Comparative Analysis of Whole Life Carbon Assessments

Key GWP parameters identified by the Concrete Sector for the appropriate accounting methodology

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1. Executive summary

1.1 Introduction

The European Union's (EU) goal to decarbonise its economy and reach climate neutrality by 2050 requires large cuts in Greenhouse-Gas (GHG) emissions across all sectors (European Climate Law, 2021/1119/EU). The construction sector accounts for about 36% of GHG emissions; embedded (embodied) carbon – emissions from construction activities and the production of materials (cement, steel, glass, insulation) – represents roughly 10–20% of those emissions. So far, EU and Member-State policies have focused mainly on Operational Energy and associated Operational Carbon (OC); however, by the revision of the Energy Performance of Buildings Directive (EPBD IV, 2024/1275/EU), the EU introduces the Embodied Carbon (EC) indicator – used to account for materials production, installation, maintenance, and end-of-life emissions. This indicator, combined with OC, yields the Whole Life Carbon (WLC) balance for a building across all life cycles (from stage A to stage C).

1.2 Context

The Energy Performance of Buildings Directive (2010/31/EU), including the transposition of the 2018 amendments, introduced key obligations to improve the energy performance of buildings. These include requirements for Nearly Zero-Energy Buildings (NZEB), Energy Performance Certificates (EPCs), deep renovation measures, and long-term renovation strategies.

EU Member States have transposed the directive, integrating these obligations into national regulatory frameworks and implementation systems, including performance requirements, energy certificates, incentive schemes, and compliance controls.

In almost all Member States, the Energy Performance of Buildings Directive (EPBD) has been transposed; however, its effective implementation varies in the stringency of requirements, the scope of enforcement, and the instruments used (technical standards, requirements for residential vs non-residential buildings, and fiscal incentives).

Recently, the introduction of the EU Climate Law (1119/2021/EU) has set the target of achieving continental climate neutrality by 2050 through the decarbonisation of the construction sector.

For this reason, the construction sector plays a pivotal role in achieving the European Union's climate and sustainability objectives. It has consequently become a key focus of both policymaking and industrial transformation.

Although initially, regulatory and market interventions primarily targeted reducing operational energy consumption – with particular emphasis on improving the energy performance of buildings and lowering demand for heating, cooling, ventilation, and lighting – as operational emissions decline due to increasingly stringent standards requirements, greater attention has shifted to GHG emissions of materials and products throughout the entire building life cycle.

This transition has led to the adoption of a Whole Life Carbon (WLC) vision (WGBC, 2023[1]), which assesses environmental impacts from stage A to stage C. Such an approach enables a more comprehensive evaluation of buildings' climate performance by accounting not only for operational emissions but also for embodied GHG emissions associated with materials, construction processes, replacement cycles, and demolition activities.

The importance of adopting a life-cycle approach has become relevant in the EU policy framework. Several plans and programmes, such as the European Green Deal, New European Bauhaus, Circular Economy Action Plan (CEAP), Fit for 55, and REPowerEU, have highlighted the importance of understanding, managing, and reducing GHG emissions across the EU, especially those from the construction sector. In this context, the recast of the Energy Performance of Buildings Directive (EPBD IV) in 2024 (1275/2024/EU) introduces a progressive framework for assessing and reporting WLC emissions.

WLC is intended by the EPBD IV as the sum of GHG emissions and removals, across building life-cycle stages from A to C, assessed by the Global Warming Potential (GWP) impact category and characterised by two main indicators:

- Embodied carbon (EC) accounts for the emissions, removals, storage and uptake associated with producing, transporting, installing, maintaining, replacing and decommissioning the building. Additionally, the practices of reuse, recycling, and waste-to-energy can account for CO_2eq emissions and removals (module D1)
- Operational Carbon (OC) accounts for emissions released or avoided associated with energy consumption (module B6) and water consumption (module B7). Any excess energy produced by the building in module B6 can be considered an avoided emission in module D2

Under the Directive, the disclosure of life cycle GHG emissions will become mandatory for large new buildings with a Useful Floor Area (UFA) greater than 1000 m^2 from 2028, and for all new buildings from 2030[2]. In parallel, Member States are required to establish national roadmaps for the introduction of limit values on buildings' WLC from 2030, with progressively stricter thresholds aligned with the EU's objective of achieving climate neutrality by 2050. The key milestones set out in EPBD IV are illustrated in the roadmap shown in Figure 1.

The systematic integration of WLC assessment is still in its early stages of adoption. However, additional documents have been set up or revised since the release of EPBD IV. It is worth mentioning Delegated Regulation 2026/52 (52/2026/EU), which establishes new parameters for integrating WLC into EPCs, and the update to EN 15978:2026, which provides a more detailed methodology for carrying out building LCA.

In this context, only a few Member States (e.g., Denmark, Finland, France, the Netherlands, Sweden, etc.) have introduced standards or technical rules (and sometimes assessment tools) to address WLC emissions, and their experiences are further investigated in this guide. In the other Member States, the integration of the WLC into the regulatory framework and the decision-making process is

[1] World Green Building Council (WGBC) (2023). Whole Life Carbon Vision. https://worldgbc.org/climate-action/whole-life-carbon-vision/

[2] EPBD IV, Article 7 paragraphs (a) and (b): https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng

less structured. However, several initiatives are investigated for some countries, including England, Italy, Ireland, and Spain. Overall, significant differences remain among Member States in terms of assessment methods, technical criteria, minimum performance thresholds, and enforcement mechanisms.

The guide aims to provide an overview of WLC approaches and initiatives toward EU harmonisation and, at the same time, to identify ways to properly assess the characteristics of cement-based materials and products at the building scale.

1.3 Purpose of the guide

The purpose of this guide is to provide a clear, structured overview of the main methodologies currently used or emerging across Europe for assessing a building's WLC.

The guide has a dual objective. First, it provides a comparative reading of existing and developing **WLC assessment approaches**, highlighting their scope, assumptions, strengths, limitations and conditions of applicability. Particular attention is given to methodological aspects relevant to policy implementation, including the definition of the reference floor area, the selection of life-cycle modules, the treatment of operational and embodied carbon, the use of default values or product-specific data, and the degree of alignment with European standards and policy frameworks.

Second, the guide examines how **concrete materials and products** are represented within WLC assessment frameworks. This includes aspects such as service life, durability, maintenance and replacement, carbonation, and end-of-life scenarios. By combining a policy-oriented comparison of WLC methodologies with a material-specific technical analysis, the guide seeks to provide policymakers, technical experts and sector stakeholders with a transparent basis for managing concrete materials and products from a WLC perspective. Where relevant, it also presents alternative methodological positions and their underlying rationale, allowing readers to assess the evidence independently and to identify which assumptions require further verification, harmonisation or policy guidance.

2. Glossary and acronyms

Acronym	Full form	Description
/	**Climate neutrality**	Climate Neutrality is a state where the activity from an entity (a company, a city, a country, or a continent) results in no effect on the Earth's climate system. To achieve that, the entity must account for GHG emissions and removals (uptake) from and into the atmosphere. Removals can be achieved through natural sinks (such as reforestation) or technical solutions (such as direct air capture technologies).
CO_2eq (or CO_2e)	Carbon Dioxide Equivalent	CO_2eq is a metric measure used to compare the emissions from various GHGs based on their GWP, by converting amounts of other gases (e.g., methane, nitrous oxide, etc.) to the equivalent amount of carbon dioxide with the same GWP[3], through a conversion factor developed by the Intergovernmental Panel on Climate Change (IPCC). Concrete's GWP is primarily expressed in kg CO_2eq (or ton CO_2e) per FU (e.g. kg CO_2eq/kg of finished product) and allows it to be expressed in a common unit comparable across all construction materials.
CU	Carbon Uptake by carbonation	The process by which concrete materials and products absorb carbon dioxide (CO_2) from the atmosphere during their service life (module B1) and, in some cases, after demolition (Module D1). This reaction partially offsets the GHGs released during the Product stage (A1-A3)[4]. CU is partially considered by EPDs, while it is more detailed in the building WLC assessment.
/	**Decarbonisation**	Construction sector decarbonisation refers to the systematic process of eliminating GHG across the whole life cycle of a building – from design (A0), manufacturing of the materials and products (A1-A3), construction and installation (A4-A5), use of the building (B1-B8), and demolition and treatment of waste (C1-C4). Overall, the EU's construction sector accounts for roughly 36% of continental GHG emissions, making building decarbonisation a core pillar of broader net-zero strategies.
/	**Durability**	Technical properties of a material, component, or product to maintain its required performance over time under specified conditions of use, maintenance, and exposure. Durability directly influences SL, replacement frequency, and life-cycle environmental impacts. Based on Article 3, paragraph 3.1, of the new Construction Product Regulation (CPR)[5], to reduce raw material extraction and environmental

[3] Eurostat (2001). Glossary:Carbon dioxide equivalent. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent&oldid=612721#:~:text=A%20carbon%20dioxide%20equivalent%20or,metric%20tonnes%20of%20carbon%20dioxide

[4] Standards EN 16757:2017: Sustainability of construction works. Environmental product declarations. Product Category Rules for concrete and concrete elements. Annex BB: CO2 uptake by carbonation – Guidance on calculation, and PD CEN/TR 17310:2019: Carbonation and CO2 uptake in concrete.

[5] 3110/2024/EU. Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011. https://eur-lex.europa.eu/eli/reg/2024/3110/oj/eng

		impacts and to pursue the CEAP, each material, component, or product should (a) “maximising durability and reliability [...]”.
EC	Embodied Carbon	The GHGs emissions or removals associated with materials and construction processes throughout the life cycle of a building or infrastructure asset. It is an indicator that includes emissions from raw material extraction, manufacturing, transport, construction, maintenance, replacement, refurbishment, demolition, and waste processing. It is assessed by GWP and expressed in kg CO_2e.
EPC	Energy Performance Certificate	An EPC is an official document that rates a building's energy performance using a standardised methodology. It provides an energy efficiency class (typically on a scale from A to G), information on energy consumption and greenhouse gas emissions, and recommendations for improving energy performance.
EPD	Environmental Product Declaration	An EPD is a standardised, independently verified and registered document that presents quantified information about a product’s environmental impact over its entire life cycle, based on a Life Cycle Assessment[6] in line with the EN 15804+A2 standard, while keeping sensitive details confidential and allowing easy comparison between products. Data on specific construction products calculated in accordance with the CPR shall be used when available. In the concrete industry, an EPD is the primary evidence document used to verify the GWP of a specific concrete mix, in accordance with the PCR “*Concrete and concrete elements (EN 16757)*”.
ESL	Expected Service Life	The expected service life refers to the period during which a building product, component or system is expected to fulfil its function under specific design, installation, exposure, use and maintenance conditions. Unlike a generic service life value, ESL reflects the element's expected performance within a defined application context.
GFA	Gross Floor Area	The total floor area (m^2) of a building is measured to the external perimeter of the enclosing walls, including all enclosed spaces on all levels. GFA is commonly used as the reference area for reporting building environmental impacts or WLC assessment.
GHG	Green House Gas	Greenhouse gases are atmospheric gases that absorb and emit infrared radiation, contributing to climate change. In WLC assessments, GHGs are usually expressed as carbon dioxide equivalents (CO_2eq) using Global Warming Potentials (GWP), aggregating different gases into a single climate impact indicator.
GWP	Global Warming Potential	Mandatory numeric indicator for new buildings that quantifies the total greenhouse gas emissions contributing to climate change associated

[6] International EPD System (2025). What is EPD? Type III Environmental Declaration in Compliance with ISO 14025. https://www.environdec.com/services/what-is-epd

		with a building over its entire life cycle[7]. GWP will be calculated and disclosed in energy performance certificates for all new buildings[8]. This includes the production and transport of construction products, construction-site activities, the use of energy in buildings, and the replacement of construction products, as well as the demolition, transport, and management of waste materials, including their reuse, recycling, and final disposal.
LCA	Life Cycle Assessment	A standardised methodology used to quantify the environmental impacts of materials and products, processes, services, or buildings, throughout a stage (e.g. A) or the entire life cycle (A-C). The methodology follows the standard EN 14040:2021 and EN 14044:2021. For the construction sector, specific standards were developed for materials and products (EN 15804:2021+A2) and for buildings EN 15643:2021 and EN 15978:2026).
/	**Module**	The building assessment system consists of four Stages (A–D), which are subdivided into Modules assigned alphanumeric codes. For example, the Product stage (A-A3) comprises three modules: extraction of raw materials and resources (A1); transport to the production or processing site (A2); and manufacture of the material, product, technical component, or system (A3).
OC	Operational Carbon	The GHGs emissions resulting from the energy consumption and from water consumption and treatment (grey and black water) during the Use stage (B) of a building. The indicator includes heating, cooling, ventilation, lighting, hot water, and auxiliary systems.
PCR	Product Category Rules	The Product Category Rules outline the guidelines for conducting LCAs and developing EPDs for specific product categories. PCRs are developed through an open, transparent and participatory process, in compliance with EN ISO 14025, EN ISO 14044 and other relevant standards. They also follow the rules set out in the General Programme Instructions (GPIs). A PCR Committee, comprising a PCR Moderator and LCA/EPD experts from multiple organisations, is responsible for developing the PCR, while the Technical Committee reviews and approves it.
RSP	Reference Study Period	The time period selected for assessing the environmental performance of a building through LCA or the CO_2eq of a building through WLC. The RSP represents the ELS of the building for the purpose of calculations and determines the number of maintenance, repair, replacement, and refurbishment cycles included in the assessment.
RSL	Reference Service Life	Service life of a product, component, assembly or system which is known to be expected under a particular set, i.e. a reference set, of in-use conditions and which can form the basis for estimating the service life under other in-use conditions (ISO 15686-1:2011).

[7] 1275/2024/EU. Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the Energy Performance of Buildings. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401275&pk_keyword=Energy&pk_content=Directive

[8] 52/2026/EU. Commission Delegated Regulation (EU) 2026/52 of 16 December 2025 amending Annex III to Directive (EU) 2024/1275 of the European Parliament and of the Council as regards the Union framework for the national calculation of life-cycle global warming potential. https://eur-lex.europa.eu/eli/reg_del/2026/52/oj/eng

SL	Service Life	The service life refers to the period after installation during which a building or one of its components continues to meet the required performance criteria[9]. For individual products, it represents the duration of use before replacement becomes necessary, a key parameter for estimating the impacts of material replacement over the selected calculation period.
FU	Functional Unit	As defined by the Level(s) framework, the Functional Unit is the quantified performance of a product system for use as a reference unit. The FU in LCA defines a quantified reference for a construction product's application, key properties, and performance over a specified time period, enabling consistent comparisons with other products serving the same function[10].
Stages A–C	A (Product and Construction Stage)	A1-A3 (Product stage): covers the initial production of construction materials, from raw materials and resource extraction (A1) and transport to the manufacturing site (A2), through to processes that prepare the finished product for shipment (A3). A4-A5 (Construction process stage): covers the processes of delivering the product to the building site (A4) and installing it into the building (A5).
	B (Use Stage)	B1-B5 (Building fabric): covers the actions and processes required to maintain the building's physical fabric (including use, maintenance, repair, replacement, and refurbishment). B6-B8 (Use of the building): covers the building's operational energy and water use for heating, cooling, ventilation, lighting, domestic hot water, etc.
	C (End-of-Life Stage)	C1-C4 (Full deconstruction of the building): covers the final phase of the building, starting with demolition (C1), followed by transport of waste to the treatment site (C2), waste processing for potential recovery (C3), and finally, landfilling of waste (C4).
	D (Scenarios for benefits and loads beyond the system boundary)	D1 (Circular Economy principles): covers the environmental benefits resulting from the reuse, recycling, and recovery (including energy recovery) of materials and waste. D2 (Energy exchange): the environmental benefits resulting from utilities such as power and heat, generated and exported during the building use (e.g. energy surplus from on-site PV electricity production).
UFA	Useful Floor Area	The building floor area (m^2) that is actually available for the intended use of occupants, excluding areas occupied by external walls, structural elements, shafts, and other non-usable spaces. It is often intended as the area covered by the air-conditioning system. For this reason, it is generally used for operational energy simulation and EPC.
WLC	Whole Life Carbon	WLC is the sum of all GHGs emissions and removals associated with a building over its entire life cycle (A-C). It includes both EC (modules A1-A5, B1-B5, and C1-C4) and OC (modules B6 and B7). WLC provides a comprehensive measure of a building's climate impact, from material

[9] JRC Technical Report (2021). Level(s) indicator 1.2: Life cycle Global Warming Potential (GWP) user manual: introductory briefing, instructions and guidance (Publication version 1.1). https://en.itec.cat/wp-content/uploads/2022/04/1.2.Indicator_GWP_EN.pdf

[10] Standards EN 15804:2021+A2, EN 15643:2021, and EN 15978:2026.

		extraction and construction through operation, maintenance, refurbishment, and end-of-life. Within the EPBD IV, it is called Whole Life Cycle - Global Warming Potential. However, for the purposes of this guide, the concept of WLC is taken to represent the principles set out in EPBD IV and referred to in the Delegated Regulation 2026/52.

3. Whole Life Carbon: legislative, technical and deployment framework in Europe

3.1 Energy Performance of Buildings Directive IV and links with EU climate policies

The revision of the Energy Performance of Buildings Directive (EPBD IV) is one of the EU's main regulatory tools for decarbonising the construction sector (1275/2024/EU) and is part of the broader European climate policy framework. In particular, the EPBD contributes to the implementation of the European Green Deal (640/2019/EU), which sets the objective of climate neutrality by 2050 (1119/2021/EU) and promotes the reduction of emissions across the entire lifecycle of buildings.

In this context, Annex III of the EPBD introduces principles for calculating the Whole Life Cycle Global Warming Potential (WLC-GWP) of buildings and encourages the adoption of harmonised methodologies to assess both embodied and operational emissions.

