Sustainable Production and Consumption 40 (2023) 252–264

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

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

Borja Izaola [a,*], Ortzi Akizu-Gardoki [a,b], Xabat Oregi [c]

[a] Life-Cycle Thinking Group, Department of Graphic Design and Engineering Projects, University of the Basque Country (UPV/EHU), Plaza Ingeniero Torres Quevedo 1, 48013 Bilbao, Spain
[b] Department of Graphic Design and Engineering Projects, University of the Basque Country (UPV/EHU), Faculty of Engineering, Plaza Ingeniero Torres Quevedo, 48013 Bilbao, Spain
[c] CAVIAR Research Group, Department of Architecture, University of the Basque Country (UPV/EHU), Plaza Oñati 2, 20018 Donostia-San Sebastián, Spain

ARTICLE INFO

Editor: Prof. K Tsagarakis

Keywords:
Life-Cycle Assessment
Greenhouse gas emissions
Whole Life Carbon
Building decarbonisation
Operational carbon
Embodied Carbon

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 processes is still in the research phase. Moreover, Global Warming Potential baselines per built square metre need 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 (WLC) emissions of the average Spanish residential buildings of the period 1981–2010, broken down into Embodied Carbon (EC) and Operational Carbon (OC). For this purpose, first, a regular average and homogenised average of existing European baselines was performed; next, the average Spanish residential building 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 WLC and their EC and OC contributions. This research shows for the average multifamily building apartment in Spain, with a mean net floor area of 73.1 m^2, a WLC baseline of 1944 kg CO_2-eq·m^{-2}, 30.8 % (559 kg CO_2-eq·m^{-2}) being EC, and the remaining 69.2 % OC. In Scenarios 1 to 3, the following are identified: a WLC reduction of 26.0 % (9.2 % EC) by using wood window frames, 0.8 % (2.7 % EC) by laying a wood inner floor, and 16.1 % (1.0 % EC) by insulating walls with recycled cork. All three items are calculated together in Scenario 4, giving a 36.9 % WLC reduction (9.5 % EC). 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 WLC reduction of 63.4 % (2.8 % EC) from the original Scenario 0. These figures support technical and policy trends towards minimising the impacts of buildings. Focusing on decarbonisation, targets of over 60 % appear feasible with existing market solutions. Reductions of >80 % are also derived from other impact categories, such as Ionizing 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 %.

1. Introduction

The environmental impacts and energy consumption trends of the construction sector must be reduced in order to face the climate emergency. In 2021, the construction sector emitted worldwide 13.6 Gt CO_2-eq. (10 Gt for operations and 3.6 Gt for the erections), 37 % of global emissions. Its energy consumption was 37,500 GWh, 36 % of global primary supply (UNEP, 2022). Residential buildings are responsible for 22 % of the sector's energy demand and 17 % of the related CO_2-eq 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

* Corresponding author.
E-mail address: bizaola001@ikasle.ehu.eus (B. Izaola).

https://doi.org/10.1016/j.spc.2023.07.001
Received 5 May 2023; Received in revised form 30 June 2023; Accepted 1 July 2023
Available online 5 July 2023

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 define environmental targets. When the focus is GHG emissions, the metric is 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 common practice yet, 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 (OC) 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, 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 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 (EC). As the share of OC diminishes, the share of EC grows (Röck et al., 2022). The new challenge is to reduce EC while keeping OC 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 EC 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 EC coefficients of common construction materials (cement, steel, etc)– 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 EC 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 EC from 420 to 1350 kg CO_2-eq$\cdot m^{-2}$ (Chastas et al., 2018), 250 to 750 kg CO_2-eq$\cdot m^{-2}$ (Wolf et al., 2014) and, in a study akin to this research (typical Spanish multifamily buildings), 603 to 627 kg CO_2-eq$\cdot m^{-2}$ (Solís 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: A1-A3 (46 to 81 %), A4 + C2 (11 to 19 %), C1 (3 to 11 %) and C3-C4 (0 to 32 %) (Hart et al., 2021). Another study from Italy takes statistical results from 24 building typologies (including the choice of this study), 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 EC and OC baselines. This is supported by standard EN15978. It 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.

The aim of this paper is to advance in finding consistent WLC baselines for European residential buildings, using a representative building of Spain's residential built stock. For this purpose, a Scenario 0 (Base) was modelled and compared with four new scenarios with different construction practices. A fifth scenario has been modelled for an updated building, now complying with NZEB standard (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 of southern Europe and Spain. Scenario 0 is compared to all others which include lower market-ready EC solutions that are progressively OC 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, EC, OC and WLC from all scenarios are compared, and another 18 indicators 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.

2. 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 Operational Energy classes are as follows (Unit is $kWh{\cdot}m^{-2}{\cdot}y^{-1}$): Class A up to 11.6; Class B, between 11.6 and 18.8; Class C, between 18.8 and 29.20, Class D between 29.20 and 44.8, Class E between 44.8 and 79.2, Class F between 79.2 and 103.8, and Class G above 103.8. The Operational Carbon classes are (Unit is kg CO_2-eq$\cdot m^{-2}\cdot y^{-1}$): A up to 6.8, B between 6.8 and 11.1, C between 11.1 and 17.2, D between 17.2 and 26.4, E between 26.4 and 59.1; F between 59.1 and 70.9, and G above 70.9.

Environmental benchmarking for buildings is demanded by 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) put the focus on normalising parameters; for instance, a lifespan of 50 years. Also, when considering OC, functional unit variations (gross floor, usable floor, net floor, built-up, living, conditioned and heated area, etc), net heated floor area is taken into account when relevant, and otherwise Net Floor Area (NFA) is used (Dodd, 2020). The range of NFA EC emissions lies between 179.3 and 1050 kg CO_2-eq·m^{-2}, with a variation of 585.6 %, and OC between 156 and 4049.9 kg CO_2-eq·m^{-2} (in 50 years). This reflects an EC share of between 9 % and 80 % of WLC. The energy efficiency standards of different buildings indicate an EC 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 the new norm, and their EC represent 71 % of the total GWP of the building (Wiik et al., 2018), due attention must be paid. When offsetting emissions through the generation of on-site renewable energy is limited, achieving low EC 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 Nearly 0 Carbon Buildings (Pan and Pan, 2021).

2.1. Embodied, operational and whole life carbon baselines

15 studies are analysed below and respective EC, OC and WLC values used to extract Average and Homogenised values. Table 1 summarises all the literature review results.

- Average Value: figure calculated by performing an average among the 15 studies. EC has a specific value in most cases. WLC adds the average of the range of OC 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.

According to Röck et al. (2022) 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. He analyses houses built in the years 2001–2021 with case studies in 5 European countries, concluding that before buildings are used, at stages A1-A5, and depending on the typology, structure and material used, emissions average 400 kg CO_2-eq·m^{-2}.

Zimmermann et al. (2021) suggested for Denmark a WLC emissions limit of 12 kg CO_2-eq·m^{-2}·y^{-1} as a voluntary baseline for new buildings from 2023, and of 8.5 kg CO_2-eq·m^{-2}·y^{-1} from 2030. In 2021, the government passed into Danish legislation the *National Strategy for Sustainable Construction*, including these values. Modules A1–3, B4, B6 and C3-C4 were taken into account when calculating EC (Danish Ministry of Interior and Housing, 2021). The Swedish authority for community planning, construction and housing drafted a similar proposal (Boverket, 2020) with reduction targets to be introduced from 2027, and Norway has engaged into the same strategy, both adopting the Danish baselines.

