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(DIATI)

Master's Degree Thesis

Comprehensive Whole Lifecycle Assessment of Buildings: Identifying Carbon Hotspots and Mitigation Strategies in Compliance with EU Taxonomy Standards

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Abstract

Sustainability has become a central concern in the construction industry, as buildings play a significant role in global resource consumption and greenhouse gas emissions. Today, sustainable construction is understood not only as reducing environmental impact, but also as addressing economic efficiency and social responsibility throughout a building's life cycle.

One of the most effective methods for evaluating the environmental performance of buildings is Life Cycle Assessment (LCA). This approach assesses the impact of materials and construction processes from extraction and manufacturing to use and end-of-life. With growing awareness of climate change and resource scarcity, LCA has evolved from a research tool into a practical method for guiding design decisions.

As industry moves toward lower-carbon, more resource-efficient buildings, applying LCA in the early design phases becomes essential. It enables architects and engineers to compare alternatives, optimize material use, and reduce environmental impact from the outset. This thesis explores how LCA can inform and improve sustainable building design through the analysis of different construction scenarios in a real office building project.

It's important to highlight just how big an impact construction has on the planet. This industry is one of the biggest sources of greenhouse gases and other harmful emissions. It uses more than 40% of all materials globally and is responsible for nearly 40% of all greenhouse gas emissions. Of that, 28% comes from the energy used to run existing buildings, while 11% comes from materials used in building and renovation work.

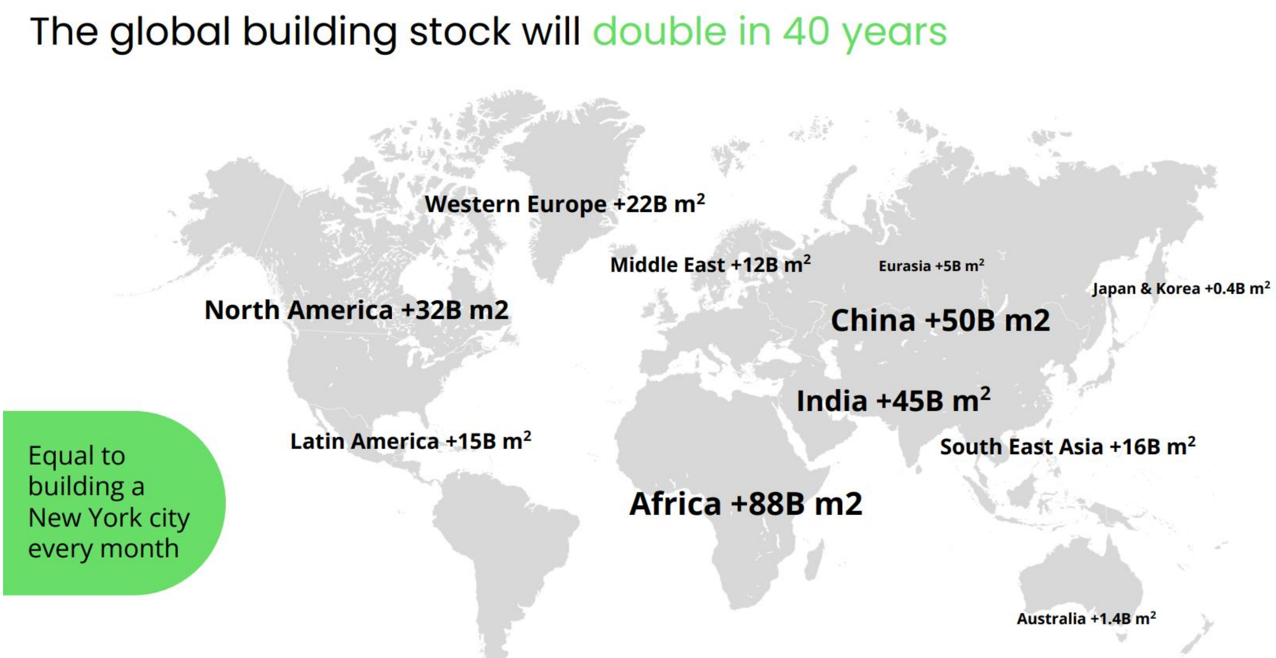

Figure 1. Numbers in billions of m2. Sources: Architecture 2030, UNEP 2017 (One click LCA boot camp 2025)

The global building stock is set to double over the next 40 years, adding a staggering 230 billion square meters of new construction. This growth is akin to building a new city the size of New

York every month. The expansion will be most pronounced in regions like India, which will see an increase of 45 billion m^2, North America with 32 billion m^2, and Southeast Asia with 16 billion m^2. This unprecedented surge highlights the critical need for sustainable building practices to curb environmental impacts and align with global climate objectives.