According to Article 7 of the revised EPBD IV, adopted in May 2024, the disclosure of GWP emissions will be mandatory for large new buildings (>1000 m2 of UFA) from 2028 and for all new buildings from 2030 onwards. Additionally, Member States are tasked with defining national roadmaps for introducing WLC-GWP by 2030, with a gradual revision of the limits to achieve buildings' decarbonisation by 2050 (Figure 1).

EPBD IV also introduces the need to work on existing stock. Almost 75% of existing buildings are energy inefficient, and more than 85% of today's buildings are likely to remain in use in 2050. Therefore, renovation interventions are a strategic action towards achieving EU climate neutrality by 2050. Although the energy renovation of buildings is ongoing, it is happening at a very slow rate[11].

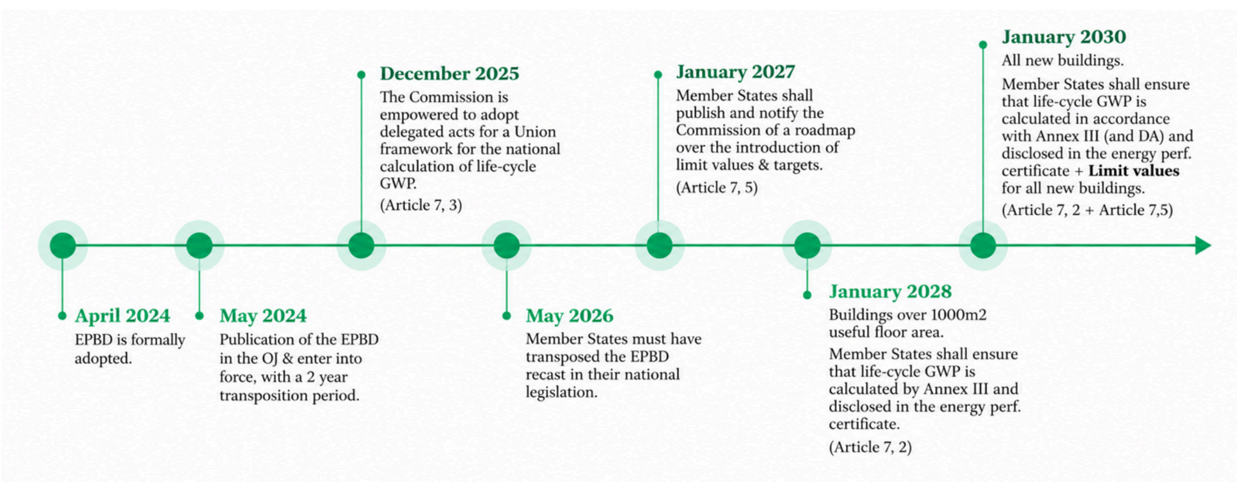

Figure 1: EPBD IV WLC-GWP assessment timeline (Source: Viegand Maagøe, COWI and exergia[12]).

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[11] European Environment Agency (EEA) (2026). Buildings and construction. https://www.eea.europa.eu/en/topics/in-depth/buildings-and-construction

[12] Viegand Maagøe, COWI and exergia (2025). Whole Life-Cycle Global Warming Potential reporting for buildings. https://www.wlc-epbd-guidance.eu/

Alongside the EU's Renovation Wave (662/2020/EU), Article 3 of EPBD IV introduced National Building Renovation Plans (NBRPs). These plans represent a strategic framework to support the transition towards a zero-emission existing building stock. Each Member State, following the Annex II template, is required to survey the building stock, set transparent decarbonisation targets for both public and private buildings, and outline the necessary financial instruments to bridge the investment gap. The EU Commission's drafting process requires each Member State to submit its NBRP by December 2025, with the final plan due following a review by 31 December 2026. The complete list of published NBRPs can be found on the dedicated EU webpage[13].

The EPBD IV is also part of a broader ecosystem of initiatives aimed at zeroing GWP emissions.

Specifically for the construction sector, it is worth mentioning three initiatives:

1) The EU Level(s) framework is an assessment and reporting tool for improving the sustainability performance of buildings. It provides a common language for the building transformation process, and one of the main goals is minimising WLC emissions of buildings[14];
2) The Delegated Regulation 2026/52 (52/2026/EU) provides a common framework for calculating the WLC-GWP of new buildings and for reporting the results in the updated Energy Performance Certificates (EPCs). It defines the system boundaries, the Reference Study Period (RSP), the type of data to be used, and the minimum building elements to be included in the assessment;
3) The update to the standard EN 15978:2026 establishes a harmonised methodology for the LCA of buildings. Key updates and features include:
    a) A more detailed structure for whole-building LCA;
    b) Introduction of Modules D1 and D2 (aligned with UNI EN 15643:2021) alongside new sub-modules for stages A4, A5, B1, and D1;
    c) Full compliance with EN 15804:2021+A2, requiring GWP to be divided into fossil, biogenic, Land Use and Land Use Change (LULUC), and total;
    d) Direct alignment with the EH Level(s) sustainability framework;
    e) Specific technical criteria covering material reuse (D1.1), recycling (D1.2), energy recovery (D1.3), and extra environmental benefits (D1.4);
    f) Clear guidelines on using generic vs. specific data depending on the project phase (from early design to as-built);
    g) Standardised definitions for system boundaries and functional equivalents.

In addition, the updated Directive is linked to the EU Taxonomy (852/2020/EU) and the EU Emissions Trading System (EU ETS), which regulates emissions in the energy and industrial sectors and indirectly helps reduce emissions associated with the production of construction materials. An amendment proposal for the EU ETS (87/2003/EU and 1814/2015/EU) was shared by the European Commission in July 2026 and is currently under consultation among the Member States

[13] European Commission, Directorate-General for Energy (2026). https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/national-building-renovation-plans_en

[14] Indicator 1.2 defines the Life cycle Global Warming Potential (CO_2eq/m2/yr) of buildings that can be assumed as the basis for WLC assessment.

(616/2026/EU). Meanwhile, a new and separate ETS system was developed in 2023 for "*Buildings, road transport and additional sectors*" (ETS2 – 959/2023/EU). This new system will address CO_2eq emissions from fuel combustion in the aforementioned sectors, as well as small industries not currently covered by the EU ETS. The ETS2, linked with the European Green Deal (640/2019/EU) and the Effort Sharing Regulation (ESR)[15], is set to become fully operational in 2028.

Together, all the initiatives define an integrated ecosystem aimed at guiding the transition toward a low-carbon construction sector (Figure 2).

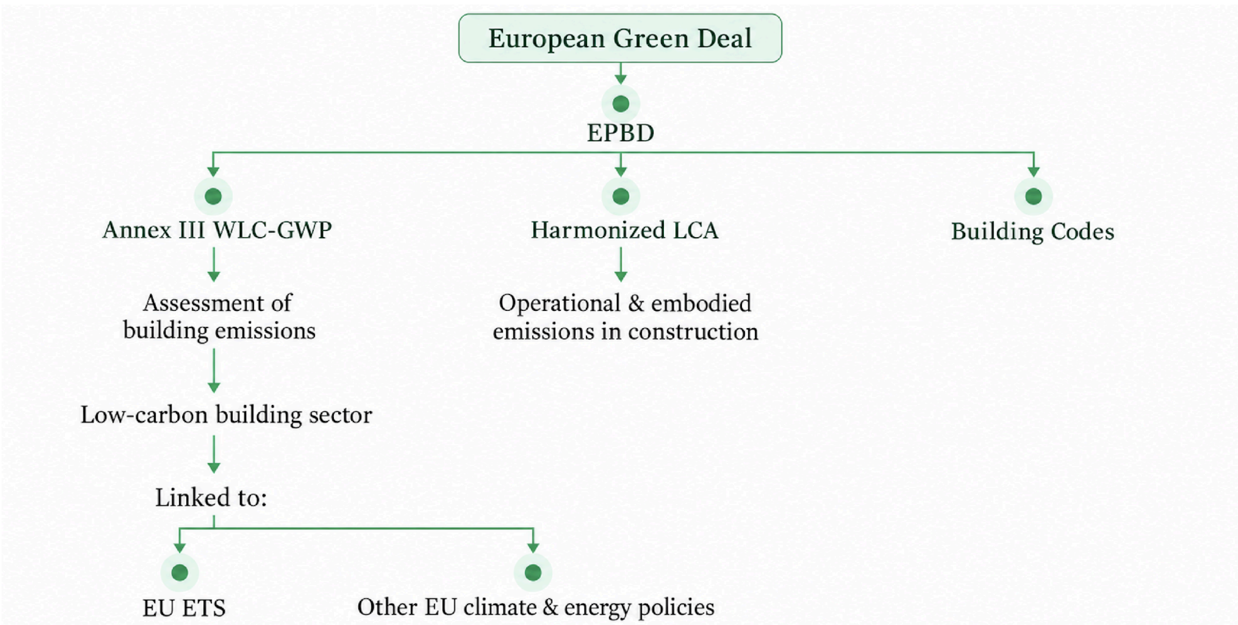


Figure 2: European Regulatory Framework (Source: Authors).

3.2 Calculation framework and essential parameters (functional unit, boundaries)

As required by the revised EPBD and specified in Commission Delegated Regulation (EU) 2026/52, the framework for calculating "*whole-life-cycle greenhouse gas emissions*" is based on EN 15978:2011, as amended or replaced by subsequent versions, or on equivalent EU harmonised standards. The scope of building elements and technical equipment is as defined in the Level(s) common EU framework for indicator 1.2. Other calculation tools or methods may be used if they fulfil the minimum criteria established by the Level(s) common EU framework.

A 50-year reference study period is commonly used as a harmonised basis in EU-related building assessment frameworks, although national methods may define specific requirements.

Results should be expressed per square metre of UFA, as defined by Member States in accordance with national rules aligned with EU requirements and recognised standards. The definition should be applied consistently and transparently, since variations in floor-area calculation can significantly influence GWP results expressed per square metre.

[15] More information can be f, as amended or replaced by subsequent versions, or on ound at the dedicated webpage: https://climate.ec.europa.eu/eu-action/carbon-removals-and-carbon-farming/, as amended or replaced by subsequent versions, or on effort-sharing-member-states-emission-targets_en

The methodology should follow the data hierarchy described in Chapter 7, prioritising product-specific data compliant with the CPR (3110/2024/EU) and, where available, representative EPDs. Where such data are not available, EU-level datasets, national datasets, or conservative default data may be used, provided that their source, representativeness and uncertainty are clearly documented.

The assessment is carried out at two stages. An initial calculation is performed at the design stage to optimise the building's environmental performance before construction. A final calculation is then performed at completion (as-built stage), and this result is the one disclosed in the energy performance certificate. The final disclosure must reflect the actual building as constructed and its verified material and technical characteristics.

Results must be reported transparently with a breakdown by life-cycle stages in line with the updated version of EN 15978:2026.

The EU framework harmonises the overall structure, indicators and minimum reporting requirements, while leaving some flexibility to Member States regarding national calculation tools, datasets and detailed modelling assumptions.

Essential parameters

Reference study period (RSP): Annex III of the EPBD, together with the Delegated Regulation 2026/52, establishes that "*the total life cycle GWP is communicated as a numeric indicator for each life-cycle stage expressed as kgCO_2eq/m^2 (of useful floor area) calculated over a reference study period of 50 years*". This 50-year RSP is the legally mandated timeframe for summing all emissions (Stages A, B, and C). It will also be used to determine a building's compliance with future maximum GWP limits to be established by Member States.

However, it is important to clarify that the 50-year RSP is not intended to represent the actual technical lifetime of buildings or structural systems. Rather, it is a methodological convention established to ensure consistency and comparability across projects, materials, and assessment methodologies, as reflected in EN 15978:2026, EN 15804:2021+A2, and the EU Level(s) framework.

In particular, the 50-year RSP provides a common basis for:

- Aggregation of life-cycle modules, especially module B6 (Operational energy)
- Comparability of buildings from different EU Member States
- Replacement cycles compliant with the EU Level(s) framework
- Alignment with main EU policy frameworks, reporting requirements, and national regulatory approaches

In the EU context, the 50-year RSP has been incorporated into several national frameworks. For example, France's RE2020 and Denmark's FBK require a 50-year study period for WLC assessments. However, the results are not comparable because different surface areas were used to normalise the WLC results. An overview of WLC methodologies and RSP across EU Member States is provided in section 3.4.

Reference surface area: according to the Delegated Regulation 2026/52, which takes into account the guidelines provided by the EU Level(s) framework, the reference surface area (m^2) used to normalise the WLC assessment results is the Useful Floor Area (UFA). It is defined as "*the useful floor area shall correspond to the area of the parts of the building that are covered by the life-cycle GWP calculation and shall not extend beyond the building envelope*"; however, each Member State "*shall set out how the definition of useful floor area is to be used in practice*" provided that it is consistent with International Property Measurement Standards (IPMS) or an equivalent standard (Delegated Regulation 2026/52, ANNEX, point 4).

The UFA is consistent with the updated EPC for new buildings, but other surface areas can be used to normalise WLC results, such as Gross Floor Area (GFA), Gross Internal Area (GIA), Heated Floor Area (HFA), Net Heated floor Area (NHA), Liveable Area (LA), etc[16]. These areas are used by some Member States, especially those in which the WLC regulations were set out before the publication of EPBD IV and Delegated Regulation 2026/52.

WLC Functional Unit: based on the RSP and reference surface area, the WLC-GWP results should be displayed as $kgCO_2e/m^2UFA$ over a 50-year RSP, and as $kgCO_2e/m^2UFA/year$. In addition, based on the standards EN 15804:2021+A2 and EN 15978:2026, the WLC-GWP results should be disclosed in four components: fossil (GWP-fossil), biogenic (GWP-bio), land use and land use change (GWP-luluc), and total (GWP-tot), given as the algebraic sum of the components fossil, bio, and luluc.

For concrete, many LCAs have historically used a simple FU, most commonly the unit volume of concrete (e.g., 1 m^3). However, this volumetric approach fails to capture the multifunctional nature of a concrete structure, which must provide adequate strength, serviceability and durability performance over time. To achieve meaningful functional equivalence in comparative LCAs of concrete, a complete FU should therefore include strength requirements, durability performance, and reference service life (RSL) of the structural element, not merely its volume[17].

3.3 Whole Life Carbon: system boundaries of the assessment

WLC measures a building's total climate impact across its entire lifecycle using the GWP indicator, expressed in CO_2e. WLC encompasses emissions from every stage of the building's lifecycle:

- Product and Construction Stages (A): raw material extraction, manufacturing, transport, and construction (A1–A3 and A4-A5)
- Use Stage (B): Operation, maintenance, and energy/water demand (B1–B8)
- End-of-Life Stage (C): Deconstruction, transport, and waste processing (C1–C4)

Where applicable, WLC integrates carbon removals, storage, and uptake – such as biogenic carbon in bio-based materials, concrete and lime carbonation, or on-site greenery.

Two indicators are used to perform a WLC assessment:

[16] In accordance with the delegated regulation, each Member State may define its own concept of UFA, in accordance with national regulations. However, in some countries, the term UFA is already largely covered by reference areas such as GIA, HFA, NHA and LA.

[17] Panesar, D.K., Seto, K.E. & Churchill, C.J. (2017). Impact of the selection of functional unit on the life cycle assessment of green concrete. Int. J. Life Cycle Assess 22, 1969–1986. https://doi.org/10.1007/s11367-017-1284-0

- Embodied Carbon (EC): Tracks emissions and removals tied to materials, products, components, and Mechanical, Electrical and Plumbing systems (MEPs) production and to processes like transport, assembly, maintenance, replacement, and demolition of the building materials
- Operational Carbon (OC): Measures emissions from operational energy (B6), water use and treatment (B7), and users' related activities (e.g., commuting, charging of electric vehicles, etc. (B8)

External benefits and loads that reflect circular design principles are reported separately within the Beyond life cycle stage (D) to ensure transparency across WLC assessments. Figure 3 highlights the building assessment framework and the different stages and modules covered by WLC, and the two main indicators, EC and OC.

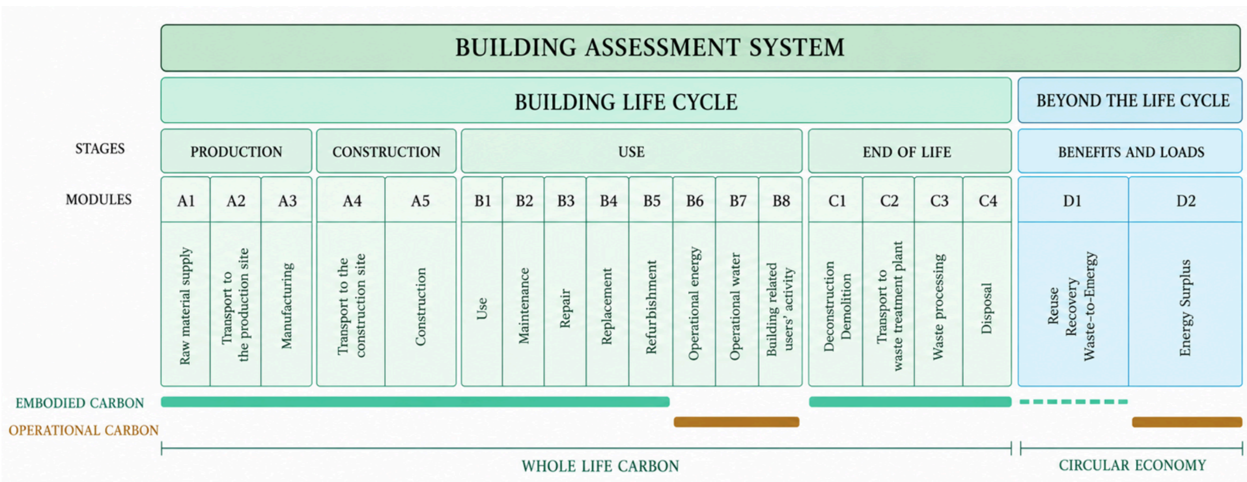


Figure 3: Building assessment framework (Source: Authors' interpretation based on EN 15978:2026).