The Finnish Ministry of the Environment commissioned OneClickLCA to analyse over 4000 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), OC (B6) and End of Life (EoL) (C1-C4). OneClickLCA has also analysed 3737 recent European buildings (1232 residential) by screening a total dataset of over 15,000 building LCA projects (Oneclick LCA, 2021). As a result, residential EC 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

Table 1
Overview of reviewed articles and regulations on Embodied, Operational and Whole Life Carbon.

Author	Country	Nr of buildings assessed	Embodied carbon (EC) kg CO_2-eq·m^{-2}	Operational carbon (OC) kg CO_2-eq·m^{-2}	Whole life carbon kg CO_2-eq·m^{-2}	Stage A	Stage B	Stage C
(Röck et al., 2022)	EU	650	400	300–3000	2050	A1–3	B6	
(Zimmermann et al., 2021)	Denmark	60 new	500	11–230	620	A1–3	B4,6	C3–4
(Suomen Ympäristöministeriö, 2021)	Finland	4000+	450	324	774	A1–5	B3,4,6	C1–4
(Oneclick LCA, 2021)	Eastern EU	1232	580			A1–4	B4–5	C1–4
	Western EU		530					
	Northern EU		350					
(Pasanen and Castro, 2019)	EU	659	303			A1–4	B4–5	C1–4
(Décret n° 2021-1004, 2021)	France	stock	527			A1–5	B1–4,6	C1–4
(Rietz et al., 2019)	Germany	stock	470			A1–5	B1–5	C1–4
(DGNB, 2021)	Germany	stock	435			A1–5	B1–5	C1–4
(Heeren et al., 2009)	Switzerland	stock	500	500–2500	2000	A1–5	B1–6	
(UK Parliament Post, 2021), (LETI, 2020)	UK	stock	410	255	665	A1–5	B1–4,6	C1–4
(World Business Council for Sustainable Development, 2021)	Europe	6	467	1033–2850	2408	A1–5	B1–7	C1–4
(Bastos et al., 2014)	Portugal	3	315	670	985	A1–5	B1–7	C1–4
(Pan and Teng, 2021)	Global	244	443			A1–5		
		Average	**445.3**	**922.8**	**1368.2**			
		Standard Deviation	(79.6–17.9 %)	(754.1–81.7 %)	(763.6–53.8 %)			
		Homogenised	**533.3**	**765.1**	**1298.4**			
		Standard Deviation	(102.1–19,1 %	(345.4–45.1 %)	(378.8–29.1 %)			

and D into account (thus approximating full EC). In addition, RE2020 introduces a new threshold of 4 kg CO_2-eq·m^{-2}·y^{-1} for the OC of new residential buildings. From 2030 on, it proposes an EC 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 their WLC (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2020). The BNB defines a 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 2000 W 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 EC 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 1000 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 to 2050, and net zero from 2050 onwards) (LETI, 2020). It includes Module D too.

The WBCSD commissioned ARUP to research 6 buildings (only 2 residential) and assess their WLC. It found an average 50-year WLC of 1500 kg CO_2-eq·m^{-2}, with 50 % EC, 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 3908.50 kg CO_2-eq·m^{-2} shares are A1-A5 = 11.95 %, B1-B5 = 7.14 %, B6-B7 = 80.59 % and C1-C4 = 0.32 %. Market verified target comes to 1126 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 %.

Bastos et al. (2014) calculated the full LCA of three neighbouring Portuguese multi-family residential buildings from 1940 with temporalities of 50 and 75 years (this one including B5). For the 50 year LCA, EC came to 315 kg CO_2-eq·m^{-2}, average OC to 670 kg CO_2-eq·m^{-2} and resulting WLC to 985 kg CO_2-eq·m^{-2} (Bastos et al., 2014). These results are lower than average, due to the older, non-insulated brick masonry with wooden beams construction, planks for the floors and single-glazed window frames.

Pan and Teng (2021) normalised 244 case studies worldwide under 11 variables, resulting in an EC of reinforced concrete buildings of 443 kg CO_2-eq·m^{-2}. 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 EC benchmark study (Carbon Leadership Forum, 2017).

Knowing the former, and in order to calculate a homogenised single value of EC, OC and WLC for the studies analysed, data were disaggregated across stages A, B and C. Fully present, relevant average percentages per module in LETI (2020), Hart et al. (2021) and Lavagna et al. (2018) were used to complete the EC of reviewed studies, and to homogenise all modules (see supporting information, Table S1). The following assumptions and decisions were taken: A5 was missing in Röck 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 EC. 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 EC. 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 was subtracted. Benefits at Modules C3-C4 appear as negative in all studies except Suomen Ympäristöministeriö (2021), Décret n° 2021-1004 (2021), World Business Council for Sustainable Development (2021) and the present study, resulting in −0.5 % of the homogenised EC. B4 is missing in Röck et al. (2022) and the present study, but a homogenised 8 % weight was added to their EC. B6 values range between 300 and 1161.3 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 OC has been included for the rest. Pasanen and Castro (2019) and UK Parliament Post (2021) have been normalised from a 60 to a 50-year lifespan. Bastos et al. (2014) with 80 year old buildings and Pan and Teng (2021) with buildings beyond Europe fall out of time or geographic scope, but within average data.

Total homogenised EC standard deviation of 19.15 % (102 out of 533.32 kg CO_2-eq·m^{-2}) falls within a useful range of certainty, as stated in recent systematic uncertainty studies such as 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 standard deviation of 17.9 %). It provides an average WLC of 1298 kg CO_2-eq·m^{-2} (see supporting information, Table S2).

2.2. 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). The key measure for decarbonisation is to stop using fossil energy (Quintana-Gallardo et al., 2021). OC can be reduced by up to 40 % with current best practices, and up to 80 % by year 2030 and 93 % by 2045 (Karlsson et al., 2021).

As net zero OC is accomplished, reducing EC 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 at stage C1 (deconstruction) represents 40 % more waste than at stage B5. But this waste is often out of LCA scope and considered urban solid waste. However, when included, reducing, recycling and reusing strategies become more efficient, 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 EC (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).

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}. 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 to replace concrete floors in steel structural systems saves an average 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, representing 1.5 % less annual global construction GHG emissions, helping to reach nearly 0 carbon buildings (D'Amico et al., 2021). Some researchers go further exploring the potential of timber buildings as global carbon sinks (Churkina et al., 2020) or estimating a best scenario for timber building in European cities, able to store up to 47 % of the emissions of the European cement industry (Amiri et al., n.d.). 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. EC of these wood houses can be as low as 244 kg CO_2-eq·m^{-2} (Al-Najjar and Dodoo, 2022). Furthermore, to reduce the EC of floors in new construction and floor substitution, Geng et al. (2017) suggest to lay hard laminated wood tiles instead of ceramic tiling on the floors of heated areas.

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 EC 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).

Regarding windows, embodied CO2 of aluminium frames have higher impact than the glazing: 70 % of total embodied impact. PVC and fibreglass frames are responsible for 58–86 % of the embodied impacts of single-glazed windows, 46–54 % of double-glazed and 22–40 % of 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 lower heat transmittance, reducing energy demand of the envelope.