Given the significant environmental impact of the construction sector, this thesis aims to explore how different material and design strategies can influence the carbon footprint of a building. By applying Life Cycle Assessment (LCA) to various construction scenarios, the study identifies the most effective approaches for reducing embodied carbon. The goal is to provide practical insights that support more sustainable architectural decisions and contribute to the development of lower-impact building practices.

Another goal is to support a broader understanding of embodied carbon and whole-life carbon in buildings, and to help define benchmarks that the construction industry can use.

This study applies a scenario-based LCA to a mid-rise office building, modelled using One Click LCA in accordance with the EN 15978 standard. Four structural and material strategies, Baseline, CAM-compliant, CLT, and Optimized, were compared to assess embodied carbon impacts. The results show that while the Baseline scenario exceeds industry benchmarks, the Optimized design achieves total embodied carbon of 525 $kgCO_2e/m^2$, successfully meeting the RIBA 2030 Climate Challenge target for non-residential buildings. The findings underscore the importance of addressing not only structural elements but also MEP systems and envelope materials to achieve deep decarbonization in office building design.

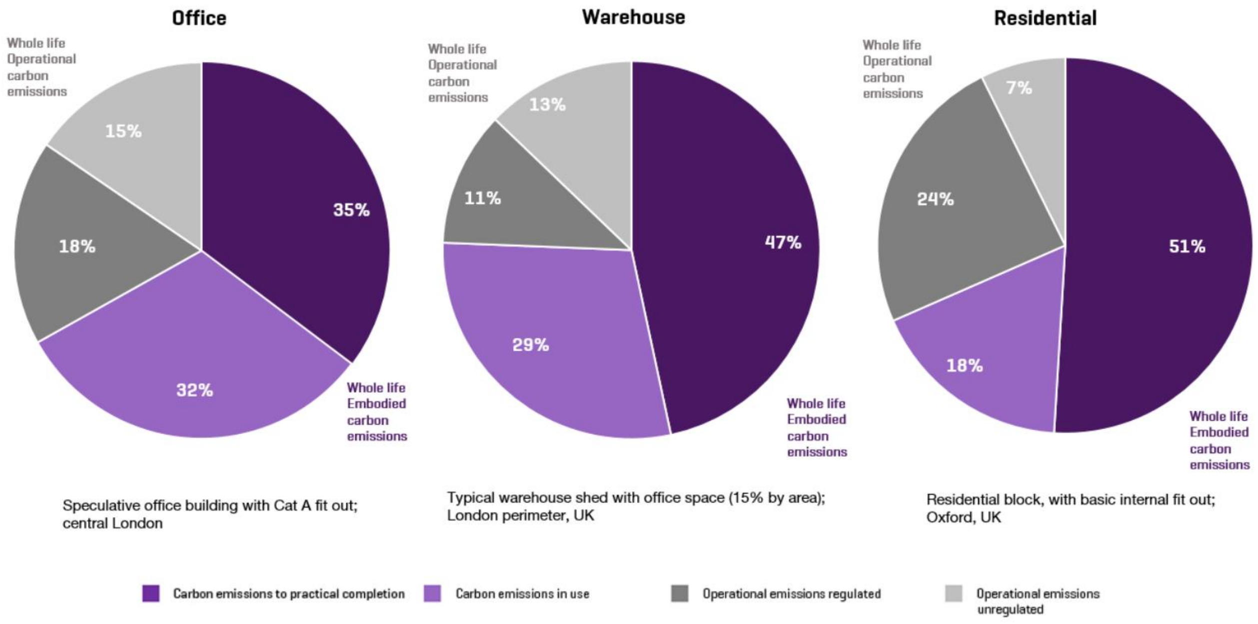

Figure 2. Total life carbon emissions breakdown for different building types © Sturgis Carbon Profiling

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1. Sustainability in the Construction Sector

In recent decades, the environmental impacts on the climate caused by greenhouse gas emissions from human activities, driven by economic and demographic growth, have been quantified. Specifically, the latest assessment report on climate change (AR6) presented by the Intergovernmental Panel on Climate Change (IPCC) has stated that the increasing frequency of heatwaves, droughts, and floods is already surpassing the tolerance thresholds of plants and animals, leading to mass mortality in certain species of trees and corals. These extreme weather events are occurring simultaneously, causing cascading impacts that are increasingly difficult to manage.

The planet's temperature has risen mainly from the second half of the 20th century onward, as shown in the image below, which shows in black the observed global surface temperature (annual average) from 1850 to 2020, in aqua green the temperature simulated by models in the absence of greenhouse gases emitted by humans, and in brown the temperature simulated taking into account both human and natural factors. The two lines diverge more and more clearly from the second half of the 1960s. Indeed, without human activities producing emissions, the temperatures would still be like those of the 19th century.