Mandatory stages and modules

According to the EPBD IV and the Delegated Regulation 2026/52, the mandatory stages and modules to be covered by WLC and updated EPC for new buildings are: A1-A3, A4-A5, B1-B4, B6, and C1-C4. Additional D1 and D2 modules, not part of the WLC assessment framework, should be accounted for in determining other CO_2eq benefits or loads. However, it's important to emphasise that, to date, module D1 remains a subject of debate and controversy within the international scientific community[18]. Further studies are needed to establish harmonised rules and assessment methods for all Construction and Demolition (C&D) waste.

WLC's indicators

WLC assessment uses GWP as the primary indicator. In compliance with EN 15804:2021+A2 and EN 15978:2026, GWP must be reported across four distinct categories: fossil (GWP-fossil), biogenic

[18] Fahlstedt, O., Nygaard Rasmussen, F., Temeljotov-Salaj, A., Huang, L., Bohne, R.A. (2024). Building renovations and life cycle assessment - A scoping literature review. Renewable and Sustainable Energy Reviews, Volume 203, 114774. https://doi.org/10.1016/j.rser.2024.114774

(GWP-bio), land use and land use change (GWP-luluc), and total (GWP-tot, given as the algebraic sum of fossil + bio + luluc).

3.4 EPBD IV implementation across Europe (overview)

Under the recast Energy Performance of Buildings Directive (EPBD IV) (1275/2024/EU), which entered into force on 28 May 2024 with a transposition deadline of 29 May 2026, each Member State is required to develop a national strategy for reducing, and then zeroing, WLC-GWP emissions from buildings by 2050. The EPBD IV applies to both new construction and the existing building stock.

For new construction, under Article 7 of the EPBD IV, disclosure of GWP emissions will be mandatory for large new buildings (>1000 m2 of UFA) from 2028 and for all new buildings from 2030.

For the existing building stock, according to Article 3 of EPBD IV, each Member State must provide a National Building Renovation Plan (NBRP), setting out national strategies and milestones for transforming its building stock into a highly energy-efficient and decarbonised stock by 2050. Draft NBRPs were due by 31 December 2025, with final plans due by 31 December 2026.

As of July 2026, sixteen Member States have submitted a complete draft of NBRPs, and it has already been revised by the EU Commission[19]: Austria, Bulgaria, Croatia, Cyprus, Germany, Denmark, Finland, France, Lithuania, Netherlands, Portugal, Romania, Spain, Slovenia, Sweden and the Walloon Region (Belgium). Additionally, Estonia and Greece submitted their drafts by the end of August, and the EU Commission's assessment of these two plans (covering the ambition of national targets, the sufficiency of policies, measures, and resources, and alignment with EU-level reporting templates) was ongoing at the time of writing.

Additionally, and potentially for both new construction and renovation works, Member States are tasked with defining national roadmaps to introduce limit and target values for WLC-GWP by 2030, with a gradual revision of the limits to achieve buildings' decarbonisation by 2050. In this context, some Member States have already introduced the limit values. These Member States, as highlighted in Figure 4, are those in which the WLC-GWP approach was developed and regulated before the introduction of the EPBD IV requirements in 2024.

[19] First assessment report by the EU Commission: https://energy.ec.europa.eu/news/national-building-renovation-plans-commissions-first-assessment-2026-07-14_e

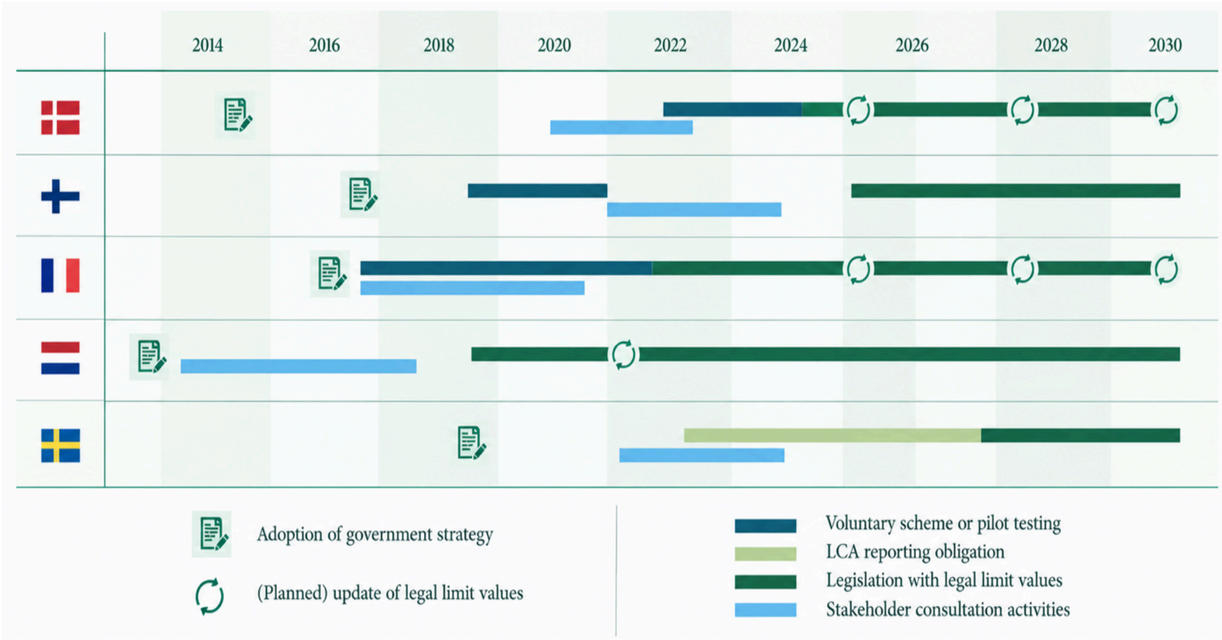


Figure 4: Timeline of the WLC-GWP approach and limit values by the frontrunners Countries

Countries not yet aligned with the EPBD IV timeline

The implementation of the EPBD IV still shows significant disparities among Member States, with some experiencing notable delays in providing NBRPs and in transposing the Directive into national regulations (as required by the European Commission by 29 May 2026). For this reason, at the time the guidelines report was developed, the EU Commission had opened infringement proceedings against all 27 EU Member States for failing to transpose EU law into national legislation fully.

At the same time, several differences can be recorded; some Member States are participating in European initiatives to develop national WLC-GWP methodologies, assessment schemes, and tools to support the introduction of limit values by January 2027 (Article 7, comma 5, of the EPBD IV). In this context, countries such as Austria, Croatia, Czechia, Ireland, Italy, Luxembourg, Spain, and Hungary (as a follower country) participated in the INDICATE initiatives. It is divided into two subsequent phases: the INDICATE pilot project (2022-2024) and the INDICATE LIFE project (2024-2026)[20].

The first phase, before the introduction of the revised version of the EPBD, had the aim to:

1. Develop WLC-GWP benchmarks for different building types
2. Set up national regulations on WLC-GWP assessment
3. Guide the EU EPBD IV negotiations

The second phase, after the disclosure of the EPBD IV, is currently ongoing, and it has the aim to:

1. Develop national tools and assessment methods for WLC-GWP calculations
2. Drive data collection and analysis to design national benchmark WLC values
3. Assess the cost-benefit of WLC to support policy-level action
4. Enable EU and national-level WLC recommendations for transparency in reporting

Within the INDICATE initiatives, some countries are working to develop a national ecosystem for assessing, monitoring, and managing WLC-GWP in buildings, grounded in regulations, tools, databases, and limit values. It is worth mentioning the efforts of Spain (the Technical Building Code updated in 2026) and Austria (the OIB Guidelines 6, which entered into force in September 2025) towards implementing EPBD IV.

Overall, countries such as Hungary and Slovenia face significant challenges in increasing building renovation rates and adopting effective measures to reduce energy consumption[21]. Other countries, including Poland, Slovakia, Greece, and Portugal, face persistent structural difficulties related to limited investment, unstable incentive schemes, and weaknesses in monitoring and energy certification systems. In Southern Europe, including Italy, obstacles remain to the full implementation of the Directive, particularly regarding the continuity of support policies and the

[20] For more information, visit the dedicated website: https://www.indicatedata.com/

[21] European Commission: Joint Research Centre, Maduta, C., Tsemekidi-Tzeinaraki, S., Castellazzi, L., Dagostino, D., Melica, G., Paci, D. and Bertoldi, P. (2025). Updates on the Energy Performance of Buildings Directive implementation in the EU Member States, Publications Office of the European Union, Luxembourg. https://build-up.ec.europa.eu/en/resources-and-tools/publications/updates-energy-performance-buildings-directive-implementation-eu

achievement of nearly zero-energy building standards. Overall, these delays can be attributed to common factors such as slow renovation processes, fragmented regulatory frameworks, and administrative challenges, highlighting the need for stronger, more coordinated policy action at both the national and European levels.

Frontrunners countries

Although the EU Commission has opened an infringement procedure against all 27 EU Member States, some countries are aware and experienced in WLC-GWP assessments. Those countries in which the concept of WLC-GWP was developed before the introduction of EPBD IV can be considered frontrunners and are close to alignment with the EPBD IV timeline.

Generally, these are the Member States that have already implemented structured policies and demonstrate tangible progress in renovation rates and energy performance standards. Among the main ones are Denmark, Estonia, Finland, France, the Netherlands (partially), Norway, and Sweden. And even though it is not part of the EU, it is close to the previously mentioned countries, such as the United Kingdom. In general, these countries share common features:

- consistent long-term policies
- stable financial incentives
- well-developed energy certification systems
- stronger administrative and monitoring capacity
- Tools and databases for supporting designers and firms towards WLC-GWP assessments

The following section provides a brief overview of the WLC assessment ecosystems in several frontrunner countries. A summary table then sets out the current assessment schemes alongside those currently being developed by certain EU Member States.

Denmark[22]: The implementation of the EPBD IV in Denmark has reached a very advanced stage, to the point that the country is often considered a benchmark at the European level. It has a national legal framework, Den Frivillige Bæredygtighedsklasse (FBK), entered into force from January 2023, and WLC_GWP limit values for buildings.

However, the current situation is not without its challenges, which emerge especially in the most recent phase of the Directive's application.

On the one hand, Denmark has a solid, fully integrated regulatory system, with high energy performance standards and effective tools, such as mandatory energy certification. On the other hand, the main challenges concern the actual ability to extend these results to the entire building stock, particularly existing buildings. It is precisely in this area that the greatest difficulties arise: energy renovation measures are often complex and costly, and not all owners are willing or able to undertake them.

In addition, there is the issue of overall system costs. While the high level of ambition in energy standards ensures excellent performance, it can also create economic accessibility challenges, especially for more vulnerable population groups. This raises potential concerns about social equity that require appropriate supporting policies.

[22] More information on FBK:
https://www.sbst.dk/byggeri/baeredygtigt-byggeri/national-strategi-for-baeredygtigt-byggeri/den-frivillige-baeredygtighedsklasse

Another important aspect is the technical and organisational complexity of the Danish model. Although effective, the system requires specialised expertise and strong coordination among multiple actors, which can make large-scale implementation challenging without adequate institutional support.

Finally, even in an advanced context such as Denmark, there remains a gap between the climate objectives set at the European level and the results achieved, especially regarding the pace of deep energy renovations.

In summary, Denmark has already developed a mature and well-functioning system for implementing the Directive. Still, it is now facing a new phase: no longer that of formal transposition, but rather that of full-scale implementation, which requires making interventions more accessible, widespread, and equitable.

Finland[23]: The roadmap adopted in Finland is a national strategic plan aimed at progressively reducing carbon emissions in the building sector across the entire life cycle of buildings. It defines targets, calculation methods, and regulatory limits to guide the construction market toward increasingly sustainable solutions aligned with European climate policies. Finland developed a national ecosystem for WLC-GWP assessment to be integrated into the Construction Act 751/2023, followed by the development of limit values for new buildings in 2025 (in force since January 2026).

Starting from January 2027, the roadmap foresees further development of the limit values set for the 2026–2029 period, to establish a progressively decreasing emissions pathway beyond 2030. This pathway will align with the EU Delegated Regulation 2026/52 and include maximum values differentiated by building typology and climatic zone.

Regarding the calculation method, Finland already uses a national low-carbon assessment system known as the "climate declaration." This approach is supported by the CO_2 data database. The emissions database is maintained by the Finnish Environment Institute, which provides emissions data. The assessment relies on product-specific GWP data, such as EPDs, the Finnish low-carbon concrete classification, and information available in the CO2data.fi database.

France[24]: The implementation of the EPBD IV in France has progressed significantly with the entry into force of RE2020 (from January 2022), which broadens the focus beyond Operational Energy consumption by including mandatory LCA and GWP emissions for buildings.

RE2020 integrates energy requirements (NZEB, Bio/CEP indicators), summer comfort metrics, and, for the first time nationally, a compulsory WLC assessment based on EPD and national values available from a France-specific database (INIES). However, the WLC assessment methodology and metrics are characterised by deviations from European standards, particularly in how biogenic carbon is accounted for.

Sweden[25]: Between 2024 and 2025, Sweden has been following a structured path to align with European requirements for building energy performance, especially those set out in the EPBD IV and the related Delegated Regulation 2026/52 of the European Commission.

[23] More information on Construction Act 751/2023: https://ym.fi/en/construction-act
[24] More information on RE2020: https://www.ecologie.gouv.fr/politiques-publiques/reglementation-environnementale-re2020
[25] More information on Boverket Climate Declaration: https://www.boverket.se/en/start/laws-and-regulations/climate-declaration/

As early as May 2024, the Swedish Concrete Federation participated in a government consultation on the introduction of limit values for new buildings, providing technical feedback and representing the sector's perspective. This marked the beginning of a broader process to integrate sustainability criteria across the entire building lifecycle.

In December 2024, the Swedish National Board of Housing, Building and Planning (Boverket) received a new official mandate to develop methodologies and thresholds for assessing lifecycle GWP and to propose limit values consistent with European guidelines. This step is directly linked to Sweden's effort to implement the EPBD IV, which increasingly emphasises not only operational energy use but also EC emissions.

In early spring 2025, the process moved into a more operational phase. The Swedish Concrete Federation participated in several meetings with the Board and its consultants, also involving its members through targeted surveys. This helped gather industry data and feedback, contributing to the development of practical and applicable criteria.

In August 2025, the Board and its consultants organised a stakeholder meeting to present their implementation proposal. This proposal outlined how GWP limits and reporting requirements could be implemented in the construction sector, in line with European obligations.

In September 2025, the final consultation phase took place: a detailed questionnaire represented the last opportunity for stakeholders to influence the outcome. This step highlighted the authorities' intention to maintain a participatory process, despite operating within a framework largely defined at the EU level.

The Netherlands[26]: The implementation of the EPBD IV in the Netherlands is achieved by transposing European provisions into national building regulations, particularly through the Besluit bouwwerken leefomgeving (Bbl) and other instruments linked to environmental and spatial planning legislation. The authorities responsible for implementation include the Ministry of Housing and Spatial Planning and the Netherlands Enterprise Agency (RVO), which developed the Environmental Performance of Buildings (MPG) scheme and the Nationale Milieudatabase (National Environmental Database).

In recent years, the country has introduced several tools to comply with European requirements, including the national energy performance calculation methodology NTA 8800, which applies to both new and existing buildings, and energy performance requirements aligned with the Nearly Zero Energy Buildings (NZEB) standards for new constructions.

Following the most recent revision of the EPBD IV, the Netherlands is also developing additional tools to integrate the assessment of greenhouse gas emissions across the entire building life cycle. In particular, the government plans to introduce the WLC-GWP indicator, which will quantify emissions associated with building materials, technical systems, and operational energy over a 50-year life cycle. According to the national roadmap, the calculation of WLC-GWP will become mandatory from 2028 for large new buildings, with limit values for life-cycle emissions expected to be introduced from 2030.

UK: There are no plans yet to adopt EPBD IV in the UK or any equivalent legislation. The measure has been debated at several parliamentary Environment Audit Committee (EAC) hearings and Calls-for-Evidence since 2022, and the Ministry of Housing, Communities and Local Government

[26] More information on MPG and Nationale Milieudatabase: https://milieudatabase.nl/en/

(MHCLG) has commissioned a study in 2022/23, which concluded that it would be feasible to introduce mandatory industry-wide whole life environmental assessments for buildings with a focus on GHG emissions. However, the UK Government explicitly noted in its March 2026 response to the EAC that no such mandatory measure will be introduced soon to avoid any burden on the sector's recovery.

However, the UK's construction industry seems to have widely adopted WLC assessments for the built environment. Several local authorities have rolled out voluntary benchmarks and requirements for Embodied and Operational Carbon, most notably the Greater London Authority (GLA), as part of the London Energy Transformation Initiative (LETI)[27]. The results from LETI have been integrated within the UK Net Zero Carbon Buildings Standard (UK NZCBS)[28].

Voluntary schemes, such as BREEAM, Future Homes Hub Whole Life Carbon Implementation Plan, and the newly introduced Net Zero Carbon Building Standard (NZCBS), are being widely adopted by developers, homebuilders and contractors to address operational and EC emissions. Government bodies, such as the National Infrastructure and Service Transformation Authority (NISTA), have also provided guidance to support the industry in reducing GHG emissions and implementing carbon management and procurement systems in accordance with PAS 2080.

There is already industry consensus over a methodology for Whole Life Carbon Assessment (WLCA) in the UK, based on the Royal Institution of Chartered Surveyors (RICS) WLCA Professional Standard. A local standard widely aligned with EN 15978: 2026.

The following Table 1 illustrates the main WLC-GWP metrics across the above-mentioned countries. It is divided into three sections. The first section defines the reference surface (m^2) and the RSP (years). The second section highlights the stages and modules covered by the WLC-GWP national methodology. The third part provides information on entry into force (e.g., yes, no, not defined) and limit values.

