distribution/3510:Electric power generation, transmission and distribution	19668.8	MJ
tap water	E:Water supply; sewerage, waste management and remediation activities/36:Water collection, treatment and supply/360:Water collection, treatment and supply/3600:Water collection, treatment and supply	9508917.44 3	kg
madera suelos	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	3.54	m³
cement, Portland	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2394:Manufacture of cement, lime and plaster	36128.0562 5	kg
ceramic tile	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:Manufacture of clay building materials	1715	kg
roof tile	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:ClayManufacture	3630	kg
plaster mixing	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2394:Manufacture of cement, lime and plaster	38.52	kg
glass wool mat, uncoated	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2399:Manufacture of other non-metallic mineral products n.e.c.	446.25	kg
bitumen seal, Alu80	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2399:Manufacture of other non-metallic mineral products n.e.c.	484	kg
reinforcing steel	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	14516.1567	kg
steel, chromium steel 18/8, hot rolled	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	37.6	kg
expansion vessel, 80l	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2512:Manufacture of tanks, reservoirs and containers of metal	1.0	Item(s)
hot water tank, 600l	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2512:Manufacture of tanks, reservoirs and containers of metal	0.33333333 3333333	Item(s)
window frame, aluminium,	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2511:Manufacture of structural metal products	17.4	m2
cable, three-conductor	C:Manufacturing/27:Manufacture of electrical equipment/273:Manufacture of wiring and wiring devices/2732:Manufacture of electric wires and cables	382	m
fluorescent lamp	C:Manufacturing/27:Manufacture of electrical equipment/274:Manufacture of electric lighting equipment/2740:Manufacture of electric lighting	32.4	Item(s)
gravel, crushed	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	229372.860	kg
glazing, double	C:Manufacturing/23:Manufacture of other non-metallic mineral products/231:Manufacture of glass and glass products/2310:Manufacture of glass	23	m2
clay brick	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:Manufacture of clay building materials	22488.6	kg
sand	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	123290.563	kg
extrusion plastic pipe	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	380	kg
metal working, average for copper	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/259:Manufacture of other fabricated metal products; metalworking service activity	75.15	kg
gas boiler	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2815:Manufacture of ovens, furnaces and furnace burners	1.0	Item(s)

Table S14. Input and Output flows of Scenario 0, Brick and Concrete house.

Input Flows	Category	Amount	Unit
metal working, average for alu	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/259:Manufacture of other fabricated metal products; metalworking service activity	15.0716	kg
door, inner, wood	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	11.72325	m2
door, outer, wood-aluminium	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2511:Manufacture of structural metal products	1.76	m2
acrylic varnish, without water	C:Manufacturing/20:Manufacture of chemicals and chemical products/202:Manufacture of other chemical products/2022:Manufacture of paints, varnishes and similar coatings, printing ink and mask	51.45	kg
Occupation, urban	Elementary flows/Resource/unspecified	126	m2*a
ventilation duct, steel	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2819:Manufacture of machinery	16	m

Output Flows	Category	Amount	Unit
waste brick	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/383:Materials recovery/3830:Materials recovery	22,489	kg
waste mineral wool	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/383:Materials recovery/3830:Materials recovery	446	kg
waste reinforced concrete	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/383:Materials recovery/3830:Materials recovery	274,408	kg
scrap copper	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	75.15	kg
used door, inner, wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	11.72325	m2
used door, outer, wood-aluminium	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	1.76	m2
used double glazing	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	23	m2
waste aluminium	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	15.0716	kg
waste bitumen sheet	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	484	kg
waste electric wiring	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	439.3	kg
waste emulsion paint	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	51.45	kg
waste gypsum	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	38.52	kg
used window frame, wood-metal	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	17.4	m2
scrap steel	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	14516.1567 5	kg
waste plastic, mixture	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	380	kg

Table S15. Input and Output flows of Scenario 1, Timber PassivHaus home.