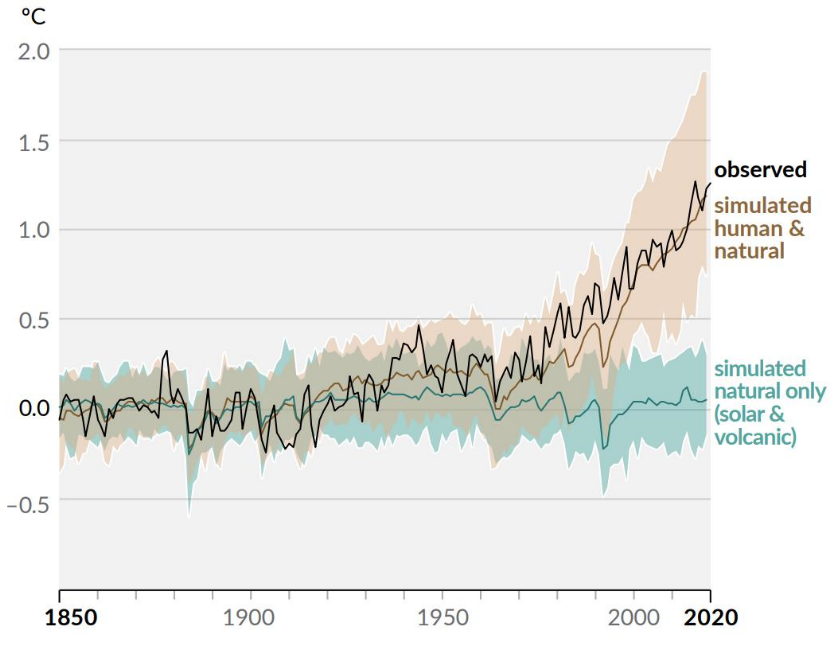


Figure 3. Planetary temperature anomalies from 1860 to 2012

The observed temperatures are the result of the combination of both natural and anthropogenic factors.

Anthropogenic factors include:

- The emission of greenhouse gases that cause warming.
- The emission of aerosols that cause cooling.
- The increase in the albedo (reflected radiation) of the Earth's surface is due to land use changes, which also causes cooling.

Natural factors that influence the climate are primarily solar activity, Earth's orbital variations, and volcanic activity. These factors have not caused significant long-term changes, except for temporary variations due to volcanic eruptions. Meanwhile, the surplus of greenhouse gases in the atmosphere has altered the planet's energy balance, which will remain changed until these gases are absorbed. Additionally, there is cooling caused by aerosols suspended in the atmosphere, which reflect part of the incident solar radiation back into space. These aerosols consist of fine particles (PM, or "particulate matter") that are microscopic substances, both liquid and solid, ranging in size from a few nanometers to several hundred micrometers. While they have negative consequences for human health, they also play an important role in the climate. Since aerosols have a relatively short lifespan in the atmosphere, usually only a few weeks, if fossil fuel combustion were to stop, the temperature would rise sharply due to cleaner air. In contrast, greenhouse gases can remain in the atmosphere for thousands of years.

The map below shows the anomalies relative to the 1951-1980 average for different regions of the planet as of early 2023.

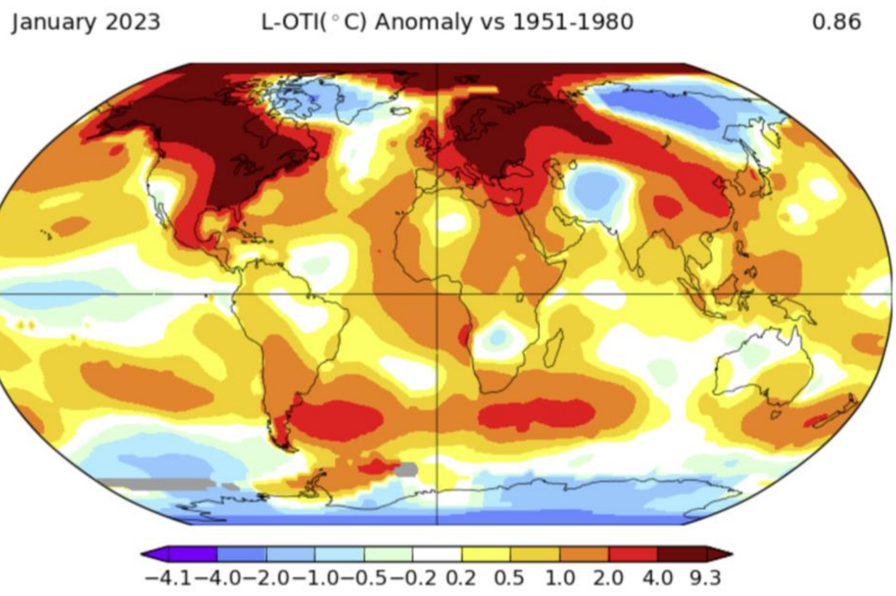


Figure 4. Temperature anomalies recorded in 2023 compared to the average for the period 1951-1980