3. Methods, data and tools

The methodology used for this research is Life Cycle Assessment (LCA). Standard EN15978 specifications for the LCA of buildings were followed to provide a means for reporting outcomes: a functional unit of one square metre of an average apartment in a 50-year lifespan, within the system boundary of a Spanish multifamily residential building (see Scenario 0). To this end, two main tools and respective databases were used to perform the calculations: OpenLCA with Ecoinvent database, and OERCO2 with the Andalusian building products database (Sections 3.1 and 3.2).

3.1. Description of scenarios

Scenarios are 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 of 73.1 m^2 per apartment and a total built area of 1700 m^2 (more information in Section 3.2 and Supporting Information Figs. S1 and S2). Windows are double-glazed in sliding aluminium frames, with 2.8 W/m^{2}K transmittance (U). Inner floors are made of ceramic tiles. Insulation in cavity walls is a 3 cm-thick mineral wool mat with thermal conductivity (λ) of 0.03 W/mK. The building envelope U is 1.3 W/m^{2}K, demanding an energy consumption of Natural Gas of 2554 kWh/year for heating and 1272 kWh/year for hot water (30 % from a 6 kWp solar thermal installation on the roof) and Electricity, of 3847 kWh/year; adding a total energy demand of 7673 kWh/year (see Table 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^{2}K) instead of aluminium ones. Building U is 1.15 W/m^{2}K.

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^{2}K.

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^{2}K.

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 2430 kWh· y^{-1} for heating and hot water (30 % solar thermal, 1701 kWh·y^{-1} non-renewable) plus 4000 kWh·y^{-1} for electric appliances (50 % photovoltaic (PV), 2000 non-renewable); making up a total energy consumption of 6430 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.

3.2. 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, methodology, etc.), 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

Table 2
Energy consumption and related GHG emissions estimates per apartment, used in the building model at OpenLCA.

Demand, consumption and emissions		Unit	years 0–14	15–29	30–49
Heating demand	Natural Gas (NG)	kWh·y^{-1}	2554	3000	1250
Hot Water demand	NG	kWh·y^{-1}	1272	2500	2000
Electricity demand	Spanish Mix	kWh·y^{-1}	3847	4200	4000
Energy consumptions	NG per period	kWh	57,390	82,500	65,000
	Electricity / period	kWh	57,705	63,000	80,000
	Total NG 50 years	kWh	204,890		
	Total E 50 years	kWh	200,705		
GHG Emissions	Total NG	kg CO_2-eq·y^{-1}	10,444.98	15,015	11,830
	Total electric	kg CO_2-eq·y^{-1}	25,967.25	28,350	36,000
	Total NG 50 years	kg CO_2-eq·y^{-1}	37,289.98		
	Total E 50 years	kg CO_2-eq·y^{-1}	90,317.25		

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 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 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. 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. 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, but fitting the scope of this study. The measures in Section 2.2 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 is compatible with EN15804 (Ciroth and Arvidsson, 2021). Decisions upon applying OpenLCA to this research are:

- 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 5. 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 (Table 5) which allowed us to calculate the Energy Footprint of the building.
- 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". This incentives 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. It is common use, mature at Ecoinvent database and properly applicable to buildings (Ecoinvent database, 2017).
- 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.
- Model parameters:
  - o Scope: Whole building construction, use and end-of-life processes (NFA: 1700 m^2) as specified in Section 3.4.
  - o Functional unit: Average Spanish multifamily building apartment (NFA: 73.1 m^2), per m^2.
  - o System boundaries: Cradle-to-grave LCA from stage A to stage C
  - o Impact categories: 19 impact categories, with focus on GWP.
  - o Inventory: Input and Output flows modelled according to the sample project.

3.3. 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 et al., 2018). Material flows are introduced from selection menus matching the representative building, thanks to the common building language used. Output data appear grouped in material families or project chapters (see Supporting information, Tables S6 to S9).

3.4. 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 terms of three factors, namely age, surface and type of building. (See supporting information Tables S3 and S4). Their energy and climate targets derive from the Spanish climate integrated plan (PNIEC, 2021). A Real Estate bubble from 1994 to 2008 peaked in 2006 with over 900,000 new dwellings built (MITMA, 2020). Due to this, the period 1981–2010 accounts for 47.75 % of all Spanish homes. 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.

Apartments between 61 and 120 m^2 built in the years 1981 to 2010 represent 32.8 % of all those in Spain and appear in residential buildings of between 2 and 4 units per 3 to 5 storeys building. There are 4 million apartments of this kind, making a 20.44 % of the total (MITMA, 2020). The selected sample building for this research shows 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 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]. Based on the SECH-SPAHOUSEC project (IDAE, 2011), the average consumption per dwelling of the chosen typology is 7673 kWh/year (85.25 kWh·y^{-1}·m^2). These figures are 47.36 % of the EU average (180 kWh·y^{-1}·m^2) (European Commission, 2016). In Spain, 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 added <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) (see supporting information Table S5). 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 were made to calculate the Operational Carbon emissions. The evolution of energy demand in 50 years was calculated taking 2010 as year 0, considering the ERESEE suggested changes in equipment at the 15th and 30th year.

4. Results

Table 3 compares the Base Scenario with the other 5 modelled scenarios and Reviewed and Homogenised figures. Table 4 shows the economic investment in modules A1 to A5, most relevant for Embodied Carbon. Table 5 shows how different elements of the scenarios

Table 3
Global Warming Potential emissions per square metre of 5 scenarios modelled for the selected average building.

Scenarios		Software used	LCA EN15978 Global Warming Potential (GWP)			Averaged	Reduction from BASE	Share of Operational Carbon (OC) B6-B7 [%]	Share of Embodied Carbon (EC) [%]
			Embodied Carbon (EC) [kg CO_2eq·m^{-2}]	Operational Carbon (OC) [kg CO_2eq·m^{-2}]	Whole Life Carbon (WLC) [kg CO_2eq·m^{-2}]	Whole Life Carbon (WLC) [kg CO_2eq·m^{-2}]	Whole Life Carbon (WLC) [%]		
Reviewed	R	Various	445.35	922.83	1368.18	1368	-29.6%	67.5%	31.5%
Homogenized		Various	533.32	765.10	1298.42	1298	-33.2%	59.1%	40.9%
Scenario 0 (BASE)		OpenLCA	528.26	1,385.52	1913.78	**1944**	**0.0%**	72.4%	27.6%
		OERCO2	455.02		1840.55				
Scenario 1		OpenLCA	484.50	938.52	1423.02	1,446	-26.0%	66.0%	34.0%
		OERCO2	415.15		1353.67				
Scenario 2		OpenLCA	520.13	1,385.52	1905.65	1,929	-0.8%	72.7%	27.3%
		OERCO2	431.57		1817.09				
Scenario 3		OpenLCA	528.57	1,089.20	1617.77	1,642	-16.1%	67.3%	32.7%
		OERCO2	443.29		1532.49				
Scenario 4		OpenLCA	485.31	734.23	1219.54	1,240	-36.9%	60.2%	39.8%
		OERCO2	415.46		1149.69				
Scenario 5		OpenLCA	530.14	201.72	731.86	745	-63.4%	27.6%	72.4%
		OERCO2	440.77		642.49				

Table 4
Summary of A1- A5 total budget and reduction from Scenario 0, with OERCO2.

Scenarios		Budget invested in A1-A5 stages	
		€/m²	% of reduction from Scenario 0
Scenario 0 (Base Scenario)		603	0.0%
Scenario 1		593	-1.7%
Scenario 2		614	1.8%
Scenario 3		606	0.4%
Scenario 4		614	1.9%
Scenario 5		760	25.9%

contribute to the impacts through the simplified contribution tree of results. Finally, Table 6 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 Supporting Information, Tables S10 and S11.