Input Flows	Category	Amount	Unit
electricity	D:Electricity, gas, steam and air conditioning supply/35:Electricity, gas, steam and air conditioning supply/351:Electric power generation/3510:Electricity	397573.2	MJ
tap water	E:Water supply; sewerage, waste management and remediation activities/36:Water collection, treatment and supply/360:Water supply/3600:Water supply	9492797.03	kg
cement, Portland	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2394:Cement product	5341.6872	kg
gravel, crushed	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	15124.56	kg
sand	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	18134.523	kg
reinforcing steel	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	2158.32	kg
ceramic tile	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:TileManufacture	1072.5	kg
roof tile	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:TileManufacture	247.2	kg
clay brick	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:ClayManufacture	438.6	kg
window frame, wood, U=1.5 W/m2K	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	29.84	m2
glazing, triple	C:Manufacturing/23:Manufacture of other non-metallic mineral products/231:Manufacture of glass and glass products/2310:Manufacture of glass	31.22	m2
door, inner, wood	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	30.6	m2
Security doors	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2511:Manufacture of structural metal products	2	m²
CLT kit estrct ntrm lig	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	30.16	m³
Closure panel OSB	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	11.18	m³
Ceilings and pladur ecowood	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	12.044676	m³
Massive timber	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	5.36364	m³
cable, three-conductor	C:Manufacturing/27:Manufacture of electrical equipment/273:Manufacture of wiring and wiring devices/2732:Manufacture of electric wires and cables	420	m
luminarias led 16w	C:Manufacturing/26:Manufacture of computer, electronic and optical products/261:Manufacture of electronic components and boards/2610:LED	0.6	kg
extrusion, plastic pipes	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	460.7	kg
mecanismos electridad + telco 2 laptop	C:Manufacturing/26:Manufacture of computer, electronic and optical products/262:Manufacture of computers and peripheral equipment/2620:Manufacture of computers and peripheral equipment	2	Item(s)
mecanismos electridad + telco 2 internet	C:Manufacturing/26:Manufacture of computer, electronic and optical products/262:Manufacture of computers and peripheral equipment/2620:Manufacture of computers and peripheral equipment	2	Item(s)
Ttelco 2 display minor	C:Manufacturing/26:Manufacture of computer, electronic and optical products/263:Manufacture of communication equipment/2630:Equipment	3	kg
sistema HVAC bomba aire/agua 7 fancoils	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2815:Manufacture of ovens, furnaces and furnace burners	1	Item(s)
PV slanted-roof	C:Manufacturing/33:Repair and installation of machinery and equipment/332:Installation of industrial machinery and equipment/3320:Equipment	0.86666667	Item(s)
ventilation of dwellings	F:Construction/43:Specialized construction activities/432:Electrical, plumbing and other construction installation activities/4322:Ventilation	0.6	m2*a
ventilation duct, steel, 100x50 mm + canalón	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2819:Manufacture of other general-purpose machinery	68	m
metal working, average for aluminium	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/259:Manufacture of other fabricated metal products; metalworking service activity	8.4	kg

Table S15. Input and Output flows of Scenario 1, Timber PassivHaus home.

Input Flows	Category	Amount	Unit
hot water tank, 600l ⅓	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2512:Manufacture of tanks, reservoirs and containers of metal	0.334	Item(s)
acrylic varnish, with water	C:Manufacturing/20:Manufacture of chemicals and chemical products/202:Manufacture of other chemical products/2022:Manufacture of paints, varnishes and similar coatings, printing ink and masks	197.8	kg
pintura ecologica alkyd without solvent	C:Manufacturing/20:Manufacture of chemicals and chemical products/202:Manufacture of other chemical products/2022:Manufacture of paints, varnishes and similar coatings, printing ink and masks	391.3	kg
aislamiento cork	A:Agriculture, forestry and fishing/02:Forestry and logging/023:Gathering of non-wood forest products/0230:Gathering of non-wood forest products	257.95	kg
aislamto fibra madera 4cm	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	9.96	m3
glass wool mat, uncoated	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2399:Manufacture of other non-metallic mineral products n.e.c.	630.75	kg
SATE EPS 2cm	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	13.2	kg
aislmto textil int 6cm	C:Manufacturing/13:Manufacture of textiles/131:Spinning, weaving and finishing of textiles/1312:Weaving of textiles	129.6	kg
bitumen seal, polymer EP4 Mebrana, imperm,	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2399:Manufacture of other non-metallic mineral products n.e.c.	81.29	kg
Occupation, const site	Elementary flows/Resource/unspecified	250	m2*a

Output Flows	Category	Amount	Unit
wastewater, unpolluted	E:Water supply; sewerage, waste management and remediation activities/37:Sewerage/370:Sewerage/3700:Sewerage	1898	m3
waste wood, postcons	E:Water supply; sewerage, waste management and remediation activities/38:Waste recovery/383:Materials recovery/3830:Materials recovery	29062.8704	kg
waste glass	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	250	kg
waste cement in concrete and mortar	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/383:Materials recovery/3830:Materials recovery	40,800	kg
waste brick	E:Water supply; sewerage, waste management and remediation activities/38:Waste recovery/383:Materials recovery/3830:Materials recovery	1,758	kg
used door, inner, wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	30.6	m2
used door, outer, alu	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	2	m2
used glazing, triple	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	31.22	m2
waste bitumen sheet	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	81.29	kg
waste electric wiring	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	168	kg
waste paint, on wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	589.1	kg
used window fr wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	29.84	m2
scrap steel	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	129.2	kg
waste plastic electronic	E:Water supply; sewerage, waste management and remediation activities/38:Waste/382:Waste treatment and disposal/3821:Non-hazardous waste	3	kg
electronics scrap	E:Water supply; sewerage, waste management and remediation activities/38:Waste recovery/383:Materials recovery/3830:Materials recovery	9	kg
used ventilation control and wiring central unit	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/383:Materials recovery/3830:Materials recovery	0.6	Item(s)
waste mineral wool	E:Water supply; sewerage, waste management and remediation activities/38:Waste recovery/383:Materials recovery/3830:Materials recovery	630.75	kg

Table S16. Input and Output flows of Scenario 2, Straw with Renewables house.