The construction industry is one of the largest contributors to global environmental impacts, particularly in terms of carbon emissions. As the world faces increasing pressure to address climate change, the built environment plays a crucial role in reducing carbon footprints. The sector accounts for a significant proportion of both operational and embodied carbon emissions, with the latter often overlooked despite its substantial contribution to the overall environmental impact of buildings. Embodied carbon refers to the carbon emissions generated during the lifecycle of a building's materials and construction processes, from extraction to manufacturing, transportation, and assembly. Addressing embodied carbon is essential for achieving significant reductions in overall greenhouse gas emissions, particularly as the operational energy efficiency of buildings continues to improve.

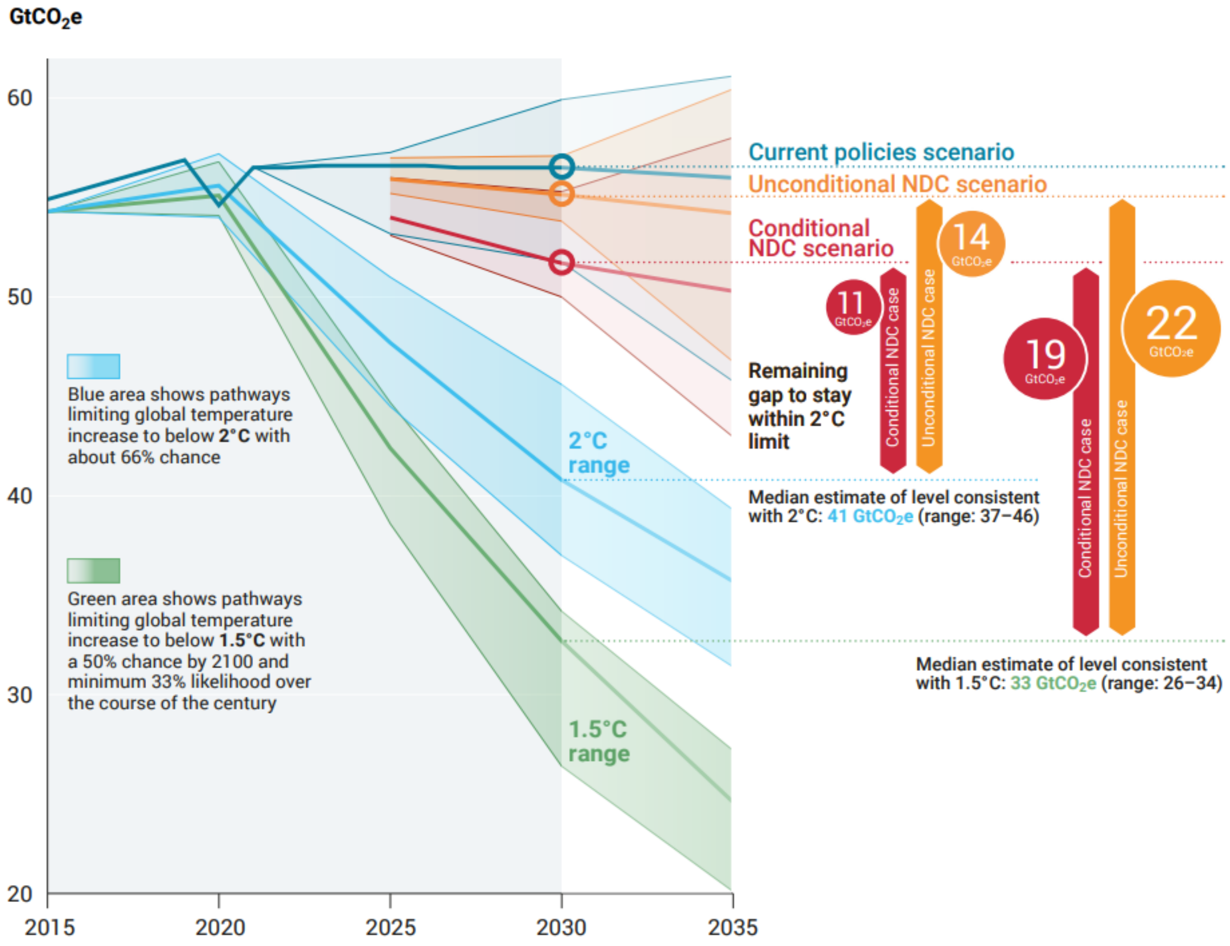


Figure 5. Global GHG emissions under different scenarios and the emissions gap in 2030 and 2035 (median estimate and tenth to ninetieth percentile range)