Table 3 shows how EC 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 3 are shown in two ways, one separating 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 EC while maintaining the OC 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 EC (533.32 vs 530.14) and Scenario 4 OC (1298 vs 1240), corresponding to their respective constructive and energy solutions. Scenario 0 stays at the upper level of OC of the reviewed literature (Heeren et al. and WBCSD studies), over

Table 5
Comparison of GWP main flows according to the contribution trees of scenarios 0 to 5.

Main GWP contribution tree flows using OpenLCA	Scenario 0		Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	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}	%
Total	**1914**	**100%**	**1423**	**100%**	**1906**	**100%**	**1618**	**100%**	**1220**	**100%**	**732**	**100%**
market for electricity, low voltage | electricity, low voltage | Cutoff, U - ES	912	47.7%	741	52.1%	912	47.9%	745	46.0%	668	54.7%	179	24.4%
market for Natural Gas | Natural Gas | Cutoff, U - ES	457	23.9%	182	12.8%	457	24.0%	328	20.3%	55	4.5%	N/A	N/A
cement production, Portland | Cutoff, U - Europe without Sw	118	6.2%	118	8.3%	116	6.1%	118	7.3%	116	9.5%	116	15.9%
reinforcing steel production |Cutoff, U - Europe without Austria	111	5.8%	111	7.8%	110	5.8%	111	6.9%	110	9.1%	110	15.1%
market for clay brick | clay brick | Cutoff, U - GLO	81	4.2%	81	5.7%	81	4.2%	81	5.0%	81	6.6%	81	11.1%
market for window frame, aluminium, U=1.6 W/m²K | Cutoff, U - GLO	52	2.7%	N/A	N/A	52	2.7%	52	3.2%	N/A	N/A	N/A	N/A
market for glazing, double, U<1.1 W/m²K | Cutoff, U - GLO	46	2.4%	46	3.3%	46	2.4%	46	2.9%	46	3.8%	46	6.3%
market for tap water | tap water | Cutoff, U - Europe without Sw	16	0.8%	16	1.1%	16	0.8%	16	1.0%	14	1.1%	14	1.9%
market for waste reinforced concrete | Cutoff, U - Europe without Sw	15	0.8%	15	1.1%	15	0.8%	15	0.9%	15	1.2%	15	2.1%
market for roof tile | roof tile | Cutoff, U - GLO	14	0.7%	14	1.0%	14	0.7%	14	0.9%	14	1.1%	14	1.9%
market for window frame, wood, U=1.5 W/m²K | Cutoff, U - GLO	N/A	N/A	13	0.9%	N/A	N/A	N/A	N/A	13	1.1%	13	1.8%
photovoltaic flat-roof installation, 30kWp, single-Si, on roof | Cutoff, U	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	45	6.1%
Remaining flows	91	4.7%	85	6.0%	86	4.5%	91	5.6%	87	7.1%	98	13.4%

Table 6
Comparison of all impact categories at all scenarios.

Impacts per m²		Scenario 0	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
Impact Category	**Unit**	**Impact**	**Impact**	**variation**	**Impact**	**variation**	**Impact**	**variation**	**Impact**	**variation**	**Impact**	**variation**
Fossil resource scarcity, FFP	kg oil eq	889.3	611.6	-31.4%	882.9	-0.3%	707.7	-20.2%	498.0	-43.6%	211.4	-76.2%
Stratospheric ozone depletion, ODP	kg CFC11 eq	0.0	0.0	-28.9%	0.0	-0.1%	0.0	-18.0%	0.0	-40.8%	0.0	-4.7%
Global warming potential, GWP	**kg CO_2 eq**	**1913.8**	**1423.0**	**-25.8%**	**1905.7**	**0.0%**	**1617.8**	**-15.2%**	**1219.5**	**-35.9%**	**731.9**	**-61.7%**
Fine particulate matter formation, PMFP	kg PM2.5 eq	3.6	2.8	-24.0%	3.6	-0.3%	3.1	-15.4%	2.4	-33.9%	1.5	-59.4%
Human carcinogenic toxicity, HTPc	kg 1,4-DCB	230.5	159.7	-30.9%	227.9	-0.7%	165.4	-28.0%	149.8	-34.6%	119.3	-48.2%
Freshwater ecotoxicity, FETP	kg 1,4-DCB	179.6	154.2	-14.3%	176.9	-1.0%	163.2	-8.8%	147.3	-17.4%	206.1	14.9% (highest)
Water consumption, WCP	m³	64.7	38.0	-41.4%	57.9	-10.1%	45.5	-29.5%	35.7	-44.5%	5.3	-91.8% (lowest)
Ozone formation, Human health, HOFP	kg NOx eq	5.4	4.0	-24.7%	5.3	0.0%	4.5	-15.9%	3.5	-34.8%	1.9	-63.7%
Ozone Formation, Terrestrial ecosystems, EOFP	kg NOx eq	5.5	4.1	-24.6%	5.4	-0.1%	4.6	-15.8%	3.5	-34.7%	2.0	-63.8%
Mineral resource scarcity, SOP	kg Cu eq	15.6	10.9	-30.7%	14.8	-4.7%	12.1	-22.2%	10.4	-32.8%	9.1	-41.7%
Marine ecotoxicity, METP	kg 1,4-DCB	227.0	167.2	-26.5%	225.4	-0.3%	191.5	-15.4%	158.4	-29.7%	181.5	-20.0%
Human non-carcinogenic toxicity, HTPnc	kg 1,4-DCB	1842.7	1526.9	-17.3%	1834.6	0.0%	1633.9	-11.1%	1385.7	-24.3%	1068.8	-41.9%
Freshwater eutrophication, FEP	kg P eq	0.6	0.4	-23.7%	0.6	-0.1%	0.5	-15.1%	0.4	-33.7%	0.2	-61.1%
Ionizing radiation, IRP	kBq Co-60 eq	703.7	480.4	-31.9%	700.7	0.0%	559.2	-20.3%	381.8	-45.4%	111.6	-84.1%
Marine eutrophication, MEP	kg N eq	0.1	0.0	-24.7%	0.1	0.0%	0.0	-16.1%	0.0	-35.1%	0.0	-88.5%
Land use, LOP	m²a crop eq	35.8	28.2	-21.5%	35.6	0.0%	30.7	-14.0%	24.9	-30.0%	22.9	-36.1%
Terrestrial acidification, TAP	kg SO_2 eq	8.7	6.4	-26.4%	8.6	-0.4%	7.2	-17.1%	5.4	-37.3%	2.9	-66.9%
Terrestrial ecotoxicity, TETP	kg 1,4-DCB	4970.0	4138.8	-16.9%	4930.0	-0.4%	4362.2	-12.0%	3841.4	-22.2%	3088.8	-37.8%
Energy footprint, EF	kWh	2337.4	1979.3	-15.5%	2280.6	-2.0%	2154.5	-7.6%	1826.9	-21.3%	1753.4	-24.9%
Average variation compared to Scenario 0				**-25.3%**		**-1.1%**		**-16.7%**		**-33.3%**		**-50.4%**
Standard deviation				**6.61%**		**2.45%**		**5.6%**		**7.79%**		**28.26%**

1000 kg CO_2-eq·m^{-2} (1385), in accordance with official Spanish Government data (PNIEC, 2021). The EC values obtained with OERCO2 are aligned with the reviewed average fig. (455.02 and 454.64 respectively). Scenario 1 brings about the best single results, lowering EC by 9 %, by replacing aluminium with wood window frames, and OC by 32 % by improving on the envelope transmittance of Scenario 0. Scenario 2 shows little impact, as mentioned above.