Input Flows	Category	Amount	Unit
electricity, low voltage	D:Electricity, gas, steam and air conditioning supply/35:Electricity, gas, steam and air conditioning supply/351:Electric power generation, transmission and distribution/3510:Electric power generation, transmission and distribution	195583.5	MJ
tap water	E:Water supply; sewerage, waste management and remediation activities/36:Water collection, treatment and supply/360:Water collection, treatment and supply/3600:Water collection, treatment and supply	6207139.78 02	kg
cement, Portland	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2394:Manufacture of cement, lime and plaster	3546.5104	kg
bitumen seal, polymer EP4 Mebrana, imperm,	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2399:Manufacture of other non-metallic mineral products n.e.c.	640.6	kg
reinforcing steel	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	1718.0976	kg
door, inner, wood	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	15.07275	m2
expansion vessel, 80l	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2512:Manufacture of tanks, reservoirs and containers of metal	1	Item(s)
hot water tank, 600l	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2512:Manufacture of tanks, reservoirs and containers of metal	0.33333333 3333333	Item(s)
window frame, wood, U=1.5 W/m2K	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	12.614	m2
cable, three-conductor	C:Manufacturing/27:Manufacture of electrical equipment/273:Manufacture of wiring and wiring devices/2732:Manufacture of electric wires and cables	254	m
Led 16w	C:Manufacturing/26:Manufacture of computer, electronic and optical products/261:Manufacture of electronic components and boards/2610:Manufacture of electronic components and boards	0.36	kg
gravel, crushed	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	33881.6208	kg
glazing, triple, U<0,5 W/m2K	C:Manufacturing/23:Manufacture of other non-metallic mineral products/231:Manufacture of glass and glass products/2310:Manufacture of glass and glass products	16.05	m2
flat glass, uncoated	C:Manufacturing/23:Manufacture of other non-metallic mineral products/231:Manufacture of glass and glass products/2310:Manufacture of glass	104.16	kg
clay brick	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:ClayManufacture	476.28	kg
sand	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	13792.2493	kg
extrusion, plastic pipes	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	520.32	kg
metal working, average for copper product	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/259:Manufacture of other fabricated metal products; metalworking service activity	11.853	kg
solar collector system, Cu flat plate collector,	F:Construction/43:Specialized construction activities/432:Electrical, plumbing and other construction installation activities/4322:Plumbing, heat and air-conditioning installation	1	Item(s)
Occupation, const site	Elementary flows/Resource/unspecified	82.564	m2*a
ventilation duct, steel, 100x50 mm	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2819:Manufacture of other general-purpose machinery	19	m
tabique pladur madera, fibreboard, soft	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	1.74924	m³
madera maciza varios	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	17.210766	m³
ECoPaint alkyd without solvent	C:Manufacturing/20:Manufacture of chemicals and chemical products/202:Manufacture of other chemical products/2022:Manufacture of paints, varnishes and similar coatings, printing ink and masks	304.7187	kg
ceramic tile	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:Manufacture of clay building materials	768.25	kg

Table S16. Input and Output flows of Scenario 2, Straw with Renewables house.

Input Flows	Category	Amount	Unit
insulation spiral-s duct	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2819:Manufacture of other general-purpose machinery	79	m
furnace, logs, 6kW	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2815:Manufacture of ovens, furnaces and furnace burners	1.1667	Item(s)
lime, hydraulic	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2394:Manufacture of cement, lime and plaster	31.9616	kg
clay	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	26.6133	kg
straw, stand-alone production	A:Agriculture, forestry and fishing/01:Crop and animal production, hunting and related service activities/011:Growing of non-perennial crops/0111:Growing of cereals (except rice), leguminous crops and oil seeds	852.39	kg
mecanism electric + telco 2 display minor	C:Manufacturing/26:Manufacture of computer, electronic and optical products/263:Manufacture of communication equipment/2630:Manufacture of communication equipment	1.5	kg
PV1,3kW slanted-roof	C:Manufacturing/33:Repair and installation of machinery and equipment/332:Installation of industrial machinery and equipment/3320:Equipment	0.43333334	Item(s)

Output Flows	Category	Amount	Unit
wastewater, unpolluted	E:Water supply; sewerage, waste management and remediation activities/37:Sewerage/370:Sewerage/3700:Sewerage	1861.5	m3
waste brick	E:Water supply; sewerage, waste management and remediation activities/38:Waste recovery/383:Materials recovery/3830:Materials recovery	476	kg
waste glass sheet	E:Water supply; sewerage, waste management and remediation activities/38:Waste recovery/383:Materials recovery/3830:Materials recovery	104	kg
used glazing, triple, U<0,5 W/m2K	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	16.05	m2
waste reinforced concrete	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	31,344	kg
scrap copper	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	16.853	kg
scrap steel	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	1778.26426 666667	kg
used door, inner, wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	15.07275	m2
waste plastic, mixture	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	520.32	kg
used cable	E:Water supply; sewerage, waste management and remediation activities/38:Waste recovery/383:Materials recovery/3830:Materials recovery	101.6	kg
waste wood, post-cons	E:Water supply; sewerage, waste management and remediation activities/38:Waste recovery/383:Materials recovery/3830:Materials recovery	4824.64716	kg
waste bitumen sheet	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	640.6	kg
waste emulsion paint, on wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	304.7187	kg
used window frame, wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	12.614	m2
waste plastic, consumer electronics	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	1.5	kg

Table S17. Input and Output flows of Scenario 3, Earth bioclimatic house.