The figure illustrates the emissions gap projected for 2030 between current global climate pledges—known as Nationally Determined Contributions (NDCs)—and the emission levels needed to limit global warming to 1.5°C and 2°C. NDCs are country-submitted climate plans under the Paris Agreement, where unconditional NDCs reflect efforts, countries will make on their own, while conditional NDCs depend on international support. If only unconditional NDCs are implemented, the 2030 emissions gap to the 1.5°C target remains at 22 $GtCO_2e$; this is reduced to 19 $GtCO_2e$ if conditional NDCs are fully implemented. In contrast, non-NDC scenarios, based on current policies without additional pledges, would lead to even higher emissions. Overall, current unconditional and conditional NDCs would reduce emissions by only 2% and 9% respectively compared to current policies, far short of the 42% cut needed to align with the 1.5°C pathway. The colored areas in the figure (green for 1.5°C, blue for 2°C) represent the required emission pathways, emphasizing that immediate and stronger action is needed to close the gap and meet global climate goals.

1.1. Environmental Issue

In this context, United Nations reports provide a clear picture of the current situation. The IPCC (Intergovernmental Panel on Climate Change) warns that without decisive action; we are heading toward a catastrophic temperature increase. The 2021 report, echoing what was already stated in the 2015 Paris Agreement (Brizzi & Viero, 2021), emphasized the need to reduce global CO_2 emissions by 45% by 2030 to limit the temperature rise to 1.5 degrees Celsius above pre-industrial levels, with the goal of reaching net-zero emissions by 2050. This means that humanity should emit only as much greenhouse gas as can be absorbed or offset through actions such as reforestation or the implementation of carbon capture and storage technologies.

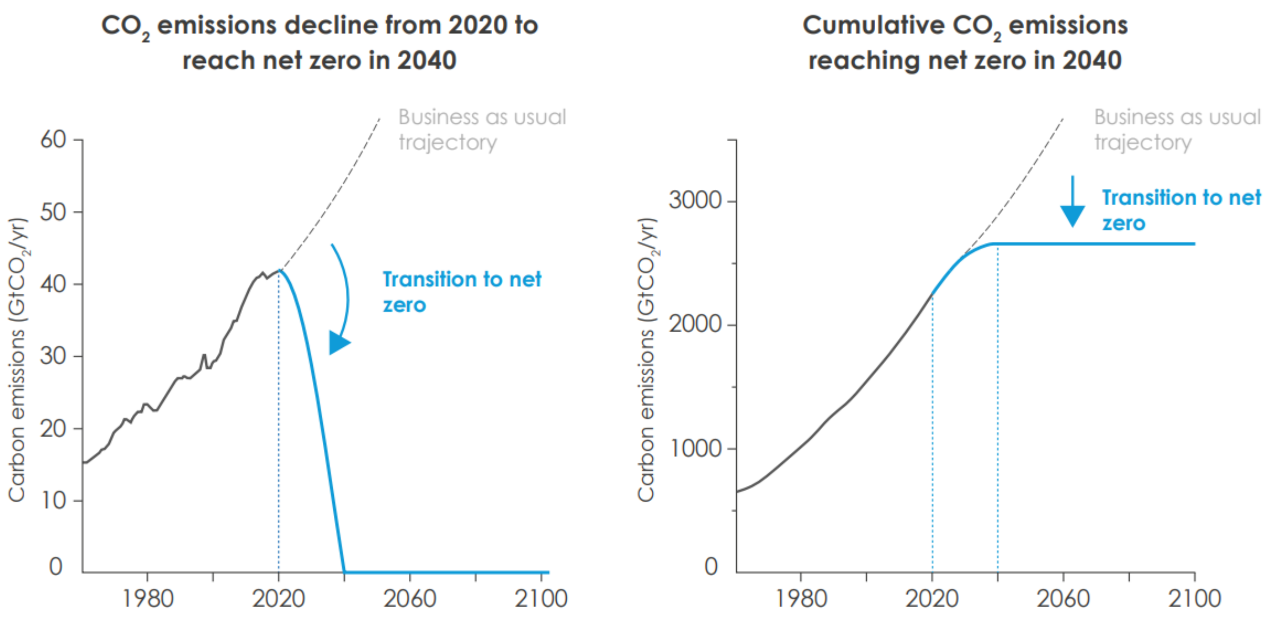


Figure 6- Magnitude of global CO2 reductions required to limit temperature rise to 1.5°C

At the same time, the role of the building sector proves to be crucial. The construction industry is responsible for a significant share of global carbon emissions, primarily stemming from production processes and the energy consumption of buildings. Making construction more sustainable by adopting low-carbon building practices and promoting energy efficiency, is essential for achieving global climate goals.