Scenario 3's EC 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 3 cm). This all meant that the general weight of the external insulation input flow (for the modelled building) in OpenLCA is 1001 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 EC 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 OC of 1089 (21 % less than in Scenario 0).

The combination of better construction solutions from Scenario 4 reduces Scenario 0 WLC 36.9 % by cutting both EC and OC, 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 EC due to the photovoltaic installation. As a result, the shares of EC and OC values become inverted between scenario 0 and scenario 5. This can be seen in Fig. 1, where EC and OC lines cross.

Table 4 briefly 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.

The contribution of different materials and processes to the WLC in Table 5 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, 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

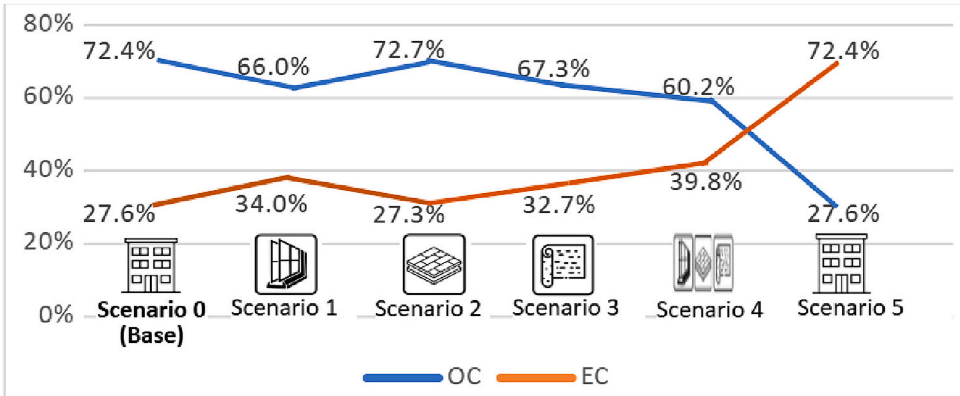

Fig. 1. Share of Embodied Carbon (EC) and Operational Carbon (OC) across Scenarios 0 to 5.

(235, 91 and 435 t respectively) speaks for their high impact. Aluminium in window frames ranks 6th with 52 kg CO_2-eq·m^{-2}, but the wood ones have 25 % its impact. 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 OC, only B6 (energy use stage) without B7 (water use stage), it is observed that tap water production consumed in the life cycle of a building 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 be seen that the photovoltaic installation in Scenario 5 contributes 6.3 % of the total emissions with 45 kg CO_2-eq·m^{-2}.

In Table 6, 19 indicators are shown: 18 impact categories are calculated using ReCiPe Midpont (H) method, 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 eco-toxicity. It has been detected that the proportion of the five joint eco-toxicity 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.

5. Discussion

This paper shows that national regulations can lower WLC, EC and OC. 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 EC of 500 kg CO_2-eq·m^{-2} and an OC 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 average aluminium frames. Also, considering budget analyses, lower EC materials do not increase the costs, but technical equipment does. New renewable energy equipment reduces OC from 734 to 201 kg CO_2-eq·m^{-2}, but also increases EC 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 6, 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 EC 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 EC 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, OC could be cut by 85 % (from 1385 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 3, the initial EC 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 EC, at least when B4 and B5 are not taken into account.

Bearing this in mind, an EC 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 in Section 2.2 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 nearly 0 carbon buildings and the decarbonisation of the building sector. Regarding OC, the Scenario 0 value of 1385.52 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.

The integration of the obtained baselines to the real building market and regulations presents uptake limitations by a sector which sees itself over-regulated by environmental pressures. The article has attempted to average literature review data by homogenizing existing values and filling the gaps with best practices, in order to draw a baseline of building emissions which might become a policy tool. But this would need more dissemination actions. Comparing the different approaches of the reviewed studies helped understand the modellers' choices and the impact of these choices on their results related to the application of standard EN15978 and overall LCA use. Uncertainty from comparing, averaging and homogenizing these results fell within an accepted deviation (Feng et al., 2022) and enabled comparing those results with the results calculated in this research. Furthermore, in future research, specific buildings' LCA uncertainty will decrease and the baseline become more precise for new different scenarios. For national stock policies, averages with lower deviation standards could imply benefits for builders. Nevertheless, this is a starting point in drafting baselines.

The scientific community worldwide might not need to consider European standards. However, this article supports the use of EN15978 and related standards, as well as the Level(s) Framework, so that they become common and therefore comparable, improvable and creating critical mass for wider scientific studies. But these standards also present limitations, and energy consumption data offers variations related to lifestyle, individual energy demand, foreseen changes in the national energy mix, change of occupants during a building lifecycle and regulatory evolution.

When attempting to baseline energy consumption data in the form of Operation Carbon emissions, limitations appear concerning climate zones and cultural issues. It can be argued that a single building in one specific zone cannot represent others, even less in countries as Spain, with large geographic differences. However, if NZEBs are to become the new normal, as stated above, climate, geography or inhabitants' use will automatically be normalised, and the relative impact of OC significantly lowered, as made evident in Scenario 5. Some of the reviewed studies (Röck et al., 2022), (Zimmermann et al., 2021), (Pasanen and Castro, 2019), (Décret n° 2021-1004, 2021), (DGNB, 2021), approach the issue similarly in terms of national stock, regardless of the climate and cultural differences, using different but complementary methodologies. In our case identifying a typology representative of 20 % of the national stock, though limited, appears useful for setting initial baselines.

While the study focuses on GWP, 18 other environmental impacts are detailed, and their weight highlighted in Table 6. However, it is out of the scope of this article to assess if other impacts than GWP would be more relevant for buildings, cities, humans and the planet. Authors consider that impacts on biodiversity should be faced in future research, in accordance with (IPBES, 2018). There is a risk to lose valuable scientific and political effort and time if we consider climate change the main planetary damage of buildings, and not biodiversity loss.

6. 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 (OC) is reduced by 85 %. The Life-Cycle Assessment (LCA) methodology applied here suggests a credible WLC baseline of 745 kg $CO_2eq \cdot m^{-2}$ (202 OC, equivalent to Class A in the EPBD). The key concept of Embodied Carbon (EC) is underlined for its relevance to accomplish climate targets. Easily attainable material choices fall at 500 kg $CO_2eq \cdot m^{-2}$ of EC and can be lowered if all Modules of EN15978 are taken into account. The more the electricity mixes are decarbonised, the bigger the OC reduction from the current average of 1386 kg $CO_2eq \cdot m^{-2}$. However, the share of EC 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 eventually 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 EC and OC. EC 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.

Declaration of competing interest

No Conflict of interest has been identified concerning the manuscript titled: "Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building" or in relation to the authors Borja Izaola, Ortzi Akizu-Gardoki, and Xabat Oregi; or their affiliations.

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 (UPV/EHU).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.07.001.

References

AENOR, 2021. DIN EN 15978-1:2021-09 Sustainability of construction works [WWW Document]. URL. https://tienda.aenor.com/norma-din-en-15978-1-2021-09-337039423 (accessed 7.24.22).