[27] More information on LETI: https://www.leti.uk/

[28] More information on UK NZCBS: https://www.nzcbuildings.co.uk/

Country	Reference surface	RSP	Production stage (A)	Construction stage (A)		Use stage (B)							End of life stage (C)				Beyond lifecycle (D)		In force	Limit values
/	/	/	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	/	/
🇩🇰	HFA & GFA	50																	YES	YES
🇪🇪	HFA	50																	UD	NO
🇫🇮	HFA	50																	YES	YES
🇫🇷	LA & UA	50																	YES	YES
🇳🇴	GFA	50																	YES	NO
🇳🇱	GFA	50-75																	YES	YES
🇸🇪	GFA	/																	YES	UD
🇦🇹	GFA, NFA, & UFA	50																	UD	UD
🇭🇷	NFA	50																	NO	UD
🇨🇿	GFA & UFA	50																	NO	UD
🇮🇪	GFA & UFA	50									*IR	*IR							UD	UD
🇮🇹	HFA & GFA	50**				**IT				**IT		**IT							NO	UD
🇱🇺	GIA & UFA	50																	NO	UD
🇪🇸	GFA & UFA	50																	UD	UD
🇬🇧***	GIA	60																	YES	YES

GFA = Gross Floor Area
GIA = Gross Internal Area
HFA = Heated Floor Area
LA = Livable Area
NFA = Net Floor Area
UA = Usable Area

*IR B6 and B7: these modules are considered as optional, cause not related to the EC of materials and products[29].

**IT B1 and B7: some metrics and assumptions are described within the methodological proposal developed by Andreotti & Giordano (2024)[30], cited within the national standard UNI 11973:2025; B5: the IT consortium of the INDICATE LIFE project considers the module B5 as an expanded lifecycle (A1-D2) for renovation works.
***GB's scheme is voluntary. The limits come from an industry-led scheme known as UK NZCBS.

UD = Under Development

[29] BPIE (2024). How to establish Whole Life Carbon benchmarks: Insights and lessons learned from emerging approaches in Ireland, Czechia and Spain. https://www.bpie.eu/publication/how-to-establish-whole-life-carbon-benchmarks-insights-and-lessons-learned-from-emerging-approaches-in-ireland-czechia-and-spain/

[30] Andreotti, J., Giordano, G. (2024). Strumenti per la decarbonizzazione. Valutazione della Whole Life Carbon (WLC) e della Circular Economy (CE) di un manufatto edilizio. Edizioni Ambiente, Milano. https://freebook.edizioniambiente.it/catalogo/579/strumenti-per-la-decarbonizzazione

Table 1: WLC-GWP methodologies and metrics across European Countries (Source: Author's interpretation based on Ramboll, 2022; BPIE, 2024; Nordic Innovation, 2024; RICS, 2024; INDICATE LIFE deliverable, 2026).

3.5 Relevance of the EPBD for WLC Assessment

In the context of the revised EPBD IV (2024/1275/EU) and the progressive introduction of life-cycle GWP calculation and disclosure requirements under Annex III of the Directive, Member States are increasingly required to define national calculation methodologies, system boundaries, reference areas, data requirements and reporting procedures. While the EU framework introduced by Commission Delegated Regulation 2026/52 fixes certain parameters (including a 50-year RSP, the general data hierarchy, and the minimum scope of building elements and life-cycle stages), it leaves other choices, such as the operational definition of Useful Floor Area (UFA), to national discretion. This combination of harmonisation and flexibility is central to understanding why national WLC methodologies, while increasingly aligned, are not yet directly comparable, a point highlighted in more detail in Paragraph 3.4.

These reporting obligations extend beyond the calculation of the GWP value itself. Annex III requires that the use, maintenance, repair and replacement of building components (Modules from B1 to B4) be accounted for over the 50-year reference study period, and that the treatment of carbon storage (whether biogenic, as in timber products, or mineral, as in the case of concrete carbonation) be handled consistently with the data hierarchy set out in the Regulation. This has direct relevance to the concrete and cement sector: the way Member States model replacement cycles, service life, and carbon uptake will materially affect how durable, long-life materials are represented in national WLC calculations.

At the same time, the EU framework leaves several methodological choices to national discretion, including the operational definition of UFA, the extent to which optional life-cycle modules (such as B5, B7 or B8) are included, and the specific rules for generic data and default values. This combination of EU-level harmonisation and national flexibility is the central methodological tension explored throughout this guide, especially in Chapter 5, where the framework and its treatment of durability-related parameters are examined in detail.

4. Importance of the development of GWP methodology for concrete

Concrete is one of the most widely used construction materials in Europe, playing a central role in many structural and infrastructural applications. For this reason, the way concrete is represented in WLC-GWP assessment frameworks can significantly influence both building-level results and policy decisions. A robust methodology should therefore account not only for the upfront emissions associated with cement and concrete production but also for the specific performance characteristics that affect impacts throughout the full building life cycle.

Several concrete-related aspects are quite relevant in this context. These include long service life, durability, structural performance, maintenance and repair needs, thermal mass, carbonation, potential reuse or recycling pathways, and the increasing availability of sector-specific environmental data through EPDs and industry datasets. At the same time, these aspects are treated differently across national methods and, in some cases, remain only partially represented in current assessment frameworks.

This chapter examines why methodological choices matter for the assessment of concrete within WLC-GWP frameworks. The objective is not to introduce preferential accounting rules for a specific material, but to identify the methodological conditions required for a transparent, consistent and technically accurate assessment.

4.1 Overview of the different methodologies adopted

Selected European approaches, including France, Sweden, Finland, Spain, and Italy, highlight relevant differences in WLC-GWP accounting frameworks. These examples are not reviewed as full national case studies, but as methodological references that may affect concrete WLC-GWP assessment at the building scale. The selected methodologies are reviewed here not as full national case studies, but as examples of methodological choices that may affect concrete WLC-GWP assessment. The focus is on aspects that are very relevant to concrete: the temporal treatment of emissions, the life-cycle modules included, module D, replacement rules, service-life assumptions, carbonation, reuse, and the availability of representative environmental data.

Table 2 summarises the main concrete-relevant lessons emerging from the selected national approaches. The countries' descriptions that follow provide detailed explanatory notes on the methodological approaches.

Country/framework	Concrete-relevant methodological metrics	Why does it matter for the concrete WLC-GWP assessment?
France - RE2020	Simplified dynamic LCA	Gives greater weight to upfront emissions, which are significant for concrete, while later benefits such as avoided replacement, carbonation and reuse may be less visible.
	Carbon discount from module D	It can change comparative results by including beyond-boundary benefits. For concrete, results depend on assumptions about recycling, structural reuse and post-demolition carbonation.

Sweden - Climate Declaration	Assessment focused on A1-A5	A narrow upfront carbon scope does not capture use-stage effects, replacement cycles, end-of-life scenarios, carbonation, or reuse. This can underrepresent the long-term performance of durable concrete systems.
Finland - Climate Declaration	National data infrastructure and concrete-specific tools	The use of national databases, EPDs and low-carbon concrete classification can improve data consistency and allow more representative assessment of concrete mixes.
Spain - CTE DB-HSA1 draft	Treatment of durability through the module B4 replacement formula	The draft methodology introduces a possible way to recognise service life that exceeds the RSP, thereby making durability operational within the WLC calculation. This is directly relevant for long-life concrete structures.
Italy - Tools for decarbonisation	Accounting metrics for concrete carbonation in module B1, C3-C4, and D1	The methodological proposal, in line with European standards and reports, defines metrics, formulas, and guidelines to account for CO_2 uptake from natural carbonation during the building lifecycle.

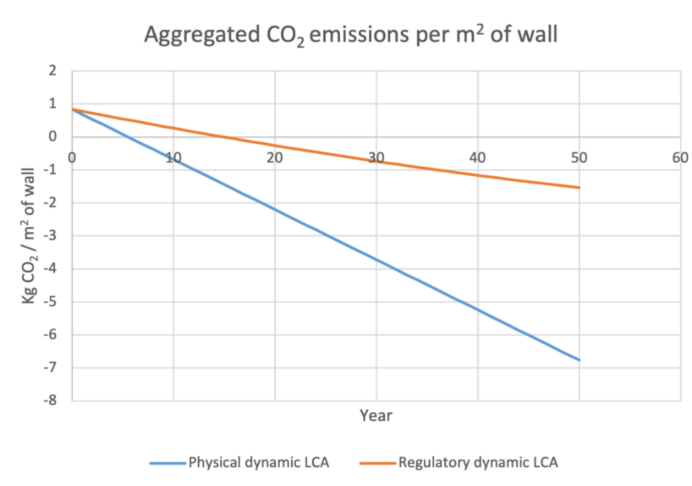
Table 2: Concrete-relevant methodological issues from selected European WLC methodologies and methodological proposals.

In France, the aforementioned RE2020 framework is among the most advanced regulatory approaches in Europe for integrating LCA into building regulation. Its calculation method is based on environmental data[31] for construction products and equipment, including EPDs. Still, it differs from a conventional static EPD-based assessment in two important respects: the use of a simplified dynamic approach to carbon accounting and the inclusion of Module D within the calculation framework.

"Simplified Dynamic approach" for LCA

RE2020 applies a simplified dynamic approach to carbon accounting, particularly for biogenic carbon in materials, such as wood. This approach, unlike conventional static LCA methods, which generally aggregate emissions over the RSP using fixed characterisation factors, applies time-dependent weighting factors according to when emissions occur. For example, emissions occurring at the beginning of the building life cycle, especially in modules A1–A5, are assigned the highest weighting factor, while emissions occurring later, such as those in modules C1-C4, are assigned progressively lower factors (Figure 5 and Table 3).

[31] The national database is INIES: https://www.base-inies.fr/tableau-de-bord



Life-cycle timing	Relevant modules	Indicative weighting factor
Year 0	Module A	1.000
Year 1 to 49	Module B	0.984 to 0.587
Year 50	Modules C and D	0.578

Figure 5 (SX) and Table 3 (DX): Simplified dynamic approach for LCA and weighting factors from RE2020 (Source: Ministerès Transition Écologique, Aménagement du Territoire Transports Ville et Logement, 2026; Lab Recherche Environnement, 2022[32]).

The approach has important implications for comparing construction materials. Materials with high upfront emissions are more strongly affected because their impacts occur early in the assessment period. Conversely, materials for which a significant share of their emissions is deferred until end-of-life may benefit from lower weighting factors.

<u>*Carbon discount from module D*</u>

In the **French** framework RE2020, module D, which is characterised by benefits and loads beyond the building system boundary, is considered an active parameter that can discount CO_2eq emissions from the main life cycle stages (A-C). It means that practices like recycling, reuse, and energy recovery, whose positive or negative impacts depend on assumptions regarding future scenarios of recovery, substitution rules, material quality, and market demand for secondary materials. For this reason, the treatment of module D proposed by RE2020, in contrast with the guidelines provided by EU standards like EN 15804 and EN 15978, requires careful interpretation when comparing material solutions, because it is very favourable for bio-based materials, as emissions are primarily released at the End-of-Life stage (C1-C4). An example of different LCA approaches and the influence of module D is provided in Table 4 below.

Concrete wall (1 m^2, 18 cm thickness)						
LCA method	**Service life**	**A1–A3**	**B1-B4**	**C1-C4**	**D1**	**Total**
		(kg CO_2eq)				
FDES EN 15804+A2	100 years	49	-3.2	5	-1.4	51
Building LCA EN 15978	50 years	49	-1.6	5	-1.4	52
IC Construction RE2020	50 years	49	-1.2	3	-0.82	50
CLT – Cross Laminated Timber (1 m^3)						
FDES EN 15804+A2	100 years	-495	0	736	-230	241
ACV Bâtiment EN 15978	50 years	-495	0	736	-230	241

[32]Lab Recherche Environnement (2022). tps://www.lab-recherche-environnement.org/en/news/dynamic-life-cycle-assessment-explained/

Concrete wall (1 m², 18 cm thickness)						
LCA method	Service life	A1–A3	B1-B4	C1-C4	D1	Total
		(kg CO_2eq)				
IC Construction RE2020	50 years	-495	0	426	-132	-202

Table 4: Comparison of WLC-GWP assessment of concrete-based and bio-based products according to different LCA metrics (Source: Syndicat National du Béton Prêt à l'Emploi - SNBPE).

Overall, the RE2020 framework tends to favour solutions for which emissions are delayed or partly offset over time, while placing greater emphasis on emissions occurring at the beginning of the building life cycle. This can improve the relative performance of bio-based materials and penalise materials with high upfront production impacts, such as concrete and steel. However, these comparisons remain highly dependent on assumptions regarding service life, durability, maintenance, replacement, end-of-life treatment, recycling, carbonation and data quality.

Technical authorities and public institutions, including CSTB and ADEME, have developed calculation methods, tools, and guidance to support designers, assessors, and verifiers in applying RE2020. In this context, it's worth mentioning the development of BETie software from SNBPE[33], which generates Déclaration Environnementale et Sanitaire (FDES) designed for stakeholders involved in the construction process (clients, project managers, HQE project support organisations, architects, design consultancies, contractors, SNBPE members, etc.).

Nevertheless, operational challenges remain, especially regarding the quality and coverage of EPD and LCI data, the need for professional training, and the integration of LCA at early design stages. These issues are central to ensuring that the framework supports robust decision-making rather than simplified material comparisons.

Sweden's approach shows formal alignment with the EU Level(s) framework. Still, it does not cover the entire lifecycle modules required by the EPBD IV (1275/2024/EU) and the Delegated Regulation (52/2026/EU). Additionally, a significant methodological gap remains. For example, site preparation and ground stabilisation activities, generally accounted for in module A5, are not incorporated into the overall calculation; instead, they are treated separately. These impacts are generally considered negligible compared with EC and OC. Still, it is unclear whether and to what extent such activities would materially influence decisions regarding the selection of construction materials for the building and the WLC-GWP releases.

A second key issue concerns the definition of the limit values themselves, which are planned to be introduced in 2030. The current proposal focuses solely on stages A1–A5 (material production, transport, and construction) and is assessed over a 50-year period rather than annually. This choice limits the ability to capture the full environmental impact across the lifecycle, effectively excluding the use, maintenance, and end-of-life phases, which can significantly contribute to overall emissions[34].

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[33] SNBPE, Solinnen and One Click LCA (2024). BETie version 4. https://www.snbpe.org/betie-4-0/
[34] Nordic Innovation (2024). Harmonised Carbon Limit Values for Buildings in Nordic Countries: Analysis of the Different Regulatory Needs.
50-yeartps://www.norden.org/en/publication/harmonised-carbon-limit-values-buildings-nordic-countries-analysis-different-regulatory

Despite the efforts by the Swedish Concrete Federation and several other organisations to advocate for the inclusion of all lifecycle modules – to characterise better replacement cycles (B4), end-of-life scenarios (C3-C4), and the potential reuse and recycling of waste (D1) – these requests have not been successful. At the same time, together with other stakeholders in the construction materials industry, concerns have been raised about the need for greater harmonisation with Nordic countries and the rest of the EU to avoid fragmented approaches and market barriers. However, because Member States retain broad discretion over which modules to include in limit values, these concerns have not been addressed positively. As a result, optimism about potential improvements to the proposal remains limited at this stage.

In the **Netherlands**, the Ministry of the Interior (BZK) is developing the national methodology for setting Whole-Life Carbon GWP (WLC-GWP) limit values for buildings. After assessing four possible methodological variants, the Ministry has decided to further develop Variant 2, which includes all life-cycle modules (A–D) and applies time weighting to both GHG emissions and biogenic carbon storage. According to BZK, this approach is compatible with the flexibility granted to Member States under EPBD IV.

The key feature of this methodology is that emissions are weighted differently depending on when they occur during the building's life cycle. Upfront impacts under Module A are weighted at 100%, while impacts occurring later receive progressively lower weightings: for example, B4 is weighted at 80%, while C and D1 are weighted at 60%. The same time-weighting principle is applied to biogenic carbon storage and its subsequent release.

This is also the main area of ongoing debate. While there is broad agreement on including modules A to D within the WLC-GWP calculation, there is no consensus within the stakeholder group on the treatment of Module D and biogenic CO_2 storage, with differing views both among stakeholders and between some stakeholders and the Ministry's proposed approach.

Despite these differences, BZK has decided to proceed with Variant 2 as the basis for developing the national methodology and setting future WLC-GWP limit values. The proposed limits are currently being developed using the third quartile (Q3) of the results from reference buildings, providing an initially relatively conservative threshold.

The direction being pursued by the Dutch government is therefore relatively clear: to assess the entire building life cycle from modules A to D, while applying time weighting to climate impacts. This gives greater weight to emissions occurring in the early stages of a building's life and progressively less weight to impacts occurring further in the future. The treatment of biogenic carbon and Module D remains the most sensitive methodological issue, as the choice of time weighting can significantly influence the final WLC-GWP result and, consequently, the assessment of different construction solutions.

The **Finnish** climate declaration method, established under the Ministry of Environment Decree 1027/2024, sets out clear and comprehensive requirements for evaluating the environmental performance of buildings. The assessment encompasses not only the building itself but also the surrounding site, while underground structures and temporary site facilities are excluded.

The Finnish approach requires a twofold report: a carbon footprint assessment (which must not exceed limit values) and a carbon handprint assessment (not counted towards regulatory limits). The carbon handprint refers to the positive climate impacts generated by a product, system, or solution compared to a conventional baseline scenario, such as avoided emissions, extended service life, improved energy efficiency, material substitution effects, circularity benefits, or carbon uptake mechanisms that contribute to reducing overall greenhouse gas emissions across the life cycle.

To support those assessments, a national database (CO2DATA.FI[35]) for building materials and products was developed, as well as a specific database for infrastructure processes. Additionally, and specific to concrete products, it was set up by Finnish Concrete Association (Suomen Betoniyhdistys ry, also referred to as BY), Confederation of Finnish Construction Industries RT and Aalto University as a tool for the Low-Carbon Concrete Class, which can be used to generate transparent GWP data for the A1–A3 stages of concrete mixes, supporting design iterations and compliance checks.