1.2. The Principles of Sustainability

Sustainability, a concept widely addressed in academic and policy literature, is commonly understood as a condition of the global system, encompassing environmental, social, and economic dimensions, where present needs are fulfilled without diminishing the ability of future generations to meet theirs. This foundational definition underscores the importance of balancing these interconnected domains in any long-term planning and development strategy.

In the context of the construction industry, the principles of sustainability have been formalized through standards such as UNI EN 15643. According to Dodd et al. (2021), this framework articulates how construction-related activities, including the production and operation of built structures, should contribute to safeguarding essential ecosystem functions and components, thereby ensuring they remain viable for future use. This approach emphasizes not only the environmental implications but also the social and economic responsibilities embedded within construction practices.

Moreover, the impacts of construction projects are not confined to the building phase alone. As the literature suggests, these effects span the entire life cycle of a structure, from the initial assessment of whether construction is necessary, through the design, operational use, and eventual decommissioning. To better represent this comprehensive perspective, a life cycle-based modular approach is often employed, with specific stages or "modules" that help illustrate the evolution and implications of construction over time (see Figure 6). This method allows for a more structured evaluation of sustainability performance at each point in a building's life span.

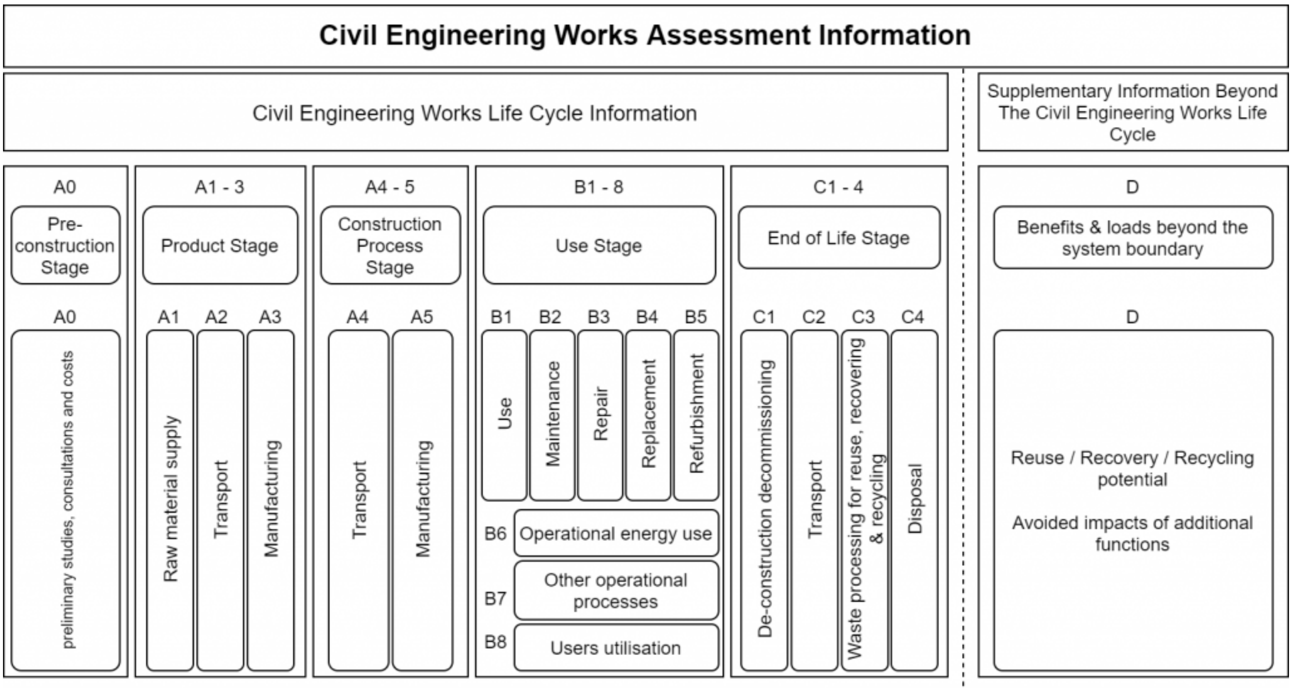


Figure 7. Division and content phases

The integrated performance of construction works encompasses environmental, social, and economic performance, as well as technical and functional performance, all of which are intrinsically interconnected.