Akizu-Gardoki, O., Bueno, G., Wiedmann, T., Lopez-Guede, J.M., Arto, I., Hernandez, P., Moran, D., 2018. Decoupling between human development and energy consumption within footprint accounts. J. Clean. Prod. 202, 1145–1157. https://doi.org/10.1016/j.jclepro.2018.08.235.

Akizu-Gardoki, O., Kunze, C., Coxeter, A., Bueno, G., Wiedmann, T., Lopez-Guede, J.M., 2020. Discovery of a possible Well-being Turning Point within energy footprint accounts which may support the degrowth theory. Energy Sustain. Dev. 59, 22–32. https://doi.org/10.1016/j.esd.2020.09.001.

Al-Najjar, A., Dodoo, A., 2022. Modular multi-storey construction with cross-laminated timber: life cycle environmental implications. Wood Mater. Sci. Eng. 0, 1–15. https://doi.org/10.1080/17480272.2022.2053204.

Amiri, A., Emami, N., Ottelin, J., Sorvari, J., Marteinsson, B., Heinonen, J., Junnila, S., 2021. Embodied emissions of buildings - a forgotten factor in green building certificates. Energy Build. 241, 110962 https://doi.org/10.1016/j.enbuild.2021.110962.

Ali Amiri, Juudit Ottelin, Jaana Sorvari and Seppo Junnila. Cities as carbon sinks-classification of wooden buildings. Environ. Res. Lett. 15 094076. **DOI** https://doi.org/10.1088/1748-9326/aba134.

Attia, S., Santos, M.C., Al-Obaidy, M., Baskar, M., 2021. Leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design. IOP Conf. Ser.: Earth Environ. Sci. 855, 012023 https://doi.org/10.1088/1755-1315/855/1/012023.

Bastos, J., Batterman, S.A., Freire, F., 2014. Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon. Energy Build. 69, 344–353. https://doi.org/10.1016/j.enbuild.2013.11.010.

Boverket, 2020. Swedish Regulation on Climate Declarations for Buildings, p. 154.

BSO, E.C., 2020. EU Building Stock Observatory [WWW Document]. URL. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/eu-building-stock-observatory_en (accessed 4.5.22).

Building Life Project, 2020. #BuildingLife [WWW Document]. World Green Building Council. URL. https://www.worldgbc.org/buildinglife (accessed 1.7.21).

Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2020. Assessment System - Bewertungssystem Nachhaltiges Bauen (BNB) [WWW Document]. URL. https://www.bnb-nachhaltigesbauen.de/en/assessment-system/ (accessed 4.15.22).

Carbon Leadership Forum, 2017. Embodied carbon benchmark study [WWW Document]. URL. https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/38017/CLF%20Embodied%20Carbon%20Benchmark%20Study.pdf?sequence=4&isAllowed=y (accessed 7.23.22).

CEN/TC350, 2022. CEN - CEN/TC 350 [WWW Document]. URL. https://standards.cencenelec.eu/dyn/www/f?p=205:110:0::::FSP_PROJECT:31325&cs=1A3C0B97A15F0E1E14D0D12BD7A5C1291 (accessed 7.24.22).

Chastas, P., Theodosiou, T., Kontoleon, K.J., Bikas, D., 2018. Normalising and assessing carbon emissions in the building sector: a review on the embodied CO2 emissions of residential buildings. Build. Environ. 130, 212–226. https://doi.org/10.1016/j.buildenv.2017.12.032.

Churkina, G., Organschi, A., Reyer, C.P.O., et al., 2020. Buildings as a global carbon sink. Nat. Sustain. 3, 269–276. https://doi.org/10.1038/s41893-019-0462-4.

Ciroth, A., Arvidsson, R. (Eds.), 2021. Life Cycle Inventory Analysis: Methods and Data, LCA Compendium. Springer, Cham, Switzerland.

Ciroth, A., Barreiros, T., Jürgens, M., 2021. Ecoinvent v3.8 in OpenLCA [WWW Document]. URL. https://nexus.openlca.org/ws/files/22528 (accessed 4.25.22).

D'Amico, B., Pomponi, F., Hart, J., 2021. Global potential for material substitution in building construction: the case of cross laminated timber. J. Clean. Prod. 279, 123487 https://doi.org/10.1016/j.jclepro.2020.123487.

Dams, B., Maskell, D., Shea, A., Allen, S., Driesser, M., Kretschmann, T., Walker, P., Emmitt, S., 2021. A circular construction evaluation framework to promote designing for disassembly and adaptability. J. Clean. Prod. 316, 128122 https://doi.org/10.1016/j.jclepro.2021.128122.

Danish Ministry of Interior and Housing, 2021. National_Strategy_for_Sustainable_Construktion.pdf [WWW Document]. URL. https://im.dk/Media/637602217765946554/National_Strategy_for_Sustainable_Construktion.pdf (accessed 4.15.22).

Décret n° 2021-1004 du 29 juillet 2021 relatif aux exigences de performance énergétique et environnementale des constructions de bâtiments en France métropolitaine, 2021. 2021-1004.

DGNB, 2021. Benchmarks für die Treibhausgasemissionen der Gebaeudekonstruktion.pdf [WWW Document]. URL. https://static.dgnb.de/fileadmin/dgnb-ev/de/themen/Klimaschutz/Toolbox/102021_Studie-Benchmarks-fuer-die-Treibhausgasemissionen-der-Gebaeudekonstruktion.pdf?m=1633093306 (accessed 4.15.22).

Dodd, N., 2020. Level(s) –a common EU framework of core sustainability indicators for office and residential buildings [WWW Document]. URL. https://susproc.jrc.ec.europa.eu/product-bureau//sites/default/files/2020-10/20201013%20New%20Level(s)%20documentation_1%20Introduction_Publication%20v1-0.pdf (accessed 10.19.20).

Ecoinvent database, 2017. System Models. ecoinvent. URL. https://ecoinvent.org/the-ecoinvent-database/system-models/ (accessed 4.25.22).

European Commission, 2016. EU Buildings Factsheets [WWW Document]. Energy - European Commission. URL. https://ec.europa.eu/energy/eu-buildings-factsheets_en (accessed 4.26.22).

European Commission, 2021a. Energy performance of buildings directive [WWW Document]. URL. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed 3.26.22).

European Commission, 2021b. Annexes to the Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast) [WWW Document]. URL. https://eur-lex.europa.eu/resource.html?uri=cellar:c51fe6d1-5da2-11ec-9c6c-01aa75ed71a1.0001.02/DOC_2&format=PDF (accessed 3.26.22).

Feng, H., Zhao, J., Zhang, H., Zhu, S., Li, D., Thurairajah, N., 2022. Uncertainties in whole-building life cycle assessment: a systematic review. J. Build. Eng. 50, 104191 https://doi.org/10.1016/j.jobe.2022.104191.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2005. The ecoinvent database: overview and methodological framework (7 pp). Int. J. Life Cycle Assess. 10, 3–9. https://doi.org/10.1065/lca2004.10.181.1.

Frischknecht, R., Balouktsi, M., Lützkendorf, T., Aumann, A., Birgisdottir, H., Ruse, E.G., Hollberg, A., Kuittinen, M., Lavagna, M., Lupišek, A., Passer, A., Peuportier, B., Ramseier, L., Röck, M., Trigaux, D., Vancso, D., 2019. Environmental benchmarks for buildings: needs, challenges and solutions—71st LCA forum, Swiss Federal Institute of Technology, Zürich, 18 June 2019. Int. J. Life Cycle Assess. 24, 2272–2280. https://doi.org/10.1007/s11367-019-01690-y.