The BY Low-Carbon Calculator[36] can serve as project-specific data in the climate declaration, provided it is accompanied by clear documentation, including the mix ID, constituents, system boundaries, and data version.

The **Spanish** draft regulation amending the national Technical Building Code (CTE), as proposed in the DB-HSA1 document, is potentially relevant to the concrete WLC-GWP methodology because its alternative B4 formula could account for durability within the Replacement module (B4). The draft methodology defines national requirements for calculating the life-cycle GWP of buildings in line with Annex III of the EPBD IV and includes a replacement formula intended to account for the Service Life (SL) of construction elements. A relevant methodological question is how the formula applies to components whose service life exceeds the 50-year RSP. In the reported B4 formula, when the product SL (Vuk) is higher than the RSP (T), the expression (T/Vuk – 1) may generate a negative replacement value. However, the draft does not explicitly clarify whether such values are intended to be retained or treated differently. If retained, they could provide a mechanism for recognising residual SL beyond the RSP.

For concrete structures, this approach is relevant because properly designed, specified and executed concrete elements may remain functional beyond the 50-year RSP. However, any durability-related benefit should not rely on generic assumptions. SL values above 50 years should be supported by design criteria, exposure conditions, durability provisions, maintenance assumptions and, where available, evidence from inspection or service-life data. Overall, the Spanish case provides an interesting regulatory example of how durability may be incorporated into WLC-GWP calculation rules. Its treatment of SL exceeding the RSP remains to be clarified, but the proposed formula highlights an important methodological question for the development of durability-sensitive

[35] For more information visit: https://co2data.fi/

[36] Finnish Concrete Association (BY): BY Low-Carbon Concrete Classification and BY Low-Carbon Calculator. www.vahahiilinenbetoni.to thefto thein the in the asa. It includess. It includes

WLC-GWP accounting. It should therefore be considered a relevant reference for further analysis, while ensuring that the final legal text, calculation formula, scope of application and documentation requirements are verified. Further details on the B4 formula and the Spanish EC benchmark, including the original formula, the LCA table, and the contribution charts, are provided in Annex E.

Finally, it's worth mentioning the **Italian** methodological proposal, developed by researchers from the Department of Architecture and Design at Politecnico di Torino, together with the Green Building Council Italia and other national stakeholders of the construction sector[37]. The methodological proposal, cited by the national standard UNI 11973:2025 as a key representative guideline for supporting designers and firms in WLC-GWP assessments, is aligned with the European standards EN 16757:2017 (Annex BB) and PD CEN/TR 17310:2019. It provides a comprehensive guide to CO_2 uptake via carbonation occurring in concrete-based materials and products, with specific procedures for Autoclaved Aerated Concrete (AAC) and lime-mixed products[38], during module B1 (Use), module C4 (Disposal), and module D1 (Reuse and recycle).

4.2 Discussion

The comparative analysis of national methodologies highlights a clear divergence in how WLC-GWP are currently addressed across Europe. While all countries are broadly aligned with EN 15978 and EN 15804 as common methodological references, significant differences remain in system boundaries, life-cycle modules included, temporal assumptions, and the treatment of biogenic and end-of-life carbon flows.

A first key observation is the increasing tendency to expand the scope of assessment beyond the traditional A1–A3 production stage. Finland represents the most comprehensive approach, already integrating modules A4–A5, B4 and B6, and stage C, and explicitly including potential benefits under module D1 and D2 within regulatory reporting. In contrast, Sweden remains more limited, focusing primarily on A1–A5 and excluding several relevant construction-related activities such as site preparation, while postponing full regulatory implementation to 2030. France, through RE2020, introduces one of the most distinctive methodological frameworks by incorporating a dynamic carbon accounting approach and explicitly including stage D as an "active" phase able to directly influence stages A to C in the regulatory calculation. This significantly alters the temporal distribution of emissions, particularly benefiting materials with delayed emissions such as wood and timber, while penalising materials with upfront emissions such as concrete and steel. This methodological choice demonstrates how assumptions about temporal modelling can substantially influence material rankings and perceived environmental performance.

In this context, the treatment of concrete is highly relevant, given its long service life, thermal inertia, potential for partial carbonation, and the wide availability of robust, sector-specific EPD data. However, its emissions are largely upfront and production-intensive, so methodologies based

[37] Andreotti, J., Giordano, G. (2024). Strumenti per la decarbonizzazione. Valutazione della Whole Life Carbon (WLC) e della Circular Economy (CE) di un manufatto edilizio. Edizioni Ambiente, Milano. https://freebook.edizioniambiente.it/catalogo/579/strumenti-per-la-decarbonizzazione

[38] Based on reports and researches from AAC-Worldwide and European Lime Association (EuLA).

on dynamic accounting or short-term emission weighting tend to penalise it disproportionately. This creates a methodological tension between physical reality (durability and long-term performance) and regulatory modelling choices (the timing of emissions and the system boundary definition). As a result, a tailored and harmonised GWP methodology for concrete within WLC frameworks is essential to ensure fair comparison with alternative materials and to properly reflect its long-term environmental behaviour, including carbonation and potential reuse or recycling pathways. Particularly notable are the efforts in Spain and Italy, where concepts such as durability and CO_2 uptake are studied and used to develop specific methodologies.

Across all countries analysed, a second common challenge concerns data quality and consistency. The Finnish, French and Spanish approaches explicitly recognise the importance of combining national databases with verified EPDs, while also allowing for project-specific data under defined conditions. As reported in Annex E, the Spanish benchmark indicates that the choice of database, for example, sector-specific EPDs versus generic datasets such as Ecoinvent, can lead to variations of around 10–15%, confirming that data selection remains one of the main sources of uncertainty in comparative assessments.

Despite methodological differences, a strong convergence emerges regarding the importance of early design decisions. Structural systems, material selection, and envelope optimisation consistently appear as the dominant drivers of EC across all national studies. Similarly, there is agreement that extending service life and improving durability significantly reduces annualised impacts, especially for structural elements, reinforcing the relevance of life-extension strategies within decarbonisation policies.

Finally, while regulatory frameworks are rapidly evolving, several operational barriers remain, including limited harmonisation between countries, variability in LCA boundaries, and the need for improved training and data transparency. These issues underline the importance of continued coordination at the European level to ensure methodological consistency and to avoid fragmented approaches that could distort material comparisons and market dynamics.

Overall, the review confirms that WLC methodologies are converging towards more comprehensive and stringent frameworks, but also that material-specific considerations (especially for concrete) remain critical to ensure scientifically robust, fair, and policy-relevant carbon accounting across the built environment.

5. How to integrate WLC methodology with the durability of concrete

This chapter defines how durability-related parameters can be integrated into WLC-GWP assessment to improve the consistency, transparency and functional equivalence of concrete assessment at the building scale.

In building-level WLC assessments, durability affects results primarily through the service life of components, the frequency of maintenance, repair, and replacement, and the ability of structural elements to remain functional during or beyond the Reference Study Period (RSP). These parameters are highly relevant when comparing construction solutions with different Expected Service Lives (ESLs), maintenance requirements or replacement cycles. If durability is not explicitly addressed, WLC-GWP results may overemphasise upfront emissions while underrepresenting long-term performance, avoided replacements and residual service potential. The objective of this chapter is not to introduce preferential rules for durable materials, but to define practical criteria for the transparent and comparable representation of durability. This includes functional equivalence, RSP, RSL/ESL, life-cycle modules, replacement rules, residual service potential, carbonation, data requirements and reporting principles. Concrete is one of the most durable and widely used construction materials. Properly designed, specified, executed, and maintained concrete structures may remain functional beyond the RSP and can contribute to safety, resilience, and long-term environmental performance at the building scale. The proposed approach aims to ensure that concrete structures and concrete-based building systems are assessed using the same life-cycle logic as other construction materials.

For concrete materials and concrete-based building systems, the selection and interpretation of life-cycle modules is highly relevant because durability-related effects are not confined to a single module.

For concrete materials and products, the selection and interpretation of life-cycle modules are especially important because **a single module may not capture durability-related effects**. A WLC methodology that aims to represent concrete performance accurately should define how durability-related assumptions are modelled.

This section is organised according to a progressive structure summarised in Table 5. The objective is to provide a guideline for practitioners, starting from the general calculation structure to the methodological issues that arise when considering long SL, replacement cycles, remaining service life after the RSP, and potential reuse.

Subsection	Focus	Role within the chapter
5.1	Relevance of modules for concrete durability	Clarifies how durability-related effects may interact with different EN 15978 life-cycle modules.
5.2	RSP, RSL/ESL and residual service potential	Explains the relationship between the assessment period, component service life and residual functionality beyond the RSP.
5.3	Durability-sensitive accounting approaches	Presents alternative or complementary approaches for representing long service life, retention, reuse and residual

		performance.
5.4	Temporary and permanent carbon storage: carbonation and mineralisation	Distinguishes natural carbonation from accelerated carbonation and clarifies their possible treatment within WLC-GWP modules.
5.5	Durability parameters: uncertainty management and sensitivity analysis	Assesses uncertainty in service life, degradation, carbonation and data quality through sensitivity analysis, scenario testing and transparent reporting.

Table 5: Structure of section 5.

5.1 Relevance of modules for concrete durability

Durability is not reflected in a single life-cycle module. It emerges from the interaction between SL, maintenance and repair needs, replacement assumptions, carbonation, end-of-life treatment and potential reuse or recovery scenarios. For this reason, WLC-GWP methodologies should explicitly define how durability-related effects are assigned to the relevant life-cycle modules. Table 6 provides a module-by-module reading of the concrete WLC-GWP assessment, distinguishing between general concrete-related effects and durability-specific aspects.

Life-cycle stage	Durability-related aspect	Relevance for concrete WLC assessment
A1-A3	/	Includes the main upfront impacts of the concrete production plant.
A4-A5	/	Relevant for ready-mix and precast concrete logistics, on-site placement, pumping, formwork-related processes where included, and construction losses.
B1	Use stage	May include **carbonation**, where allowed by the assessment method.
B2-B3	Maintenance and repair	Durable concrete structures may require **fewer or less frequent interventions**, depending on exposure, design and maintenance strategy.
B4	Replacement cycles	Accounts for the **replacement** of components with an SL shorter than the RSP. For long-life concrete elements, B4 is central to showing whether replacements are avoided.
C1-C4	End-of-life processes	Assumptions on demolition, crushing, sorting and waste treatment can significantly affect end-of-life impacts.
D	Benefits and burdens beyond the system boundary	May capture potential effects related to reuse, recycling, recovery or substitution. For concrete, reuse or retention of structural function should be distinguished from recycling as aggregate.

Table 6: Life-cycle modules and durability-related effects for concrete WLC-GWP assessment.

This module-by-module reading highlights that **concrete durability** should not be reduced to the absence of replacements in Module B4. Its WLC relevance also depends on maintenance assumptions, carbonation modelling, end-of-life scenarios, and the potential preservation or reuse of structural value beyond the life cycle.

5.2 Methodological issue: RSP, RSL and residual service potential

A key methodological issue in WLC assessment concerns the relationship between the **building RSP** and the **SL** of components or structural systems. The RSP defines the assessment's time horizon. At the same time, the RSL or ESL describes the period during which a component is expected to fulfil its intended function under defined design, exposure, use and maintenance conditions.

When the service life of a component is shorter than the RSP, replacement cycles are accounted for in module B4. Each **replacement** introduces additional impacts related to **production, transport, installation and end-of-life treatment**. Conversely, when a component's service life exceeds the RSP, no replacement is normally recorded in B4. However, the **remaining functional capacity beyond** the **RSP** is often not explicitly represented unless the assessment method includes specific rules for continued use, reuse, residual value or allocation across multiple life cycles.

The 50-year RSP has become a common baseline across Europe, supporting comparability between national assessment approaches and alignment with long-term policy objectives such as the EU's 2050 climate neutrality target[39]. A review of 41 LCA studies on building rehabilitation found that around 80% of studies adopted a study period of either 50 or 60 years, indicating that this timeframe is widely used in both research and professional practice. At the same time, the choice of RSP remains a critical methodological assumption, as it significantly influences assessment results. Studies show that maintenance and replacement impacts become increasingly significant when analyses extend beyond 50 years, especially over 80- or 150-year scenarios[40]. From this perspective, the challenge is not the 50-year timeframe itself, but rather how effectively the methodology captures long-term performance, durability, adaptability, and potential for reuse within that common framework.

This issue becomes quite relevant for materials such as concrete, whose service life and long-term processes, including carbonation, often extend well beyond the 50-year assessment boundary. In such cases, the standard fixed-RSP approach may assess durability properties only **indirectly**, through avoided replacements, without considering the structure's residual service potential at the end of the assessment period. The main cases between RSP-ESL values are summarised in Table 7, and the methodological implications are presented accordingly.

Condition	Usually represented in WLC	Methodological implication
RSL/ESL < RSP	One or more replacements are included in module B4.	Shorter-life components generate additional impacts over the assessment period.
RSL/ESL = RSP	The component is assumed to fulfil its function over the full assessment period.	No replacement is generally needed, but no residual service potential remains beyond the RSP.

[39] Steinmann, J., Röck, M., Lützkendorf, T., Allacker, K. Le Den, X. (2022). Whole life carbon models for the EU27 to bring down embodied carbon emissions from new buildings: Review of existing national legislative measures. https://c.ramboll.com/reducing-whole-life-carbon

[40] Francart, N., Widström, T., Malmqvist, T. (2021). Influence of methodological choices on maintenance and replacement in building LCA. International Journal of Life Cycle Assessment 26, 2109–2126. https://doi.org/10.1007/s11367-021-01985-z

RSL/ESL > RSP	No replacement is generally included in module B4.	Remaining service potential may be unreported unless specific rules address continued use, reuse or allocation beyond the RSP.

Table 7: Main methodological implications of different RSP-ESL values.

Service-life conventions: short-life versus long-life elements

Within a defined RSP, building components are assigned individual service lives that determine the frequency of maintenance, repair, and replacement events in life-cycle assessment. EN 15978, Section 9.2, explicitly distinguishes between "*components that will not be replaced under normal conditions*" and "*replaceable components*".

- **Short-life** elements are replaceable components that typically include technical building systems (heating, cooling, ventilation), finishes, and building services components. EN 15978, Section 8.5.2, requires that scenarios for maintenance, repair, and replacement be based on the expected frequency and type of such activities during the reference study period. Their ESL (typically 15–30 years) requires that they be modelled and replaced at least once within the 50-year RSP, thereby increasing the building's total GWP through Module B4;
- **Long-life** structural elements, such as the concrete frame, foundations, floors, and structural walls, will not be replaced under normal conditions. These elements can be modelled with a service life equal to or exceeding the 50-year RSP, provided they are designed in accordance with durability standards. Consequently, no replacement burden (Module B4) is allocated;

Buildings with a high share of short-life components may accumulate substantial additional embodied impacts over time due to repeated replacement cycles. As a result, when longer timeframes or building reuse are considered, durable structural materials such as concrete may offer environmental advantages, as they avoid the repeated production and replacement cycles required by shorter-lived components[41].

Figure 6 illustrates how the relationship between RSP and component service life affects WLC modelling. Components with a shorter service life generate replacement impacts within B4, whereas durable elements with a service life exceeding the RSP may retain functional capacity beyond the assessment boundary. This residual service potential is a key issue for concrete structures and elements and provides the rationale for durability-sensitive approaches.

[41] Dervishaj, A., Räsänen, A., Gudmundsson, K., Lahdensivu, J. (2026). From durability to circularity: ensuring service life and enabling reuse of concrete in circular construction. Materials and Structures 59, Article 28. https://doi.org/10.1617/s11527-025-02914-4

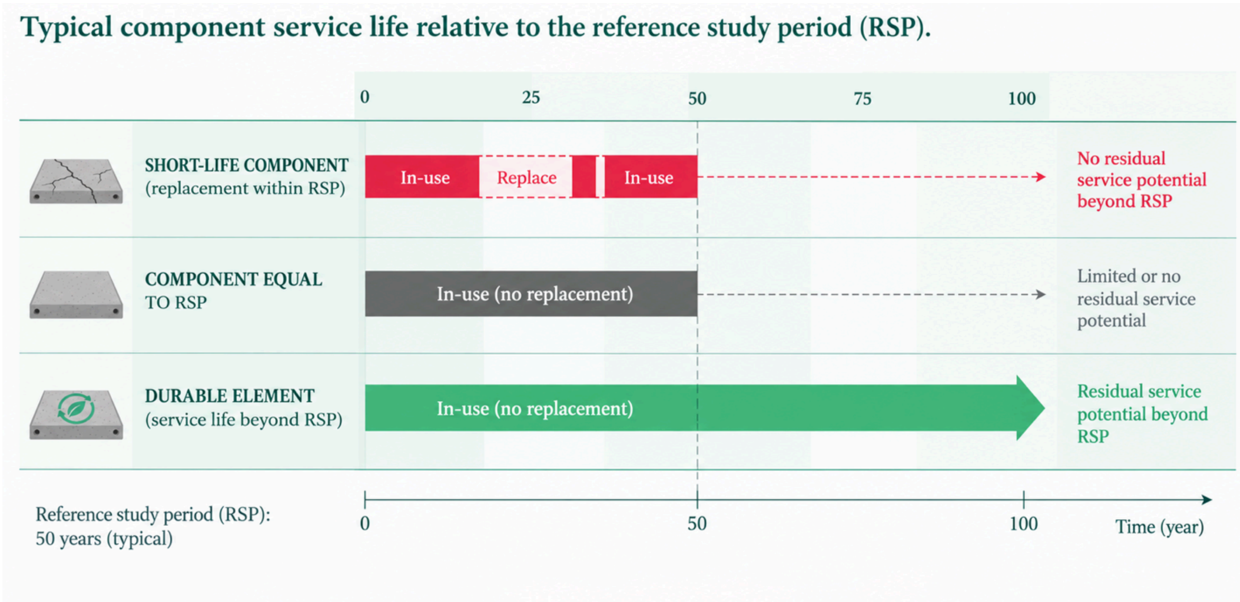

Figure 6: Relationship between RSP, service life and replacement modelling.