Input Flows	**Category**	**Amount**	**Unit**
Demolition, site prep	F:Construction/43:Specialized construction activities/431:Demolition and site preparation/4312:Site preparation	40	m³
electricity, low voltage	D:Electricity, gas, steam and air conditioning supply/35:Electricity, gas, steam and air conditioning supply/351:Electric power generation, transmission and distribution/3510:Electric power generation, transmission and distribution	-16488	MJ
tap water	E:Water supply; sewerage, waste management and remediation activities/36:Water collection, treatment and supply/360:Water collection, treatment and supply/3600:Water collection, treatment and supply	12063696	kg
cement, Portland	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2394:Manufacture of cement, lime and plaster	20352	kg
sand	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	50622	kg
gravel, round	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	174200	kg
rammed earth extrct	A:Agriculture, forestry and fishing/01:Crop and animal production, hunting and related service activities/016:Support activities to agriculture and post-harvest crop activities/0161:Support activities for crop production	387	m2
Occupation, urban	Elementary flows/Resource/unspecified	140	m2*a
reinforcing steel	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	6921.3	kg
ceramic tile	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2392:Manufacture of clay building materials	2663.4	kg
wooden slates	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	122	m2
massive structural timber	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	23.195	m³
Timber part fibreboard soft no adhesive	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	4.84	m³
Clay 4 RE, radiant wall	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	154949	kg
seal, natural rubber	C:Manufacturing/20:Manufacture of chemicals and chemical products/202:Manufacture of other chemical products/2029:Manufacture of chemical prods	1222.5	kg
fibre cotton insulation	A:Agriculture, forestry and fishing/01:Crop and animal production, hunting and related service activities/016:Support activities to agriculture and post-harvest crop activities/0163:Post-harvest crop activities	522.5	kg
electric motor, for electric sblinds	C:Manufacturing/27:Manufacture of electrical equipment/271:Manufacture of electric motors, generators, transformers and electricity distribution and control apparatus/2710:Manufacture of electric motors, generators, transformers and electricity di	22	kg
glazing, triple	C:Manufacturing/23:Manufacture of other non-metallic mineral products/231:Manufacture of glass and glass products/2310:Manufacture of glass	39	m2
flat glass, uncoated	C:Manufacturing/23:Manufacture of other non-metallic mineral products/231:Manufacture of glass and glass products/2310:Manufacture of glass and glass products	424	kg
window frame, wood, U=1.5 W/m2K	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	19	m2
door, inner, wood	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1622:Manufacture of builders' carpentry and joinery	28.8	m2
polymethyl methacrylate, sheet	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	36	kg
cable, three-conductor	C:Manufacturing/27:Manufacture of electrical equipment/273:Manufacture of wiring and wiring devices/2732:Manufacture of electric wires and cables	388.666667	m
Led 16w	C:Manufacturing/26:Manufacture of computer, electronic and optical products/261:Manufacture of electronic components and boards/2610:Manufacture of electronic components and boards	0.4	kg
extrusion, plastic pipes	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	354.15	kg
ventilation duct, steel, 100x50 mm	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2819:Manufacture of other general-purpose machinery	25.5	m

Table S17. Input and Output flows of Scenario 3, Earth bioclimatic house.

Input Flows	Category	Amount	Unit
Ecopaintalkyd without solvent	C:Manufacturing/20:Manufacture of chemicals and chemical products/202:Manufacture of other chemical products/2022:Manufacture of paints, varnishes and similar coatings, printing ink and mas	466.2	kg
heat pump 4kW	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2815:Manufacture of ovens, furnaces and furnace burners	1	Item(s)
hot water tank, 600l	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/251:Manufacture of structural metal products, tanks, reservoirs and steam generators/2512:Manufacture of tanks, reservoirs and containers of metal	0.33333333 3333333	Item(s)
I4'5 kW PV flat-roof installation	C:Manufacturing/33:Repair and installation of machinery and equipment/332:Installation of industrial machinery and equipment/3320:Installation of industrial machinery and equipment	1.5	Item(s)
furnace, pellet, 15 (17)kW	C:Manufacturing/28:Manufacture of machinery and equipment n.e.c./281:Manufacture of general-purpose machinery/2815:Manufacture of ovens, furnaces and furnace burners	1.133	Item(s)
mecanism electric+ telco chassis internet	C:Manufacturing/26:Manufacture of computer, electronic and optical products/263:Manufacture of communication equipment/2630:Manufacture of communication equipment	1.5	kg