Geng, A., Zhang, H., Yang, H., 2017. Greenhouse gas reduction and cost efficiency of using wood flooring as an alternative to ceramic tile: a case study in China. J. Clean. Prod. 166, 438–448. https://doi.org/10.1016/j.jclepro.2017.08.058.

Giorgi, S., Lavagna, M., Wang, K., Osmani, M., Liu, G., Campioli, A., 2022. Drivers and barriers towards circular economy in the building sector: stakeholder interviews and analysis of five european countries policies and practices. J. Clean. Prod. 130395 https://doi.org/10.1016/j.jclepro.2022.130395.

Griffin, P.W., Hammond, G.P., McKenna, R.C., 2021. Industrial energy use and decarbonisation in the glass sector: a UK perspective. Adv. Appl. Energy 3, 100037. https://doi.org/10.1016/j.adapen.2021.100037.

Hart, J., D'Amico, B., Pomponi, F., 2021. Whole-life embodied carbon in multistory buildings: steel, concrete and timber structures. J. Ind. Ecol. 25, 403–418. https://doi.org/10.1111/jiec.13139.

Heeren, N., Gabathuler, M., Wallbaum, H., 2009. Gebäudeparkmodell SIA Effizienzpfad Energie Dienstleistungs- und Wohngebäude [WWW Document]. URL. https://www.osti.gov/etdeweb/servlets/purl/22122434 (accessed 4.26.22).