Durability should also be considered together with the adaptability of the structural system. Buildings designed with robust and flexible structural layouts can accommodate functional changes over time, reducing the likelihood of premature demolition and reconstruction. From a WLC perspective, this can extend the building's effective service life and support future retention or reuse scenarios. This provides the link between residual service potential and the durability-sensitive accounting approaches discussed in Section 5.3.

Further discussion of the cross-material implications of recognising an extended SL is provided in Annex B.

5.3 Alternative proposals for durability-sensitive accounting

Standard WLC assessment methods often account for durability mainly through replacement assumptions in module B4. However, for long-lasting concrete structures, durability may also affect residual service potential, reuse opportunities and the distribution of environmental burdens across multiple life cycles. Several methodological approaches can be used to make these effects more transparent. In Table 8, different approaches are presented, along with their potential relevance for concrete and their main limitations.

Approach	**Relevant modules**	**Main principle**	**Practical relevance for concrete**
Durability-adjusted FU[42]	System boundaries effects	The comparison is based not only on quantity, but also on strength, exposure class, durability performance and service life.	Improves functional equivalence when comparing concrete mixes, elements or systems with different durability performance.
Reuse-oriented Module D scenario / structural retention[43] [44]	Mainly **Module D**, linked to **C1-C4,** where end-of-life scenarios are modelled	Considers the preservation or reuse of structural capacity rather than only recycling concrete as aggregate.	Makes residual service potential and the reuse of concrete structures more visible, particularly where structural layouts allow future adaptation, retention, or reuse rather than demolition and recycling as aggregate.
Partial allocation models[44]	System boundaries effects	Environmental burdens are allocated across multiple life cycles according to remaining service life or use-cycle assumptions.	Useful when comparing renovation, retention, reuse and reconstruction scenarios.
50:50 and Linearly Degressive allocation[45]	System boundaries effects	Production and end-of-life burdens are shared between current and future use cycles according to fixed or sequence-based allocation rules.	Provides a structured way to distribute impacts when concrete elements or structures are reused across multiple life cycles.
Degradation-rate allocation[46]	Mainly **B2-B4**, potentially **D**	Allocation is linked to physical deterioration or loss of functional performance over time.	Connects WLC-GWP modelling to actual durability performance, using indicators such as carbonation depth, chloride ingress, corrosion risk or condition assessment.
Spanish methodology / CTE DB-HSA1[47]	Mainly **B4**, with indirect effects on **A1-A3** and **C1-C4**	Introduces a potential durability-related adjustment in **B4** when service life exceeds the RSP, according to the reported draft formula.	Provides a regulatory example of how durability can be operationalised within an EN 15978-based framework. Final wording should be subject to verification of the official legal text and formula.

[42] Panesar, D.K., Seto, K.E., Churchill, C.J. (2017). Impact of the selection of functional unit on the life cycle assessment of green concrete. International Journal of Life Cycle Assessment 22, 1969–1986. https://doi.org/10.1007/s11367-017-1284-0.

[43] Dervishaj, A., Räsänen, A., Gudmundsson, K., Lahdensivu, J. (2026). From durability to circularity: ensuring service life and enabling reuse of concrete in circular construction. Materials and Structures 59, Article 28. https://doi.org/10.1617/s11527-025-02914-4

[44] Decorte, Y., Van Den Bossche, N. Steeman, M. (2023).Guidelines for defining the reference study period and system boundaries in comparative LCA of building renovation and reconstruction. International Journal of Life Cycle Assessment 28, 111–130. https://doi.org/10.1007/s11367-022-02114-0

[45] Eberhardt, L.C.M., van Stijn, A., Rasmussen, F.N., Birkved, M., Birgisdottir, H. (2020). Towards circular life cycle assessment for the built environment: A comparison of allocation approaches. IOP Conference Series: Earth and Environmental Science 588, 032026. https://doi.org/10.1088/1755-1315/588/3/032026

[46] Xia, B., Ding, T. & Xiao, J. (2020). Life cycle assessment of concrete structures with reuse and recycling strategies: A novel framework and case study. Waste Management 105, 268–278. https://doi.org/10.1016/j.wasman.2020.02.015

[47] Ministerio de Vivienda y Agenda Urbana (MIVAU). Proyecto de real decreto por el que se modifica el Código Técnico de la Edificación, aprobado por Real Decreto 314/2006, de 17 de marzo. Borrador para audiencia e información pública, including proposed DB-HSA1 – Potencial de Calentamiento Global, November 2025.

Table 8: Alternative approaches for durability-sensitive WLC accounting in concrete assessment.

The approaches summarised above clarify how **durability**, residual service potential and multi-cycle use may be addressed within, or alongside, existing life-cycle assessment modules. At the methodological level, the selected approach should clearly define its system boundaries, the modules it affects, the allocation logic, and the underlying assumptions.

These approaches share a common objective: avoiding comparisons in which durability is reduced only to the **absence of replacements** within a fixed RSP. Instead, they attempt to represent the residual functionality of components that remain serviceable beyond the assessment boundary or across multiple use cycles. For concrete, this is highly relevant when structural elements are retained in renovation projects, reused in subsequent life cycles, or designed for service lives that substantially exceed the building-level reference study period.

However, these approaches also introduce additional **methodological complexity**. They require assumptions about future use, degradation, maintenance, feasibility of reuse, market demand, technical suitability, and allocation of benefits across life cycles. For this reason, durability-related benefits should not be treated as automatic credits for concrete or for any other durable material. They should be supported by project-specific documentation, conservative assumptions and verifiable evidence of residual performance.

Among the approaches reviewed, the Spanish CTE DB-HSA1 draft is quite relevant because it offers a way to translate durability concept into a calculation rule within module B4, while remaining within an EN 15978-based regulatory structure. It can therefore be considered a priority reference for further development of durability-sensitive WLC accounting, subject to verification of the final legal text and scope of application.

Implications for concrete WLC-GWP methodology

The methodological options discussed above lead to four operational principles, briefly illustrated in Table 9 for a concrete WLC-GWP assessment. These principles are intended to guide the treatment of durability-related claims and to avoid treating durability either as an automatic credit or as a purely qualitative attribute.

Principle	Operational implications for concrete WLC-GWP assessment
Durability as a performance-related parameter.	Durability should be linked to documented service life, exposure conditions, maintenance assumptions and the concrete element's ability to continue fulfilling its function over time and beyond the RSP.
Replacement modelling is necessary but not sufficient.	Module B4 captures avoided replacements within the RSP, but residual service potential should also be made transparent when concrete elements remain technically functional beyond the assessment boundary.
Reuse and **retention** before downcycling.	Reuse or retention of structural function should be assessed before assuming recycling as aggregate, provided that technical feasibility, future use and allocation rules are clearly documented.
No automatic credits.	Service-life extensions, avoided replacements, reuse potential, and degradation-based allocation should be supported by conservative, verifiable evidence, such as design specifications, exposure class, maintenance strategy, condition assessment, or recognised technical standards.

Table 9: Main methodological implications for integrating concrete durability into WLC-GWP assessment.

5.4 Handling temporary vs permanent carbon storage (mineralisation, carbonation)

Concrete can partially reabsorb atmospheric CO_2 through **carbonation**, a chemical process in which CO_2 penetrates the pore structure and reacts with calcium-bearing hydration products to form stable calcium carbonate. This uptake should not be treated as a generic or automatic credit, as it depends on specific composition, exposure conditions, surface area, moisture, carbonation depth, service life, and end-of-life treatment. A more detailed explanation of the carbonation mechanism, relevant parameters and modelling assumptions is provided in Annex C. For WLC assessment, it is important to distinguish between **natural** and **accelerated carbonation**, since they differ in timing, CO_2 source, process control and module allocation. Table 10 summarises the operational treatment of the two carbonation routes within the concrete WLC assessment.

Carbonation route	Relevant modules	Description	Operational treatment in WLC assessment
Natural carbonation / permanent mineral storage	**B1** during service life; **C3/C4** for post-demolition exposure; **D** where uptake is linked to processes beyond the system boundary.	Passive and gradual uptake of atmospheric CO_2 during the service life of concrete and, where relevant, after demolition when concrete is crushed or exposed to air.	Account for CO_2 uptake through time-consistent and scenario-specific assumptions. The calculation should consider exposure conditions, concrete composition, exposed surface area, carbonation depth, RSP and end-of-life scenario. Product-level EPD carbonation values should not be mechanically transferred to building-level WLC calculations when the time horizons differ.
Accelerated carbonation/ utilisation	**A3** when carbonation occurs during manufacturing; **A5** where carbonation occurs on site; **C3/D** was applied to recycled aggregates or end-of-life streams, depending on the system boundary.	Controlled process in which CO_2 uptake is intentionally enhanced, for example, through CO_2 curing of concrete elements or carbonation treatment of recycled concrete aggregates.	This is distinct from slow natural carbonation and should be treated as a negative input in module A3, or in module A5, where the process occurs on site, provided that the CO_2 source, permanence, additional energy use, process emissions and material performance are documented.[48]

Table 10: Operational distinction between natural carbonation and accelerated carbonation in concrete WLC assessment.

Overall, carbonation is a relevant feature of concrete WLC assessment, but it should be accounted for through transparent, time-consistent and verifiable assumptions, rather than as a generic carbon credit. Further methodological details are provided in Annex C.

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[48] Chen, T., Nelson, J.P., Gupta, V. & Mobley, P.D. Life-cycle assessment of concrete production with carbon capture and carbon upcycling process. Journal of Environmental Management 391, 126303 (2025). https://doi.org/10.1016/j.jenvman.2025.126303.

5.5 Biogenic carbon accounting

In the context of material-neutral whole-life carbon regulation, the treatment of biogenic carbon in bio-based construction products deserves careful consideration. Current life-cycle accounting can recognise the atmospheric CO_2 absorbed during biomass growth and subsequently stored in a construction product. However, this product-level accounting does not necessarily capture all changes in forest carbon stocks and fluxes that may occur following harvesting, including changes in standing biomass, soil carbon and the rate of subsequent CO_2 uptake. Research indicates that the magnitude and duration of these effects depend strongly on forest type, harvesting practice, growth rates and the time horizon considered[49] [50] [51]. For the development of future whole-life carbon regulation, it would be important to distinguish between carbon physically stored in a wood product and the broader forest-system carbon balance associated with its production. Where biogenic carbon storage in a bio-based construction product is credited as a climate benefit, the corresponding effects of harvesting on the forest carbon balance should also be accounted for, to ensure that the accounting does not attribute a carbon benefit to the product without considering relevant changes in the forest carbon balance. An alternative approach is to treat the short biogenic carbon cycle as carbon neutral, in which case temporary carbon storage in the product would not be credited as an additional climate benefit.

In summary, carbon stored in a bio-based construction product does not necessarily equal carbon saved from the atmosphere. This distinction is important when whole-life carbon regulations compare bio-based construction materials such as timber with materials such as concrete and steel: the carbon stored in a bio-based material can be measured, but its overall climate benefit also depends on changes in the forest carbon balance after harvesting. If timber is given an advantage because of the biogenic carbon it stores, it is important to be clear about what is actually being accounted for. The fact that a certain amount of CO_2 previously absorbed from the atmosphere is stored in a timber product should not be interpreted as an equivalent reduction in atmospheric CO_2 compared with alternative materials, as this also depends on the wider carbon balance of the forest system and what would have happened in the absence of harvesting.

5.6 Durability parameters: uncertainty management and sensitivity analysis

The integration of durability parameters into LCA introduces additional sources of data variability and model uncertainty that standard deterministic calculations often ignore. Given that SL predictions and carbonation rates rely on environmental assumptions and long-term degradation

[49] Mattsson, E., Dellås, S., Wallander, A., Vrasdonk, E., Roos, T., Johansson, H. and Rydberg, T. (2025). Trä vs. Betong: Biologisk mångfald i livscykelanalyser för byggmaterial [Wood vs. Concrete: Biodiversity in life-cycle assessments for building materials]. IVL Swedish Environmental Research Institute, Report B11039, November 2025.

[50] Lundmark, T., Bergh, J., Nordin, A., Fahlvik, N. and Poudel, B.C. (2016). "Comparison of carbon balances between continuous-cover and clear-cut forestry in Sweden." Ambio, 45(Suppl. 2), pp. 203–213. https://doi.org/10.1007/s13280-015-0756-3

[51] Korkiakoski, M., Ojanen, P., Tuovinen, J.-P., Minkkinen, K., Nevalainen, O., Penttilä, T., Aurela, M., Laurila, T. and Lohila, A.K. (2023). "Partial cutting of a boreal nutrient-rich peatland forest causes radically less short-term on-site CO_2 emissions than clear-cutting." Agricultural and Forest Meteorology, 332, Article 109361. https://doi.org/10.1016/j.agrformet.2023.109361

models, a robust WLC-GWP methodology needs to account for uncertainty to ensure reliable comparisons. Research shows that when unit process inputs are treated as separate, unrelated probability distributions (as is often done by default), the physical mass balance is broken. This can lead to impossible concrete mix designs, such as unrealistic cement-to-water ratios, undermining a fair comparison. For concrete specifically, strict mix design constraints (e.g., water-to-cement ratio) must be maintained to ensure that the assessed durability and strength are valid[24].

To align with the goal of transparency and consistency, the following technical criteria for uncertainty management could be applied: Parameter Correlation and Mass Balance[52], Monte Carlo Simulation[53], and Sensitivity Analysis of Durability Variables[54].

Developing a standardised way to compute uncertainty and interpret results for all EU countries adds another layer of complexity. Still, it is important to keep in mind that uncertainty and data variability can cause mass imbalances.

[52] Marsh, E., Hattam, L. Allen, S. (2025). Stochastic error propagation with independent probability distributions in LCA does not preserve mass balances and leads to unusable product compositions—a first quantification. Int J Life Cycle Assess 30, 221–234 https://doi.org/10.1007/s11367-024-02380-0

[53] Huang, ., Huang, Z., Zhou, Y., Hu, R., Hu, B. (2025). Life cycle assessment and cost analysis of LC3 concrete considering sustainability and uncertainty, Journal of Building Engineering 102, https://doi.org/10.1016/j.jobe.2025.111960

[54] Ventura A, Ta V-L, Kiessé TS, Bonnet S. (2021),Design of concrete: Setting a new basis for improving both durability and environmental performance. J Ind Ecol., 25:233–247. https://the doi.org/10.1111/jiec.13059

6. Data quality, standardisation and reporting

Reliable data governance is essential to ensure that WLC-GWP assessments are consistent, comparable and auditable across projects and countries. Data governance in this context refers to the structured management of data sources, modelling assumptions, data quality, documentation and review processes throughout the LCA workflow, supported by clearly defined responsibilities, version control and traceability. European standards – EN 15804:2021+A2 and EN 15978:2026 – for product-level and building-level LCA require that datasets be transparent, representative and methodologically aligned with harmonised calculation rules, so that results can be reproduced and independently verified.

6.1 Mandatory building elements to be covered by WLC-GWP assessment

Based on EPBD IV (1275/2024/EU) and the Delegated Regulation (52/2026/EU), the building elements to be covered by the WLC-GWP assessment – for both new constructions and renovation works – to ensure comprehensive, comparable, and accurate calculation should follow the hierarchical Tiers framework (1-4)[55].

The Tiers follow a progressive detailing of the building elements, starting, for example, with Shell (Tier 1), then moving to Substructure (Tier 2), Foundations (Tier 3), and Ground floor slabs and beams (Tier 4). Tiers 1 and 2 should be aligned across all EU Member States and included in the future Energy Performance Certificate (EPC), which requires integrating climate performance. At the same time, Tiers 3 and 4 may vary across EU Member States and may be excluded from the EPC. An example of the hierarchical Tier framework for Shell is shown in Table 11, while the entire set of building elements (Core and External Works) is illustrated in the Delegated Regulation. It is important to note that Shell and Core are the only two mandatory Tiers.

Tier 1	Tier 2	Tier 3	Tier 4
Shell	Substructure	Foundation piling and underpiling	Permanent piles and caisson
			Underpinning
		Foundations	Lateral supports
			Raft footings, pile caps, column bases, wall footings; strap beams, tie beams
			Substructure walls and columns
			Ground floor slabs and beams (when the building includes a basement, basement bottom slabs should be counted within the relevant Tier 3 “Basement elements”)
			Lift pits (slabs and walls)
	Structure	Frames and slabs (above top of ground floor slabs)	Structural walls, braces and columns
			Upper floor beams, joists, braces and slabs
			Roof beams, joists, braces and slabs
			Staircases (forming part of the structure)
			Fireproofing to steel structure
Non-exhaustive list of Shell.			

[55] With reference to the Table 4 of the Delegated Regulation 52/2026/EU.

Table 11: Hierarchical scope of building elements and technical equipment (Source: Delegated Regulation 52/2026/EU).

6.2 Data hierarchy

Following the stage of the building's decision-making process, and according to the Level(s) framework indicator 1.2[56] and the new EN 15978:2026, the new EPC required by Delegated Regulation 52/2026/EU should take into account the "*as-built stage*"[57] of a building[58].

For this building stage, the environmental data of materials and products must be aligned to the following hierarchy:

1. Product-specific EPDs and/or data available pursuant to CPR Regulation 3110/2024/EU
2. Data available under ecodesign and energy labelling legislation, according to 125/2009/EC, 1369/2017/EU, and 1781/2024/EU
3. Product- and project-specific EPDs
4. Generic or sector-average EPDs
5. LCA studies compliant with EN 15941:2024 and EN 15804:2021+A2
6. Generic data from the national database
7. Generic data from EU databases

If product-specific data is unavailable, alternative data sources can be used in accordance with the hierarchy. The use of generic data or default values should be kept to a minimum, must be explicitly justified in the calculation report and must ensure an adequate level of traceability, transparency and comparability of the assessment results.