Output Flows	Category	Amount	Unit
wastewater	E:Water supply; sewerage, waste management and remediation activities/37:Sewerage/370:Sewerage/3700:Sewerage	8760	m3
waste concrete	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	4140	kg
waste wood, post-consumer	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/383:Materials recovery/3830:Materials recovery	10502.45	kg
scrap steel	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	6921.3	kg
waste emulsion paint, on wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	466.2	kg
used window frame, wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	19	m2
waste electric wiring	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	155.466666 666667	kg
used door, inner, wood	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	28.8	m2
waste brick	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/383:Materials recovery/3830:Materials recovery	2,663	kg
waste plastic, consumer electronics	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	641.65	kg
used glazing, triple, U<0,5 W/m2K	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	39	m2
waste glass sheet	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/383:Materials recovery/3830:Materials recovery	424	kg
waste electric and electronic equ	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/383:Materials recovery/3830:Materials recovery	15	kg
waste rubber, unspecified	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	1222.5	kg

Table S18. Comparison on three Midpoint impacts of the four scenarios between *(Moňoková and Vilčeková, 2020) and this research*.

Midpoint Impact category	**Unit**	**SC0 Brick**	**SC1 Timber**	**SC2 Straw**	**SC3 Earth**
		This research four scenarios			
Stratospheric ozone depletion	kg CFC11 eq/m²	3.81E-04	3.25E-04	2.91E-04	2.14E-04
Global warming potential	kg CO_2 eq/m²	1292.87	684.58	745.96	1709.28
Water consumption	m^3/m^2	57.52	23.16	568.21	686.49
		(Moňoková and Vilčeková, 2020)			
Stratospheric ozone depletion	kg CFC11 eq/m²	5.60E-04	1.20E-03	2.10E-05	2.40E-05
Global warming potential	kg CO2 eq/m²	1700	970	330.00	1400.00
Water consumption	m^3/m^2	110.00	110.00	760.00	87.00
		Variation in % of this research against *(Moňoková and Vilčeková, 2020)*			
Stratospheric ozone depletion	kg CFC11 eq/m²	67.96%	27.08%	1383.66%	892.06%
Global warming potential	kg CO2 eq/m²	76.05%	70.58%	226.05%	122.09%
Water consumption	m^3/m^2	52.29%	21.05%	74.77%	789.07%