Himes, A., Busby, G., 2020. Wood buildings as a climate solution. Dev. Built Environ. 4, 100030 https://doi.org/10.1016/j.dibe.2020.100030.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.
IDAE, 2011. documentos_Informe_SPAHOUSEC_ACC_f68291a3.pdf [WWW Document]. URL. https://www.idae.es/uploads/documentos/documentos_Informe_SPAHOUSEC_ACC_f68291a3.pdf (accessed 3.27.22).
IPBES, 2018. Summary for Policymakers of the Regional Assessment Report on Biodiversity and Ecosystem Services for Europe and Central Asia of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.
Iswara, A.P., Farahdiba, A.U., Nadhifatin, E.N., Pirade, F., Andhikaputra, G., Muflihah, I., Boedisantoso, R., 2020. A comparative study of life cycle impact assessment using different software programs. IOP Conf. Ser.: Earth Environ. Sci. 506, 012002 https://doi.org/10.1088/1755-1315/506/1/012002.
Izaola, B., Akizu-Gardoki, O., Oregi, X., 2022. Life cycle analysis challenges through building rating schemes within the European framework. Sustainability 14, 5009. https://doi.org/10.3390/su14095009.
Karlsson, I., Rootzén, J., Toktarova, A., Odenberger, M., Johnsson, F., Göransson, L., 2020. Roadmap for decarbonization of the building and construction industry—a supply chain analysis including primary production of steel and cement. Energies 13, 4136. https://doi.org/10.3390/en13164136.
Karlsson, I., Rootzén, J., Johnsson, F., Erlandsson, M., 2021. Achieving net-zero carbon emissions in construction supply chains – a multidimensional analysis of residential building systems. Dev. Built Environ. 8, 100059 https://doi.org/10.1016/j.dibe.2021.100059.
Lavagna, M., Baldassarri, C., Campioli, A., Giorgi, S., Dalla Valle, A., Castellani, V., Sala, S., 2018. Benchmarks for environmental impact of housing in Europe: definition of archetypes and LCA of the residential building stock. Build. Environ. 145, 260–275. https://doi.org/10.1016/j.buildenv.2018.09.008.
Lechtenböhmer, S., Schüring, A., 2011. The potential for large-scale savings from insulating residential buildings in the EU. Energy Effic. 4, 257–270. https://doi.org/10.1007/s12053-010-9090-6.
LETI, 2020. LETI Embodied Carbon Primer.
Li, H., Luo, Z., Xu, X., Cang, Y., Yang, L., 2021. Assessing the embodied carbon reduction potential of straw bale rural houses by hybrid life cycle assessment: a four-case study. J. Clean. Prod. 303, 127002 https://doi.org/10.1016/j.jclepro.2021.127002.
Living Future, 2020. Zero carbon standard 1.0. International living Future institute. URL. https://living-future.org/zero-carbon/zero-carbon-certification/ (accessed 7.23.22).
Lopes Silva, D.A., Nunes, A.O., Piekarski, C.M., da Silva Moris, V.A., de Souza, L.S.M., Rodrigues, T.O., 2019. Why using different Life Cycle Assessment software tools can generate different results for the same product system? A cause–effect analysis of the problem. Sustain. Prod. Consum. 20, 304–315. https://doi.org/10.1016/j.spc.2019.07.005.
Marrero, M., Rivero-Camacho, C., Alba-Rodríguez, M.D., 2020. What are we discarding during the life cycle of a building? Case studies of social housing in Andalusia, Spain. Waste Manag. 102, 391–403. https://doi.org/10.1016/j.wasman.2019.11.002.
Martínez-Rocamora, A., Solís-Guzmán, J., Marrero, M., 2016. LCA databases focused on construction materials: a review. Renew. Sust. Energ. Rev. 58, 565–573. https://doi.org/10.1016/j.rser.2015.12.243.
Martínez-Rocamora, A., Rivera-Gómez, C., Galán-Marín, C., Marrero, M., 2021. Environmental benchmarking of building typologies through BIM-based combinatorial case studies. Autom. Constr. 132, 103980 https://doi.org/10.1016/j.autcon.2021.103980.
Mastrucci, A., Marvuglia, A., Leopold, U., Benetto, E., 2017. Life cycle assessment of building stocks from urban to transnational scales: a review. Renew. Sust. Energ. Rev. 74, 316–332. https://doi.org/10.1016/j.rser.2017.02.060.
Mata, É., Korpal, A.K., Cheng, S.H., Navarro, J.P.J., Filippidou, F., Reyna, J., Wang, R., 2020. A map of roadmaps for zero and low energy and carbon buildings worldwide. Environ. Res. Lett. 15, 113003 https://doi.org/10.1088/1748-9326/abb69f.
McConahey, E., 2022. Why whole life carbon assessment is important. ASHRAE J. 64 (48–50), 52–55.
MITMA, 2020. ERESEE es_ltrs_2020.pdf [WWW Document]. URL. https://www.mitma.gob.es/recursos_mfom/paginabasica/recursos/es_ltrs_2020.pdf (accessed 3.27.22).
Monteiro, H., Freire, F., Fernández, J.E., 2020. Life-cycle assessment of alternative envelope construction for a new house in South-Western Europe: embodied and operational magnitude. Energies 13, 4145. https://doi.org/10.3390/en13164145.
Muñoz, P., Dominguez, D., Morales, M.P., Muñoz, L., Sanchez-Vazquez, R., 2021. The effect of infill walls made by eco materials on mechanical response, energy performance and CO2 print of residential and non-residential low-rise buildings. Energy Build. 243, 110996 https://doi.org/10.1016/j.enbuild.2021.110996.
Nägeli, C., Jakob, M., Catenazzi, G., Ostermeyer, Y., 2020. Policies to decarbonize the Swiss residential building stock: an agent-based building stock modeling assessment. Energy Policy 146, 111814. https://doi.org/10.1016/j.enpol.2020.111814.
Nägeli, C., Camarasa, C., Delghust, M., Fennell, P., Hamilton, I., Jakob, M., Langevin, J., Laverge, J., Reyna, J.L., Sandberg, N.H., Webster, J., 2022. Best practice reporting guideline for building stock energy models. Energy Build. 260, 111904 https://doi.org/10.1016/j.enbuild.2022.111904.
Oneclick LCA, 2021. Embodied carbon benchmarks for european buildings [WWW Document]. URL. https://www.oneclicklca.com/wp-content/uploads/2021/06/Embodied-Carbon-Benchmarks-for-European-Buildings-10-June-2021-FINAL.pdf?vgo_ee=PY3emMgU%2FQlGP2xLIRmkF3wvT3F2uI14Y2xWLYpg3os%3D (accessed 4.16.22).
Pamu, Y., Kumar, V.S.S., Shakir, M.A., Ubbana, H., 2022. Life Cycle Assessment of a building using Open-LCA software. In: Materials Today: Proceedings, International Conference on Smart and Sustainable Developments in Materials, Manufacturing and Energy Engineering, 52, pp. 1968–1978. https://doi.org/10.1016/j.matpr.2021.11.621.
Pan, W., Pan, M., 2021. Drivers, barriers and strategies for zero carbon buildings in high-rise high-density cities. Energy Build. 242, 110970 https://doi.org/10.1016/j.enbuild.2021.110970.
Pan, W., Teng, Y., 2021. A systematic investigation into the methodological variables of embodied carbon assessment of buildings. Renew. Sust. Energ. Rev. 141, 110840 https://doi.org/10.1016/j.rser.2021.110840.
Pasanen, P., Castro, R., 2019. Carbon heroes benchmark program – whole building embodied carbon profiling. IOP Conf. Ser.: Earth Environ. Sci. 323, 012028 https://doi.org/10.1088/1755-1315/323/1/012028.
PNIEC, 2021. BOE-A-2021-5106 Resolución de 25 de marzo de 2021, conjunta de la Dirección General de Política Energética y Minas y de la Oficina Española de Cambio Climático, por la que se publica el Acuerdo del Consejo de Ministros de 16 de marzo de 2021, por el que se adopta la versión final del Plan Nacional Integrado de Energía y Clima 2021-2030 [WWW Document]. URL. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2021-5106 (accessed 3.1.23).
Pomponi, F., Moncaster, A., 2018. Scrutinising embodied carbon in buildings: the next performance gap made manifest. Renew. Sust. Energ. Rev. 81, 2431–2442. https://doi.org/10.1016/j.rser.2017.06.049.
Pomponi, F., Moncaster, A., De Wolf, C., 2018. Furthering embodied carbon assessment in practice: results of an industry-academia collaborative research project. Energy Build. 167, 177–186. https://doi.org/10.1016/j.enbuild.2018.02.052.
Quintana-Gallardo, A., Schau, E.M., Niemelä, E.P., Burnard, M.D., 2021. Comparing the environmental impacts of wooden buildings in Spain, Slovenia, and Germany. J. Clean. Prod. 329, 129587 https://doi.org/10.1016/j.jclepro.2021.129587.
Rasmussen, F., Birkved, M., Birgisdóttir, H., 2019. Upcycling and Design for Disassembly – LCA of buildings employing circular design strategies. IOP Conf. Ser.: Earth Environ. Sci. 225, 012040 https://doi.org/10.1088/1755-1315/225/1/012040.
RIBA, 2021. RIBA 2030 Climate Challenge.
Rietz, A., Kerz, N., Welsch, M., 2019. Experiences from the implementation of the assessment system for sustainable building (BNB) in Germany. IOP Conf. Ser.: Earth Environ. Sci. 290, 012059 https://doi.org/10.1088/1755-1315/290/1/012059.
Röck, Martin, Sørensen, Andreas, Steinmann, Jacob, Lynge, Kirsten, Horup, Lise Hvid, Tozan, Buket, Le Den, Xavier, Birgisdottir, Harpa, 2022. Towards embodied carbon benchmarks for buildings in Europe - #1 facing the data challenge. Zenodo. https://doi.org/10.5281/ZENODO.6120522.
Saadatian, S., Freire, F., Simões, N., 2021. Embodied impacts of window systems: a comparative assessment of framing and glazing alternatives. J. Build. Eng. 35, 102042 https://doi.org/10.1016/j.jobe.2020.102042.
Sandberg, N.H., Næss, J.S., Brattebø, H., Andresen, I., Gustavsen, A., 2021. Large potentials for energy saving and greenhouse gas emission reductions from large-scale deployment of zero emission building technologies in a national building stock. Energy Policy 152, 112114. https://doi.org/10.1016/j.enpol.2020.112114.
Solís-Guzmán, J., Rivero-Camacho, C., Alba-Rodríguez, D., Martínez-Rocamora, A., 2018. Carbon footprint estimation tool for residential buildings for non-specialized users: OERCO2 project. Sustainability 10, 1359. https://doi.org/10.3390/su10051359.
Suomen Ympäristöministeriö, 2021. Carbon footprint limits for common building types [WWW Document]. URL. https://mrluudistus.fi/wp-content/uploads/2021/03/Bionova_MinEnv_Finland_embodied_carbon_limit_values_report_1March2021.pdf (accessed 3.31.21).
Trigaux, D., Allacker, K., Debacker, W., 2019. Critical analysis of environmental benchmarks for buildings. IOP Conf. Ser.: Earth Environ. Sci. 323, 012031 https://doi.org/10.1088/1755-1315/323/1/012031.
Trigaux, D., Allacker, K., Debacker, W., 2021. Environmental benchmarks for buildings: a critical literature review. Int. J. Life Cycle Assess. 26, 1–21. https://doi.org/10.1007/s11367-020-01840-7.
UK Parliament Post, 2021. Reducing the whole life carbon impact of buildings [WWW Document]. URL. https://researchbriefings.files.parliament.uk/documents/POST-PB-0044/POST-PB-0044.pdf (accessed 4.27.22).
UNEP, U.N., 2021. 2021 Global Status Report for Buildings and Construction [WWW Document]. UNEP - UN Environment Programme. URL. http://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction (accessed 3.28.22).
UNEP, 2022. 2022 Global Status Report for Buildings and Construction [WWW Document]. UNEP - UN Environment Programme. URL. http://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction (accessed 12.28.22).
WGBC, 2022. EU WLC Roadmap [WWW Document]. URL. https://viewer.ipaper.io/worldgbc/eu-roadmap/?page=8 (accessed 7.23.22).
Wiik, M.K., Fufa, S.M., Kristjansdottir, T., Andresen, I., 2018. Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre. Energy Build. 165, 25–34. https://doi.org/10.1016/j.enbuild.2018.01.025.
Wolf, D., Lieve, C., Catherine, E., 2014. Material Quantities in Building Structures and their Environmental Impact (Thesis). Massachusetts Institute of Technology.
World Business Council for Sustainable Development, 2021. Net zero buildings. Where do we stand? [WWW Document]. URL. https://www.arup.com/-/media/arup/files/publications/n/net-zero-buildings-arup-wbcsd.pdf (accessed 4.28.22).
Zimmermann, R.K., Andersen, C.M.E., Kanafani, K., Birgisdottir, H., 2021. Whole Life Carbon Assessment of 60 Buildings: Possibilities to Develop Benchmark Values for LCA of Buildings (Report), Whole Life Carbon Assessment of 60 Buildings. Lyngby, Polyteknisk Boghandel og Forlag, Kgs.