6.3 WLC-GWP databases

WLC-GWP assessment of buildings relies on accurate lifecycle information about construction materials, products, and processes, which is stored and managed in environmental databases. These databases play a central role in WLC-GWP assessments because they provide the emissions and resource-use data needed to calculate the CO_2eq releases and uptake of buildings from material production through construction, use, and end-of-life.

Two main types of databases are used:

- Specific databases that contain EPDs, Carbon Footprint (CF), Product Environmental Footprint (PEF) and LCA studies
- Generic databases that contain average or representative data for materials and processes, typically derived from industry averages, literature, or statistical sources

[56] JRC Technical Report (2021). Level(s) indicator 1.2: Lienvironmentalfeenvironmental cycle Global Warming Potential (GWP) user manual: introductory briefing, instructions and guidance (Publication version 1.1). https://en.itec.cat/wp-content/uploads/2022/04/1.2.Indicator_GWP_EN.pdf

[57] ANNEX III, point 1 (General Framework) of the Delegated Regulation 52/2026/EU.

[58] It correspond to Level 3 of the EU Level(s) framework that contain EPDs, Carbon Footprint (CF), Product Environmental Footprint (PEF)user-friendly,

The aforementioned types of database can be additionally divided into two other categories:

- Final data, user-friendly databases which allow the assessor to extract a final value of EC-GWP for one or more modules and stages of the material's lifecycle. An example of those databases is: Ökobaudat, CO2data.fi, and INIES
- Metadata: non-user-friendly databases that require specific knowledge of LCA software such as SimaPro, Gabi, and OpenLCA, and rely on in-depth environmental databases like Ecoinvent

While generic data are useful when specific information is unavailable, research shows that they can introduce substantial inaccuracies in life-cycle results, with deviations of roughly 25% for climate-related indicators and even larger differences for other environmental impacts[59].

Each country has its own national database, consisting of both specific and generic data. France and Sweden apply a corrective factor (malus) when generic data are used to encourage the use of more specific and accurate data[60]. The national databases, however, differ by country and are mostly inaccessible to the general public.

It is very important to create a public database with accessible specific data to improve transparency.

Transition period to the CPR 2024

During the transition period from EPDs to Declarations of Performance and Conformity (DoPCs), LCA practitioners will likely need to operate in a hybrid data environment where both instruments coexist but are not yet fully methodologically aligned. This creates a comparability challenge rather than a simple data availability issue. While EPDs are currently developed under programme operators with some degree of variability in PCR interpretation and modelling choices, DoPCs under the revised CPR (3110/2024/EU) framework are expected to be based on more prescriptive and harmonised EU-wide requirements.

As a result, practitioners will need to treat datasets as context-dependent rather than directly interchangeable, ensuring transparent documentation of system boundaries, data sources, compliance status (market-based EPD versus regulatory DoPC), and underlying methodological assumptions. Until full convergence is achieved, a formal reconciliation mechanism – whether through conservative selection rules, scenario analysis, or potential normalisation factors – will likely be necessary to avoid the inappropriate comparison or aggregation of heterogeneous GWP values.

At the same time, questions remain regarding how this transition will be managed in practice and whether the coexistence of the two systems could generate additional uncertainty for manufacturers, regulators, and LCA practitioners. It is therefore hoped that the implementation process will provide clear guidance, robust alignment mechanisms, and sufficient transitional

[59] Lasvaux, S., Habert, G., Peuportier, B. et al. (2015). Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. Int J Life Cycle Assess 20, 1473–1490. https://doi.org/10.1007/s11367-015-0938-z

[60] Steinmann, J., Le Den, X., Röck, M., Allacker, K., Lützkendorf, T. (2023). Whole Life Carbon Models to Bring Down Embodied Emissions From New Buildings – Towards an EU Whole Life Carbon Policy Model. https://doi.org/10.5281/zenodo.7846226

support to ensure consistency, maintain confidence in environmental assessments, and avoid creating further complexity in an already evolving regulatory landscape.

6.4 Reporting templates and key indicators

Under the revised EPBD IV (1275/2024/EU) and the Delegated Regulation (52/2026/EU), EPCs form the foundation for WLC-GWP assessments reporting by providing a harmonised A–G rating of a building's current energy performance, which is recorded in national databases to support monitoring and analysis. This rating helps identify buildings with the greatest need for renovation. Minimum reporting elements include:

- an energy performance class on a standard A–G scale
- information on primary energy use and operational emissions
- and, where applicable, life cycle GWP displayed on the front page

The Delegated Regulation 52/26 further specifies that WLC-GWP must be disclosed in EPCs for:

- new buildings >1000 m^2 from 2028
- all new buildings from 2030

The results have to be reported in a transparent and structured format, showing at least the total WLC-GWP value, and the breakdown by life-cycle stages and modules. To ensure consistency, the Delegated Regulation 52/26 mandates that WLC-GWP be calculated in accordance with EN 15978 (and any subsequent European standards on building environmental assessment) by displaying it into four components: GWP fossil, GWP biogenic, GWP Land Use and Land Use Change, and GWP total.

6.5 Verification, third-party audit and quality control

At the product level, Environmental Product Declarations (EPDs) must undergo independent third-party verification to ensure credibility and regulatory acceptance. This requirement is established by ISO 14025 and EN 15804, which mandate that an independent verifier confirms the life-cycle assessment methodology, system boundaries, data quality, and conformity with applicable Product Category Rules (PCRs) before an EPD can be published[61]. Verification follows a structured process: the verifier reviews the LCA background report, checks the data's accuracy and completeness, validates assumptions, and confirms compliance with the programme operator's rules, after which a signed verification report is submitted for EPD registration. In the European construction sector, the ECO Platform provides harmonised audit and verification guidelines used across national EPD programmes.

At the building level, the EPBD IV establishes quality control requirements for national building databases. Member States must ensure that data collected, including energy performance certificates, inspection reports, and smart meter data, are subject to verification mechanisms.

Finally, EN 15941:2024 establishes strict audit-trail requirements to support WLC-GWP assessments. Every data point must be traceable to its source, with documentation of data age, any

[61] Ecoplatform (2024). Verification Guidelines for ECO EPD Programme Operators. Version 8.0 (December 2024). https://www.eco-platform.org/our-documents.html

modifications made, and the calculation steps leading to the final result. This ensures that assessment outcomes can be independently verified and reproduced, supporting both regulatory compliance and market transparency.

While these frameworks provide a robust basis for verifying environmental data, emerging requirements under the revised CPR 3110/2024, particularly for GWP reporting in DoPC and Digital Product Passports (DPP), may introduce additional or modified verification and data-structuring mechanisms. These include evolving digital reporting concepts (e.g. AVS3+ for environmental characteristics), which are not yet fully defined at the time of these guidelines.

Conclusions

The revision of the Energy Performance of Buildings Directive (EPBD) marks a significant shift in European building policy, moving from a predominant focus on operational energy performance towards a comprehensive Whole Life Carbon (WLC) approach that integrates both operational and embodied greenhouse gas emissions. This evolution will progressively transform the way buildings are designed, assessed, and regulated across Europe, making life-cycle environmental performance a central criterion for decision-making.

The analysis of the different national approaches demonstrates that, while Member States are converging towards common European objectives, substantial differences remain in the implementation of Global Warming Potential (GWP) methodologies, the scope of life-cycle stages included, data requirements, and the treatment of durability, carbon storage, and end-of-life scenarios. These differences create a risk of market fragmentation and may lead to inconsistent comparisons between materials and construction solutions.

For the concrete sector, the transition towards Whole Life Carbon assessment presents both challenges and opportunities. Concrete remains associated with significant upfront emissions, primarily linked to cement production, which can place it at a disadvantage in methodologies that emphasise short-term climate impacts or dynamic carbon accounting. At the same time, concrete offers several characteristics that are not yet fully reflected in many assessment frameworks, including long service life, durability, thermal mass, adaptability, carbonation potential, and the possibility of reuse and recycling.

The review confirms that durability should play a more explicit role within future WLC methodologies. Structural systems capable of remaining in service well beyond the conventional 50-year reference study period provide clear environmental benefits by reducing replacement cycles, limiting resource consumption, and supporting circular economy objectives. Recent developments, such as the Spanish proposal for the treatment of Module B4, suggest possible ways to better recognise these benefits within regulatory frameworks.

Equally important is the need for high-quality, transparent, and harmonised data. The growing role of EPDs, future DoPCs, national databases, and digital building information systems will require greater consistency in data governance and reporting practices. Improving interoperability, data quality, and verification procedures will be essential to ensure credible and comparable assessments across Europe.

An important consideration regarding dynamic LCA is also necessary. Several studies warn that it is important to proceed with caution when choosing the most appropriate LCA approach. Discounting CO_2 emissions is meaningless, since CO_2 is chemically stable and remains in the atmosphere for thousands of years, so the timing of emissions should not be relevant; what matters is the total cumulative quantity[62].

[62] Zhang, X. (2023). *Basics and recommendations on influence of future electricity supplies on LCA-based building assessments: A contribution to IEA EBC Annex 72*. Report. https://doi.org/10.3929/ethz-b-000630554

Furthermore, dynamic characterization factors are often based on models that are not always clearly described, incompletely documented, and inconsistent, with implementations that are inadequately described and of unclear merit[63].
There is also an ethical consideration regarding dynamic LCA and discounting: it is believed that environmental damage could become less significant in the future for uncertain reasons, passing the problem on to future generations. This risks reducing incentives to develop future innovations, as LCA results would present a more optimistic outlook today[64].
Looking ahead, the development of a robust and harmonised methodology for assessing the GWP of concrete within Whole Life Carbon frameworks should remain a strategic priority. Such a methodology should accurately account for durability, carbonation, maintenance requirements, service-life extension, and circularity potential, while maintaining consistency with European standards and regulatory requirements.

Ultimately, achieving the objectives of the EPBD will require not only methodological harmonisation but also close cooperation between policymakers, standardisation bodies, industry stakeholders, and the scientific community. A balanced and scientifically sound approach is essential to ensure that future regulations effectively support decarbonisation while recognising the real performance and long-term value of different construction materials and systems.

In this context, the concrete industry has an important opportunity to contribute proactively to the development of future European methodologies, ensuring that durability, resilience, adaptability, and long-term environmental performance are fully integrated into the next generation of Whole Life Carbon assessment frameworks.

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[63] Dynamic characterization factors and dynamic global warming potentials: a critical methodological review', *The International Journal of Life Cycle Assessment*, 31(5), Article 64. https://doi.org/10.1007/s11367-026-02634-z

[64] Lueddeckens, S., Saling, P. and Guenther, E. (2022). 'Discounting and life cycle assessment: a distorting measure in assessments, a reasonable instrument for decisions'. *International Journal of Environmental Science and Technology*, 19, pp. 2961–2972. https://doi.org/10.1007/s13762-021-03426-8

ANNEX

A) Whole Life Carbon: combining embodied and operational impact

> *"The construction and use of buildings creates both embodied and operational carbon emissions. Historically, Government policies and voluntary efforts from the industry have primarily focused on the reduction of operational carbon emissions of buildings. However, to reach its 2050 net zero target, focusing efforts on reducing the embodied carbon of buildings is also critical."*[65]

This paragraph explains why embodied and operational carbon must be assessed together in a Whole Life Carbon (WLC) approach. It outlines how to align temporal boundaries (annual vs lifetime), aggregate embodied emissions (production, transport, construction, maintenance, replacements, end-of-life) with cumulative operational energy emissions, and address interactions and trade-offs (e.g., insulation or thermal mass, which raise embodied but lower operational carbon). It summarises accounting rules (common functional unit, reference period, modules A–D), the treatment of maintenance/replacement cycles, the handling of temporary vs permanent carbon storage, and the need for sensitivity and uncertainty analyses to support robust, policy-relevant comparisons and decisions.

Embodied carbon emissions' impact on the WLC calculation

Embodied carbon (EC) comprises all GHG emissions associated with the extraction, manufacture, transport, construction, maintenance, replacement, and disposal of building materials.

In LCA, as defined by EN 15978, these emissions are primarily captured in modules A1–A3 (production stage), A4-A5 (construction stage), B1–B5 (use stage processes excluding operational energy), and C1–C4 (end-of-life stage). Production modules (A1–A3) typically dominate EC impacts at the beginning of a building's life. Emissions arise from raw material extraction, transport to the factory and manufacturing processes. These upfront emissions, together with transport to the site and construction activities (A4-A5), occur before the building becomes operational and represent an immediate addition to atmospheric carbon concentrations. During the use stage, additional EC emissions arise from maintenance (B2), repair (B3), and replacement of building components (B4). Components with shorter SL than the building RSP may require one or more replacement cycles during the building's life cycle. This is of specific relevance for non-structural and technical elements, such as façade components, internal finishes, or building services equipment, which may be replaced multiple times within the RSP. Each replacement cycle entails additional material production, transport, installation and waste treatment processes, which are reflected in module B4 and, where applicable, in related end-of-life modules. Therefore, WLC assessments should consider not only upfront EC but also the **durability** and replacement frequency of building systems. This is especially important when comparing materials or construction solutions with different **expected service lives** (ESLs), as longer-lasting systems may reduce the number of replacement cycles and consequently affect the overall life-cycle balance. At the end-of-life stage (C1–C4), emissions arise

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[65] Ministry of Housing, Communities & Local Government (2025). The practical, technical and economic impacts of measuring and reducing embodied carbon in new buildings: Executive summary. https://www.gov.uk/government/publications/consideration-of-embodied-carbon-in-new-buildings/the-practical-technical-and-economic-impacts-of-measuring-and-reducing-embodied-carbon-in-new-buildings-executive-summary

from demolition or deconstruction, waste transport, processing, and disposal. The EN 15978 framework also includes the optional module D, which accounts for benefits or burdens beyond the system boundary, such as recycling or energy recovery.

Including module D can provide a broader representation of circular material flows by accounting for potential benefits and burdens beyond the building system boundary, such as recycling, reuse, material substitution or energy recovery. However, its interpretation requires caution, as results depend on assumptions about future end-of-life scenarios, recovery rates, the quality and market uptake of secondary materials, substitution rules and the allocation of benefits between product systems. For this reason, module D is generally best reported separately from modules A–C, so that potential future benefits do not obscure the impacts occurring within the building life cycle.

In the WLC-GWP assessment, embodied emissions and removals are usually aggregated over a defined RSP, commonly set at 50 years in several European and EU-related building assessment frameworks. However, national methods may adopt different periods. Within conventional static LCA approaches, emissions and removals occurring at different points in the building life cycle are summed using fixed characterisation factors, with limited or no explicit differentiation of their timing. By contrast, dynamic LCA approaches account for when emissions and removals occur, thereby allowing the timing of upfront emissions, delayed emissions, temporary carbon storage and future removals to influence the resulting climate impact. This distinction is significant when assessing materials or systems whose carbon flows are distributed over long periods, such as bio-based products, carbonation in concrete, or future end-of-life recovery scenarios.

An important methodological issue in WLC-GWP assessment is the treatment of carbon storage, delayed emissions, and carbon uptake processes. Conventional static LCA methods generally aggregate greenhouse gas emissions and removals over the reference study period using fixed characterisation factors. However, several construction materials involve carbon flows that occur at different points in time, either through temporary storage of atmospheric carbon, delayed release at the end of life, or gradual uptake of carbon dioxide during use and post-demolition. Correctly representing these processes is essential to avoid misleading comparisons between materials with different carbon flow profiles.

Bio-based materials absorb carbon dioxide from the atmosphere during biomass growth, and part of this carbon may remain stored in the construction product for the duration of the building's service life. In the WLC-GWP assessment, this biogenic carbon uptake is typically reported as a negative flow during the product stage (A1) and a corresponding release in module C or D, depending on end-of-life scenarios such as combustion, landfill degradation, or reuse. While this approach reflects mass balance, it introduces methodological challenges because the climate benefit depends strongly on the storage duration and the timing of eventual release relative to climate targets.

In contrast, mineral materials such as concrete follow a different carbon uptake mechanism. Concrete does not store biogenic carbon during production, but it can gradually absorb atmospheric CO_2 through carbonation. During this process, carbon dioxide reacts with calcium-bearing hydrated cement phases, forming calcium carbonate. Carbonation can therefore reabsorb part of the CO_2 associated with the calcination process in cement production. Nevertheless, the magnitude and timing of this uptake depend on exposure conditions, concrete composition, surface area, strength class, cover depth, moisture conditions and the degree of crushing or exposure after demolition. During the building-use stage, carbonation generally progresses slowly from exposed surfaces inward, so only a limited fraction of the potential uptake is usually realised within the service life of intact structural elements. Additional uptake may occur after demolition, particularly when concrete is crushed, stockpiled or reused as recycled aggregate, because the exposed surface area increases significantly. The methodological relevance of carbonation, therefore, depends not only on the material itself, but also on the assumed SL, demolition scenario, recycling route and allocation of post-demolition uptake.

The standard EN 16757 provides guidance on quantifying CO_2 uptake by carbonation in concrete and other cementitious products and can support its inclusion in EPDs and building-level LCA calculations. Depending on the assessment framework and the timing of uptake, carbonation may be accounted for either within module B1 (use-phase chemical processes) or within modules C3 or D1 when uptake occurs after demolition and recycling.

The choice of module affects the temporal distribution of emissions and removals, thereby influencing the calculated global warming potential, especially when dynamic LCA methods are used[66].

Operational carbon emission impact in the WLC calculation

Operational Carbon (OC) refers to greenhouse gas emissions associated with energy and water use during the building's service life. Within the EN 15978 framework, these emissions are captured primarily in module B6 (operational energy) and B7 (operational water).