Figure S3. *Lay-out of Scenario 0, Brick and Concrete house in Getafe.*

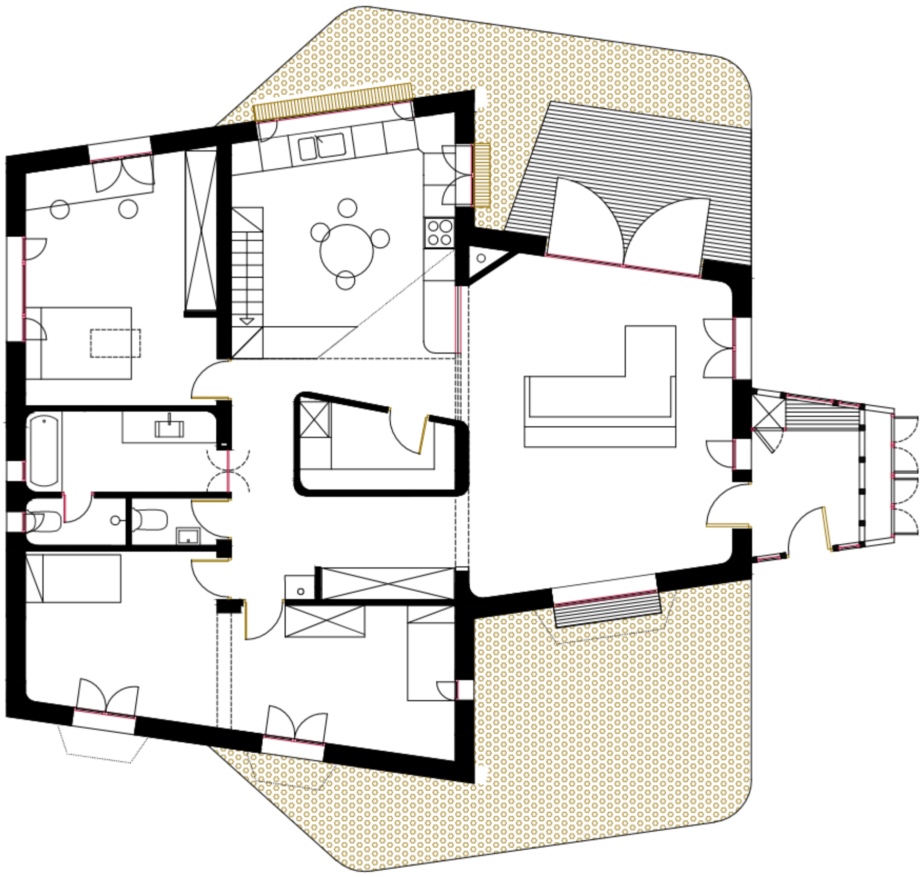


Figure S4. *South elevations of Scenario 0, Brick and Concrete house in Getafe.*

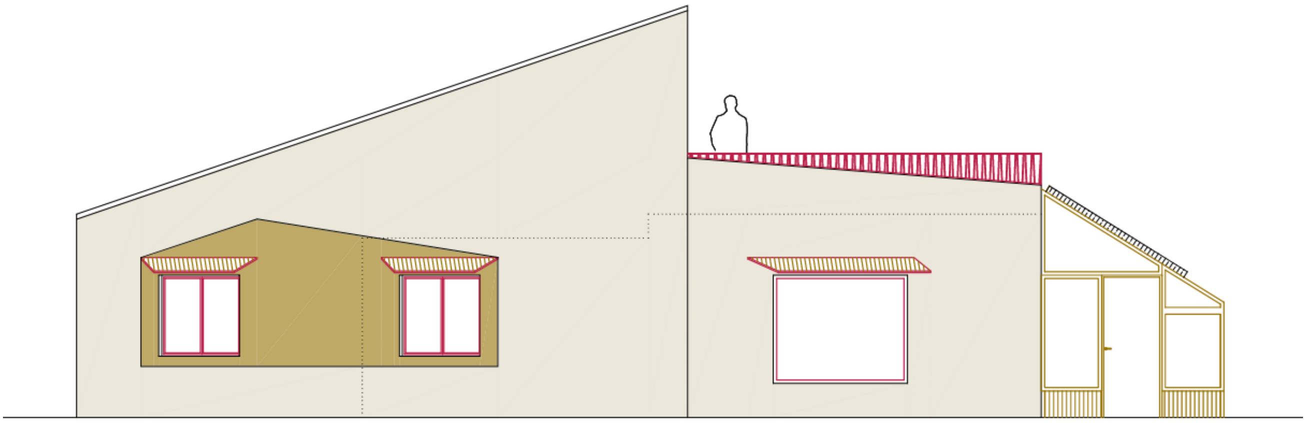


Figure S5. *Lay-out of Scenario 1, Timber PassivHaus home in the outskirts of Madrid.*

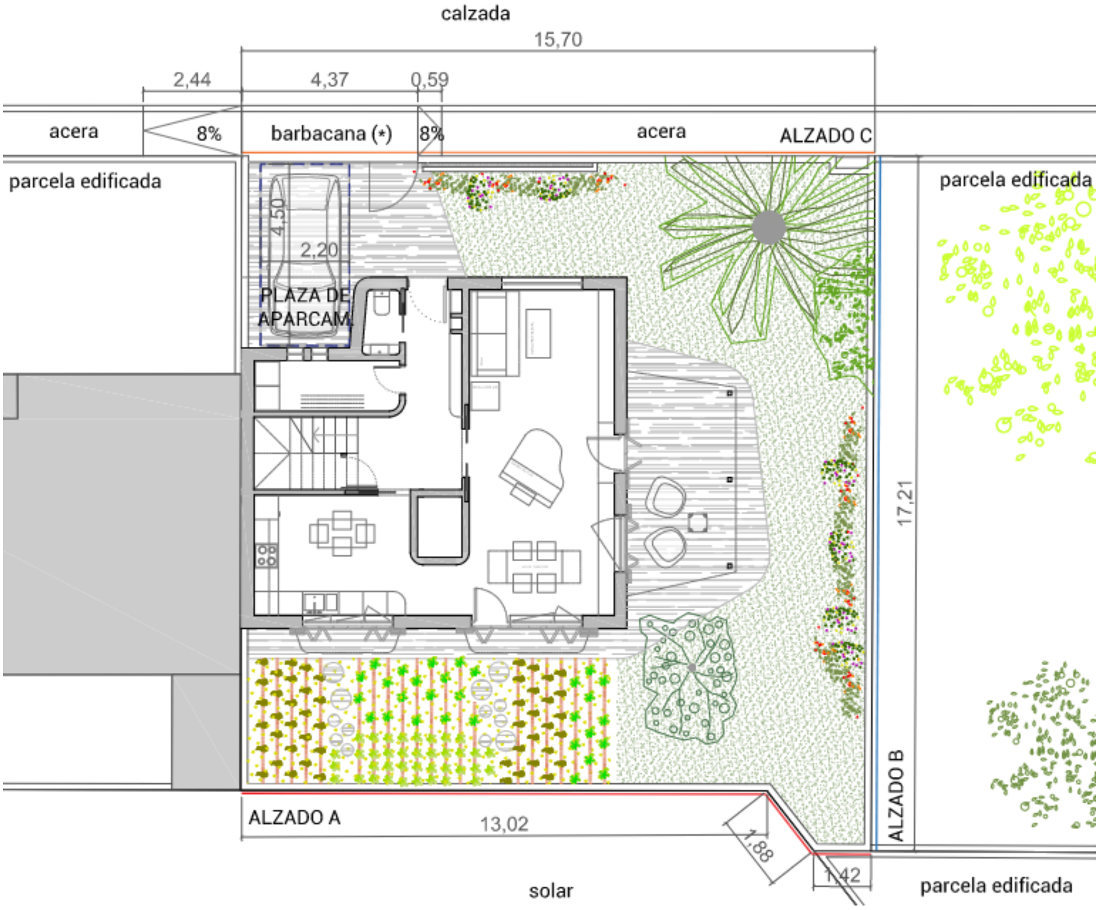


Figure S6. *Northeast and Southeast elevations of Scenario 1, Timber PassivHaus home in the outskirts of Madrid.*