Figure 8. Pillars of sustainability

The BS EN 15643 standard provides a foundation for demonstrating or communicating environmental, social, and economic aspects based on quantitative indicators that align with the United Nations Sustainable Development Goals (SDGs).

Figure 9. SDG Poster "17 goals to transform our world" Source: UN Communication Material

1.2.1. Environmental Sustainability

Environmental impacts associated with construction and related processes have been extensively identified and categorized in the literature through various measurable indicators. These indicators serve to quantify the effects of specific activities on natural systems, and they are typically expressed using standardized units to ensure consistency across assessments.

One of the key areas of impact is water usage, commonly measured through the Water Footprint (WF), which accounts for the net consumption of freshwater, expressed in cubic meters (m^3). Energy consumption is another significant factor and is often broken down into non-renewable primary energy consumption (NRPE) and general energy use or consumption (EUC), both of which are quantified in megajoules (MJ). These indicators distinguish between the use of energy for operational purposes and energy embodied in raw materials.

Material consumption (MC) further adds to the environmental burden and includes the use of secondary materials (measured in kilograms) and both renewable and non-renewable secondary fuels, also recorded in megajoules. Waste generation is monitored through the Waste Generation Indicator (WGI), capturing the quantities of hazardous, non-hazardous, and radioactive waste produced, each represented in kilograms.

Airborne emissions, particularly those contributing to climate change, are typically assessed using the Global Warming Potential (GWP), a widely adopted metric that calculates the warming impact of greenhouse gases in terms of carbon dioxide equivalents (CO_2eq). GWP enables the comparison of different gases by estimating their relative contribution to global warming over a defined period, typically 100 years. For instance, a gas with a GWP of 25 implies that it has 25 times the warming potential of CO_2 over the same period.

Additional environmental categories include acidification potential (AP) for soil and water systems, measured in sulfur dioxide equivalents (kg SO_2 eq), and ozone-related indicators such as ozone depletion potential (ODP) and photochemical ozone creation potential (POCP), expressed in CFC-11 equivalents and ethene equivalents, respectively. These metrics capture risks related to atmospheric degradation and smog formation.

Impacts on ecosystems and biodiversity are reflected through indicators such as eutrophication potential (EP), which measures nutrient over-enrichment in aquatic systems in phosphate equivalents (kg PO_4^{3-} eq), and abiotic depletion potential (ADP), which considers the depletion of non-living natural resources. The latter includes both elemental depletion (measured in antimony equivalents, kg Sb eq) and fossil fuel depletion (MJ).

Among these indicators, GWP is the most widely utilized due to its effectiveness in providing a common framework for evaluating the climate impacts of varied greenhouse gases, thus supporting more informed decision-making in sustainability assessments.

1.2.2. Social Sustainability

Social impacts within the built environment, although most prominently observed during the use phase of a building (commonly referred to as Module B), are often implicitly embedded as early as the design stage. As outlined by Dodd et al. (2021), these impacts can be systematically categorized to evaluate the social quality of a construction project, reflecting a holistic approach to human well-being, inclusivity, and interaction with the built environment.

One of the core categories is accessibility, which addresses the ease with which individuals, particularly those with additional needs, such as the elderly, individuals with disabilities, or parents with young children, can interact with and utilize building spaces and services. Closely related is the adaptability of spaces, which refers to the building's capacity to evolve in response to the changing needs of its users over time.

Another fundamental aspect concerns health, comfort, and indoor environmental quality. Thermal comfort, as Dodd et al. (2021) recommend, should be assessed in accordance with EN 15251, taking into account operative temperature, humidity, air velocity, user activity levels, clothing, and the availability of occupant control systems. Indoor Air Quality (IAQ) considerations include emissions from construction materials, indoor CO_2 levels, ventilation effectiveness, mold prevention, and radon presence. Acoustic quality, based on standards such as EN 12354-2 and EN ISO 3382 (especially for open spaces), and visual comfort, as guided by EN 12464-1, are also critical. These cover indicators like illuminance, glare, color rendering, daylight availability, and the potential for user-controlled lighting. Additional spatial characteristics further influence user experience and functionality.

The impact on the surrounding area is another domain of concern. This includes noise pollution, managed through appropriate acoustic insulation; light pollution, referring to both night and day glare and shadowing effects on neighboring properties; and external emissions such as particulates, odors, heat, or water discharges, often linked to HVAC systems. Structural vibrations and shocks are also relevant, especially in densely built urban settings.