Historically, operational energy has been the dominant contributor to building life-cycle emissions, especially in heating-dominated climates such as Northern and Central Europe. As a result, European policy has focused on improving building envelope performance, increasing system efficiency, and promoting the use of renewable energy. The EPBD II (2010/31/EU) introduced Nearly-Zero Energy Building (NZEB) requirements in 2020, and the revised EPBD IV (2024/1275/EU) sets a 2030 transition to a Zero-Emission Building (ZEB) standard, aiming to eliminate on-site fossil-fuel emissions and significantly reduce OC.

In WLC-GWP calculations, operational emissions are estimated by multiplying predicted annual energy consumption by emission factors for each energy carrier and summing these emissions over the reference study period. This requires assumptions about[67]:

- future energy demand profiles
- system performance degradation
- maintenance and replacement of equipment
- and the decarbonisation trajectory of the electricity grid

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[66] Elliot, T., Kouchaki-Penchah, H., Brial, V., Levasseur, A., McLaren, S.J. (2024). Dynamic environmental payback of concrete due to carbonation over centuries. Sustainable Production and Consumption, Volume 51, pp. 236-247. https://doi.org/10.1016/j.spc.2024.09.009

[67] Müller, A., Diepers, T., Jakobs, A. et al. (2025). Time-explicit life cycle assessment: a flexible framework for coherent consideration of temporal dynamics. Int. J. Life Cycle Assess. 30, 3052–3071. https://doi.org/10.1007/s11367-025-02539-3

Static life-cycle approaches using current emission factors may overestimate future operational impacts, whereas dynamic approaches model changing grid emission factors over time to produce more realistic results[68]. This temporal interaction means that the relative importance of embodied versus operational carbon may shift during the building's life, reinforcing the need for integrated WLC modelling.

Interactions between operational and embodied carbon are particularly evident in envelope design. For concrete structures, the relationship between embodied and operational carbon involves unique considerations, including thermal mass, carbonation, and durability. Increasing insulation thickness, improving airtightness, or incorporating thermal mass generally reduces operational energy demand but increases embodied emissions due to additional material use. WLC-GWP analysis optimises these competing effects, ensuring that disproportionately high EC impacts do not offset reductions in operational energy.

OC is not only determined by total annual energy demand but also by when energy is consumed. Electricity grids typically exhibit higher carbon intensity during peak demand periods, when fossil-fuel power plants are dispatched. Buildings that use thermal mass or smart controls to shift heating and cooling loads away from peak periods may therefore reduce operational carbon even if annual energy consumption remains similar. This temporal dimension is not fully captured by annual energy-based WLC-GWP calculations, which may underestimate the benefits of demand-side flexibility and thermal storage in heavy structural systems such as concrete[69].

B) Extended service life and cross-material consistency

Improved recognition of long SL should be applied consistently across structural materials. While this may support the assessment of durable concrete structures, it may also strengthen claims related to other long-life systems, including engineered timber products. For this reason, extended service life should not be treated as a material-specific advantage, but as a performance-related parameter that must be demonstrated through technical evidence, design assumptions and maintenance scenarios.

Durability should also be considered alongside the adaptability of the structural system. A key strategy for reducing whole-life carbon is to design buildings with robust, flexible structural layouts, including universal load-bearing systems, adequate floor-to-floor heights and spans, and structural configurations that accommodate functional transformation over time. Such an approach can reduce the likelihood of premature demolition and reconstruction, thereby extending the building's effective SL.

From a WLC perspective, this issue is both methodological and strategic. Concrete may benefit from improved recognition of durability, thermal mass, carbonation processes and long service life. At the same time, timber-related WLC claims may combine long service life with biogenic carbon storage

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[68] European Commission (2025). Nearly-zero energy and zero-emission buildings. https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/nearly-zero-energy-and-zero-emission-buildings_en?

[69] Lind, J., Möllerström, E., Averfalk, H., & Ottermo, F. (2023). Energy flexibility using the thermal mass of residential buildings. Energy and Buildings, 301, 113698. 10.1016/j.enbuild.2023.113698

and delayed end-of-life emissions. Therefore, assumptions about extended service life, temporary carbon storage, carbonation and reuse should be assessed using consistent rules across materials, avoiding both under-recognition of durability and unintended methodological advantages.

The objective is not to assign automatic credits to any specific material, but to ensure that long-term performance, adaptability and residual service potential are represented transparently and consistently within WLC assessment frameworks.

C) Carbonation and CO_2 uptake in concrete

Concrete can partially reabsorb atmospheric CO_2 during its life cycle through carbonation, a chemical process in which carbon dioxide penetrates the pore structure of concrete and reacts with calcium-bearing hydration products, especially portlandite ($Ca(OH)_2$), to form calcium carbonate ($CaCO_3$). This process is gradual and depends on several parameters, including concrete composition, porosity, exposure conditions, relative humidity, CO_2 concentration, surface protection, cracking, and the surface area exposed to air.

Carbonation is relevant for WLC-GWP assessment because it represents a form of mineral CO_2 uptake that can occur during the use stage and, under specific conditions, after demolition. However, its treatment in building-level LCA is not always straightforward. Existing standards and EPD practices provide methods for quantifying carbonation in concrete and cementitious products (according to EN 16757:2017 (Annex BB) and PD CEN/TR 17310:2019)[70]. Still, their consistent integration into building-level WLC-GWP calculations remains methodologically sensitive. In particular, the timing of uptake, the module in which it is reported, the reference study period, and the relationship between product-level EPD assumptions and building-level calculation rules need to be clearly defined.

A first tentative attempt to include CO_2 uptake from the carbonation of concrete-based materials and products used in building is provided by the Italian methodological proposal[71].

To integrate carbonation into a durability-aware WLC-GWP methodology for concrete, the following operational distinctions should be made.

Natural Carbonation during Service Life and End-of-Life

Natural carbonation occurs progressively when concrete surfaces are exposed to air. During the building use stage, carbonation may be accounted for in module B1, where the assessment framework allows material-related processes during use to be included. For some masonry products, however, part of the carbonation may occur earlier and be accounted for in modules A3 and A5. After demolition, additional carbonation may occur when concrete is crushed, stockpiled, reused as aggregate or otherwise exposed to air, because the surface-area-to-volume ratio increases

[70] EN 16757:2017. Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements, Annex BB: CO_2 uptake by carbonation – Guidance on calculation; PD CEN/TR 17310:2019. Carbonation and CO_2 uptake in concrete.

[71] Andreotti, J., Giordano, G. (2024). Strumenti per la decarbonizzazione. Valutazione della Whole Life Carbon (WLC) e della Circular Economy (CE) di un manufatto edilizio. Edizioni Ambiente, Milano. https://freebook.edizioniambiente.it/catalogo/579/strumenti-per-la-decarbonizzazione

substantially. Depending on the end-of-life scenario and the applicable calculation rules, this uptake may be reported in module C4 or in module D1.

The amount of CO_2 uptake should not be treated as a fixed generic credit. It depends on exposure conditions, carbonation depth, concrete composition, strength class, cover depth, moisture conditions, degree of crushing, particle size distribution, storage duration and final use or disposal route. In simplified WLC-GWP assessments, carbonation depth may be estimated using diffusion-based models. Still, assumptions should be reported transparently and aligned with the reference study period used in the building assessment.

A specific methodological issue arises when product-level EPDs and building-level WLC-GWP calculations use different time horizons. For example, if a product-level dataset assumes carbonation over a longer period than the building RSP, the uptake cannot be transferred mechanically into the building assessment without adjustment. A linear reduction, such as simply dividing a 100-year carbonation value by two for a 50-year assessment period, may be misleading because carbonation is not necessarily linear over time. A simplified yet technically robust approach is therefore needed to support practitioners in consistently calculating carbonation in module B1 at the building level.

This issue is highly relevant for concrete elements with a high exposed surface area, such as concrete blocks or concrete walls. For these elements, CO_2 uptake during the use stage, where reported in module B1, may be significant when compared with the initial production-stage emissions reported in module A1-A3.

Accelerated Carbonation and CO_2 Utilisation

Accelerated carbonation refers to controlled processes in which CO_2 uptake is intentionally enhanced, for example, through CO_2 curing of concrete products or carbonation treatment of recycled concrete aggregates[72]. Unlike natural carbonation, which occurs gradually through passive atmospheric exposure, accelerated carbonation occurs within a shorter, controlled timeframe and may use captured industrial CO_2.

In WLC-GWP calculations, accelerated carbonation should be distinguished from natural carbonation. If CO_2 uptake occurs during manufacturing, for example, during curing of concrete products, it may be reported in module A3, provided that the CO_2 source, permanence of storage, process energy use and associated emissions are documented. If the process occurs on-site, it may be reported in module A5 where applicable. When accelerated carbonation is applied to recycled concrete aggregates or other end-of-life streams, the appropriate module depends on the system boundary and the stage at which the process occurs.

The environmental benefit of accelerated carbonation should be assessed on a net basis. This means that the amount of CO_2 permanently mineralised should be balanced against the additional energy use, transport, processing requirements, CO_2 capture and purification burdens, and any changes in

[72] Chen, T., Nelson, J.P., Gupta, V. & Mobley, P.D. Life-cycle assessment of concrete production with carbon capture and carbon upcycling process. Journal of Environmental Management 391, 126303 (2025). https://doi.org/10.1016/j.jenvman.2025.126303.

material performance. It should not be treated as an automatic negative emission unless permanence, additionality and system boundaries are clearly documented.

D) Promote permanent carbon storage and establish rules for temporary carbon storage

When calculating the GWP of construction materials, particularly for concrete, it is essential to account for the integration of permanent carbon storage into the climate balance. In addition to accounting for emissions associated with cement production and concrete manufacturing processes, LCA methodology must systematically recognise CO_2 removals achieved through permanent storage mechanisms in concrete, such as mineralisation and carbonation[73]. In these processes, CO_2 is stably incorporated into the cementitious matrix of concrete as carbonates, achieving a chemically and physically durable state that prevents its release into the atmosphere over very long timescales. Including this contribution in the GWP enables a more accurate representation of concrete's actual climate performance, highlighting not only emission reductions but also its intrinsic potential to act as a carbon sink. Promoting the recognition of permanent carbon storage in concrete, therefore, strengthens the coherence of environmental assessment frameworks and encourages the development and adoption of concrete technologies that ensure stable, verifiable, and long-lasting carbon removal.

E) Spain: durability recognition in CTE DB-HSA1 and EC benchmark

National regulation approach to module B4

Spain published a draft regulation amending the national Technical Building Code (CTE - Código Técnico de la Edificación), including the proposed DB-HSA1 document[74], which defines national requirements for calculating the life-cycle GWP of buildings in line with Annex III of the EPBD IV.

A highly relevant aspect of the draft methodology is the formula for determining emissions associated with module B4, replacement. This approach has the potential to recognise durability by considering the relationship between the product SL (Vuk) and the RSP (T), which is set at 50 years. According to the reported formula, when Vuk exceeds T, the expression (T/Vuk – 1) may become negative. This negative value could be interpreted as a durability-related adjustment in the replacement module.

[73] EN 16757:2017. Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements, Annex BB: CO_2 uptake by carbonation – Guidance on calculation; PD CEN/TR 17310:2019. Carbonation and CO_2 uptake in concrete.

[74] Ministerio de Vivienda y Agenda Urbana (MIVAU). Proyecto de real decreto por el que se modifica el Código Técnico de la Edificación, aprobado por Real Decreto 314/2006, de 17 de marzo. Borrador para audiencia e información pública, including proposed DB-HSA1 – Potencial de Calentamiento Global, November 2025.

4 La determinación de las emisiones de cada producto correspondientes al módulo “B4: Sustitución” de la etapa de uso, mantenimiento y reemplazo, se podrá realizar según la siguiente expresión:

$$E_{B4} = \sum[(C_k \cdot (e_{A1,k} + e_{A2,k} + e_{A3,k}) \cdot f_c \cdot \left(\frac{T}{V_{u_k}} - 1\right)]$$

Siendo:

- E_{B4} las emisiones correspondientes al módulo B4 [kg CO_2 eq.];
- C_k la cantidad total del producto k [kg];
- $e_{A1,k}$ el valor de emisión del producto k para el módulo A1 [kg CO_2 eq./ kg];
- $e_{A2,k}$ el valor de emisión del producto k para el módulo A2 [kg CO_2 eq./ kg];
- $e_{A3,k}$ el valor de emisión del producto k para el módulo A3 [kg CO_2 eq./ kg];
- f_c el factor corrector definido en el apartado 3 de la presente sección;
- T Período de estudio de referencia [años]. Según lo dispuesto en la presente sección se adoptará un valor de 50 años;
- Vu_k *Vida útil del producto* k;

Figure E.1: Formula for the calculation of replacement emissions in Module B4 according to the Spanish CTE DB-HSA1 draft (Source: draft regulation amending the CTE, p. 97).

From a circular economy perspective, the approach is relevant because it links reducing replacement cycles to the objective of keeping products and materials in use for as long as possible. By reducing or avoiding replacements in module B4, the methodology may reduce the demand for new production processes and the generation of end-of-life waste. If the Spanish formula is ultimately confirmed to recognise residual service life beyond the 50-year RSP, it could provide an additional way of reflecting these durability benefits in WLC-GWP calculations. For concrete structures, this is very important because structural elements may remain functional beyond the 50-year RSP when properly designed, specified, executed, and maintained.

However, any durability-related benefit should not be assumed automatically. The SL assigned to building components should be considered a project-level performance parameter, supported by explicit design criteria, exposure conditions, durability provisions and maintenance assumptions. Where possible, future development of this approach should be supported by statistical evidence on the actual service life of concrete structures in existing buildings, based on inspection, maintenance, renovation and demolition data. Such evidence would provide a stronger basis for calibrating service-life values and for applying durability-sensitive WLC-GWP accounting consistently.

Spanish EC benchmark

In addition to the draft regulatory approach, a second relevant Spanish contribution is the national EC benchmark promoted by IECA, together with ANEFHOP, ANDECE and HISPALYT, with the support of the Ministerio de Vivienda y Agenda Urbana[75]. Arup developed the benchmark through building-level LCA in accordance with EN 15978 and based on a 50-year reference study period. Although this benchmark does not constitute a regulatory methodology in itself, it provides useful evidence for interpreting the methodological relevance of early design choices, structural systems, data quality, service-life assumptions and replacement scenarios in building-level WLC assessment.

[75] IECA, ANEFHOP, ANDECE and HISPALYT, with the support of the Ministerio de Vivienda y Agenda Urbana. Benchmark de carbono embebido de edificios en España. Study developed by Arup.

For this reason, it is reported here as supporting evidence for the discussion on concrete durability and WLC-GWP methodology.

kgCO₂eq por m² útil del edificio						
	A1-A3	**A4-A5**	**B1-B4**	**C1-C4**	**Total por elemento constructivo**	**TOTAL**
estructura	142,95	4,96	-2,76	8,31	153,46	**378,33**
fachada	17,46	0,89	9,79	0,65	28,79	
cubierta	11,22	0,29	3,55	1,55	16,61	
Acabados y tabiques interiores	57,96	4,25	82,73	5,06	150,01	
a nivel edificio		18,28	4,17	7,00	29,45	
TOTAL por fases	**229,59**	**28,68**	**97,48**	**22,58**	**-**	
+9% factor de incertidumbre	20,66	2,58	8,77	2,03	-	**34,05**
TOTAL con factor de incertidumbre	**250,25**	**31,26**	**106,25**	**24,61**	**-**	**412,38**

The analysis shows that the production stage (A1–A3) accounts for the largest share of EC across the building typologies considered. The structural system is the main contributor in most cases, including industrial, commercial, office, and multi-family residential buildings. In contrast, the envelope is quite relevant in detached single-family houses due to their higher envelope-to-floor-area ratio. Interior finishes also contribute significantly, especially where compartmentalisation and replacement cycles are high.

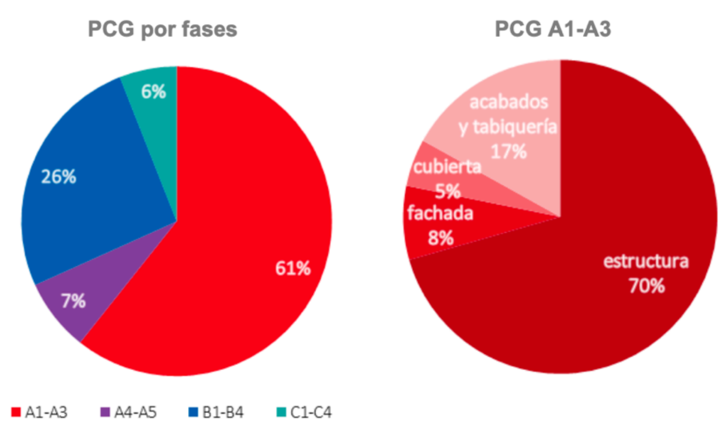

Figure E.2: Relative contribution of building elements and life-cycle stages to the total environmental impact of the commercial / shopping centre typology (Source: IECA embodied carbon benchmark study, developed by Arup).

The study also indicates that climate-zone variation has a limited effect on total EC at the building level, around ±2%, because the main variation is in insulation thickness, which accounts for a relatively small share of total embodied impacts. In contrast, foundation type can have a more significant effect, especially where the structural system plays a major role.

A key finding concerns SL sensitivity. Extending the building SL can significantly reduce annualised EC, especially for structural elements. The benchmark reports that the impact of the structure may decrease by up to around 40% when the reference period is extended from 50 to 80 years. This is due to the absence of replacement cycles for structural elements, whose initial impact is distributed over a longer period. By contrast, components such as finishes and parts of the envelope are less sensitive to this extension because they are subject to maintenance and replacement over time.

Another relevant result concerns data quality. Replacing sector-specific EPDs with generic Ecoinvent data leads to an average increase of approximately 13% in EC. This confirms that data selection is a major source of uncertainty and that representative datasets are essential for fair comparison between construction solutions.

Overall, the Spanish benchmark supports three key conclusions for concrete WLC-GWP methodology: early design choices strongly influence EC; structural systems and replacement assumptions are central to long-term results; and high-quality sector-specific data are necessary to ensure comparability and transparency.