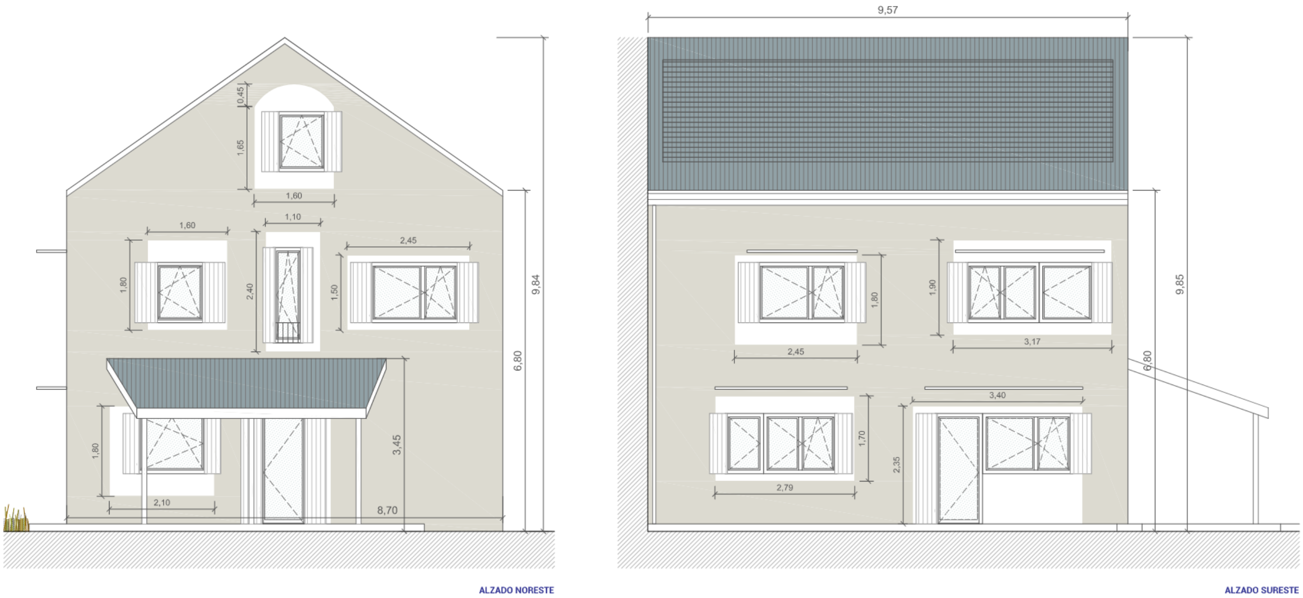


Figure S7. *Lay-out of Scenario 2, Straw with renewables house in the north mountains of Madrid.*

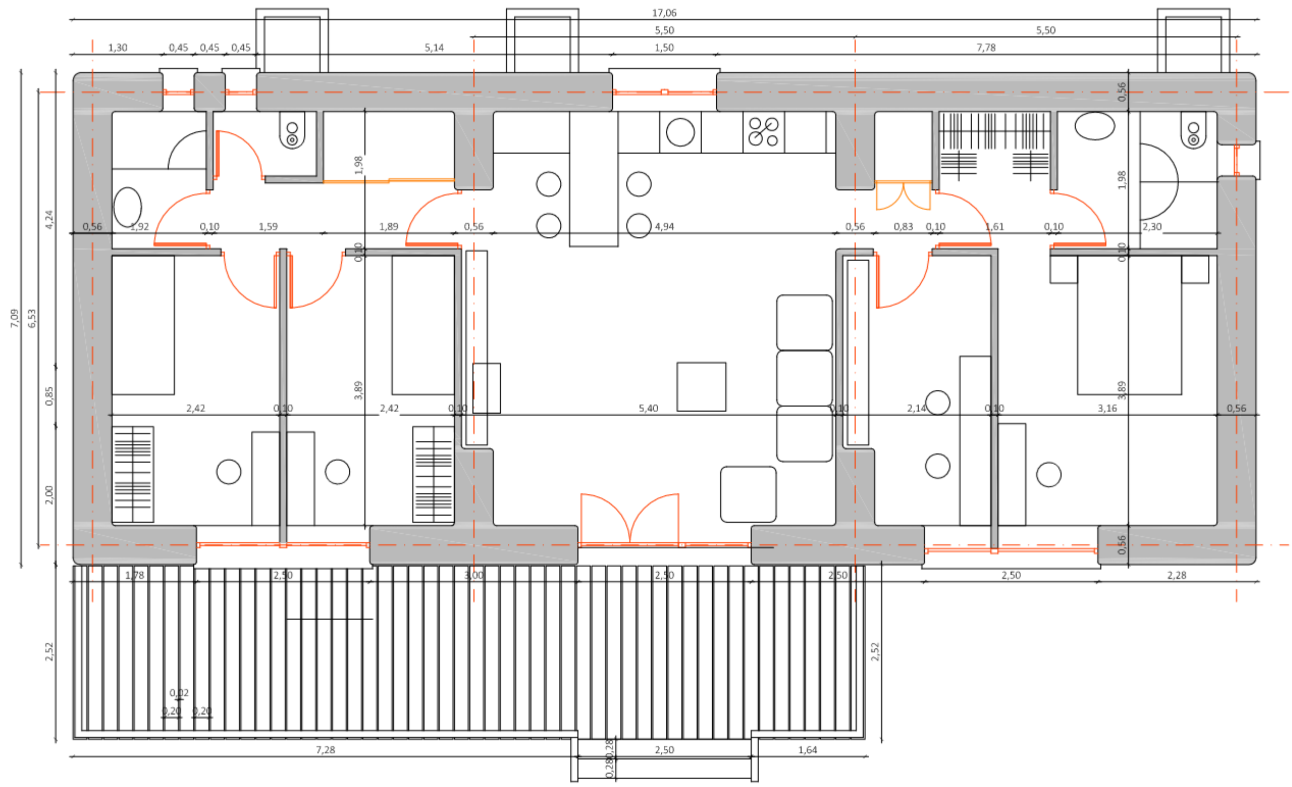


Figure S8. *South and East elevations of Scenario 2, Straw with renewables house in the north mountains of Madrid.*

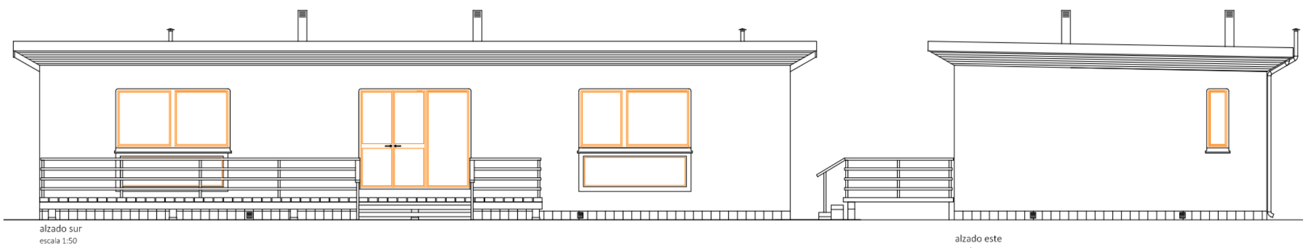


Figure S9. *Lay-out of the ground floor and first floor of Scenario 3, Earth bioclimatic house in Balager, Catalonia*

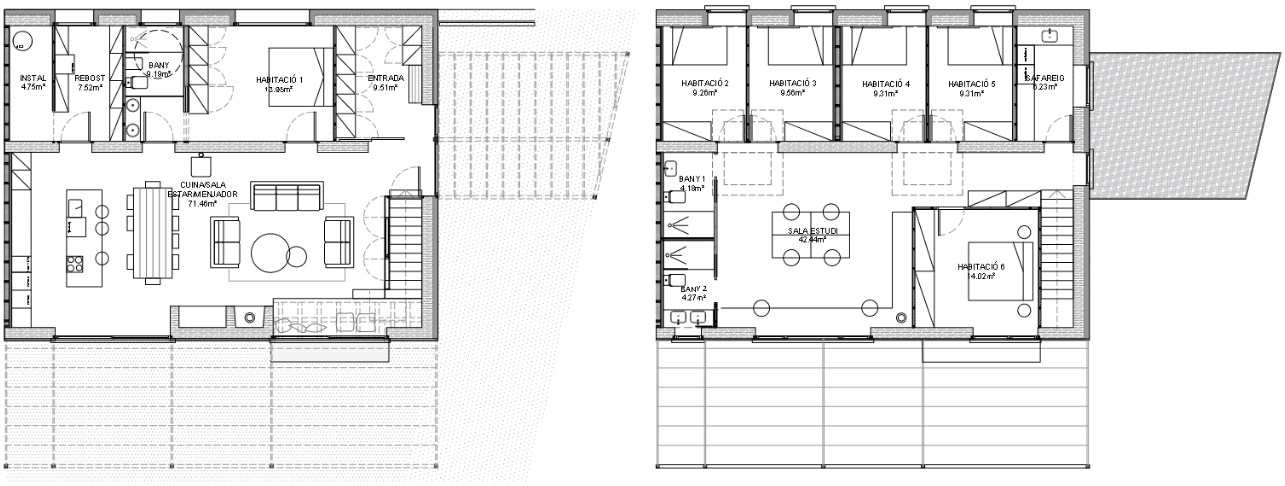


Figure S10. *South and East elevations of Scenario 3, Earth bioclimatic house in Balager, Catalonia*