Security and protection considerations encompass both crime prevention and resilience to accidental events and climate-related risks. In the context of climate adaptation, buildings must be dimensioned to withstand worsening climate conditions. This includes features like enhanced waterproofing and drainage systems to resist driving rain and flooding, snow load resistance via roof design and structural reinforcement, and protection against solar radiation through orientation strategies and solar control systems. Additionally, accidental event resistance includes earthquake-resilient design, explosion-proofing, optimized fire safety systems, and mitigating impacts from nearby traffic. Personal security is addressed through design strategies that enhance user safety, such as high-security locking systems, illuminated access paths, durable facades, and integrated alarm and surveillance systems. To ensure continuity during crises, provisions for service reliability, such as emergency power supply and lighting, are also considered.

Furthermore, maintenance and maintainability influence social impact through the frequency and complexity of repair work and the associated effects on health, safety, and building usability during those interventions. Broader social aspects extend to material procurement practices, the degree of community and stakeholder engagement, contributions to local employment, and the protection of cultural heritage, all of which form part of a socially responsible and sustainable approach to building design and operation.

1.2.3. Economic Sustainability

In the broader context of sustainability assessment, the economic dimension of an investment also warrants consideration. As discussed by Dodd et al. (2021), several methodologies exist to quantify the economic sustainability of a project. Among the most recognized are Life Cycle Costing (LCC), the evaluation of external costs and benefits, and the assessment of the long-term value and stability of the asset. While these methods offer valuable insights into the financial implications of sustainable design and construction choices, this thesis does not delve into a detailed numerical analysis of economic sustainability. Instead, a qualitative discussion is provided, acknowledging that a comprehensive exploration of LCC would require a dedicated study. Similarly, the social dimension of sustainability has been addressed primarily during the design phase and will not be examined further in this work.

The primary focus of this thesis lies in environmental sustainability, particularly through the application of Life Cycle Assessment (LCA) as a tool for evaluating the environmental impacts of buildings. LCA is increasingly recognized as a critical methodology in the transition toward sustainable construction practices. By encompassing the entire life cycle of a building, from the selection of materials and construction methods to its operational use and final demolition, LCA provides a holistic understanding of where environmental impacts occur. This approach allows professionals in the building industry to identify critical areas, or "hotspots," where carbon emissions are most significant and where targeted mitigation strategies can be implemented.

One of the most influential developments in this area is the Low Embodied Carbon framework (LETI), introduced in the United Kingdom. The LETI framework establishes a clear trajectory toward net-zero embodied carbon in buildings by the year 2030. It places strong emphasis on early-stage design decisions, informed material selection, and the integration of innovative technologies aimed at minimizing embodied carbon. Since its introduction, the framework has gained broad acceptance within the construction industry and has become a central reference for sustainable building design and carbon reduction strategies.

Accordingly, this thesis investigates the application of LCA in the context of embodied carbon assessment, with a particular emphasis on the LETI framework. By analyzing the carbon footprint associated with different materials and construction techniques, the study aims to contribute to ongoing discussions around how the built environment can align with ambitious climate goals. Special attention is given to the latest LCA data and evolving standards, particularly those projected for implementation in 2025, which are shaping current and future methodologies in the sector.

Through this analysis, the research seeks to enhance understanding of how construction-related decisions influence embodied carbon and to promote evidence-based approaches to decarbonization. By supporting the design of more sustainable buildings, the findings of this thesis aim to contribute to the ongoing development of low-carbon strategies and help ensure that future construction efforts are aligned with long-term sustainability objectives.

1.3. Importance of sustainability in construction industry

In the context of global environmental challenges, the construction industry stands out as a major contributor to greenhouse gas emissions, including carbon dioxide and other pollutants that exacerbate global warming. The sector is responsible for the consumption of more than 40% of all raw materials used within the global economy, highlighting its significant environmental footprint. As the world's population continues to grow and demands higher living standards and increased comfort, the environmental burden associated with construction activities intensifies correspondingly.

Based on the analyses conducted by Michelucci (2022-2023), it has been shown that the construction sector is estimated to generate approximately 40% of total global greenhouse gas emissions. This total is typically divided into two main categories: operational carbon and embodied carbon. Operational carbon, which accounts for roughly 28% of global emissions, arises from the energy consumed during the use phase of buildings, primarily through heating, cooling, lighting, and other operational demands within the existing building stock. In contrast, embodied carbon, comprising about 11% of total emissions, is associated with the extraction, processing, transportation, and installation of construction materials used in both new buildings and renovations of existing structures. These figures illustrate the dual challenge of reducing emissions not only during a building's operational lifespan but also throughout its entire material life cycle.

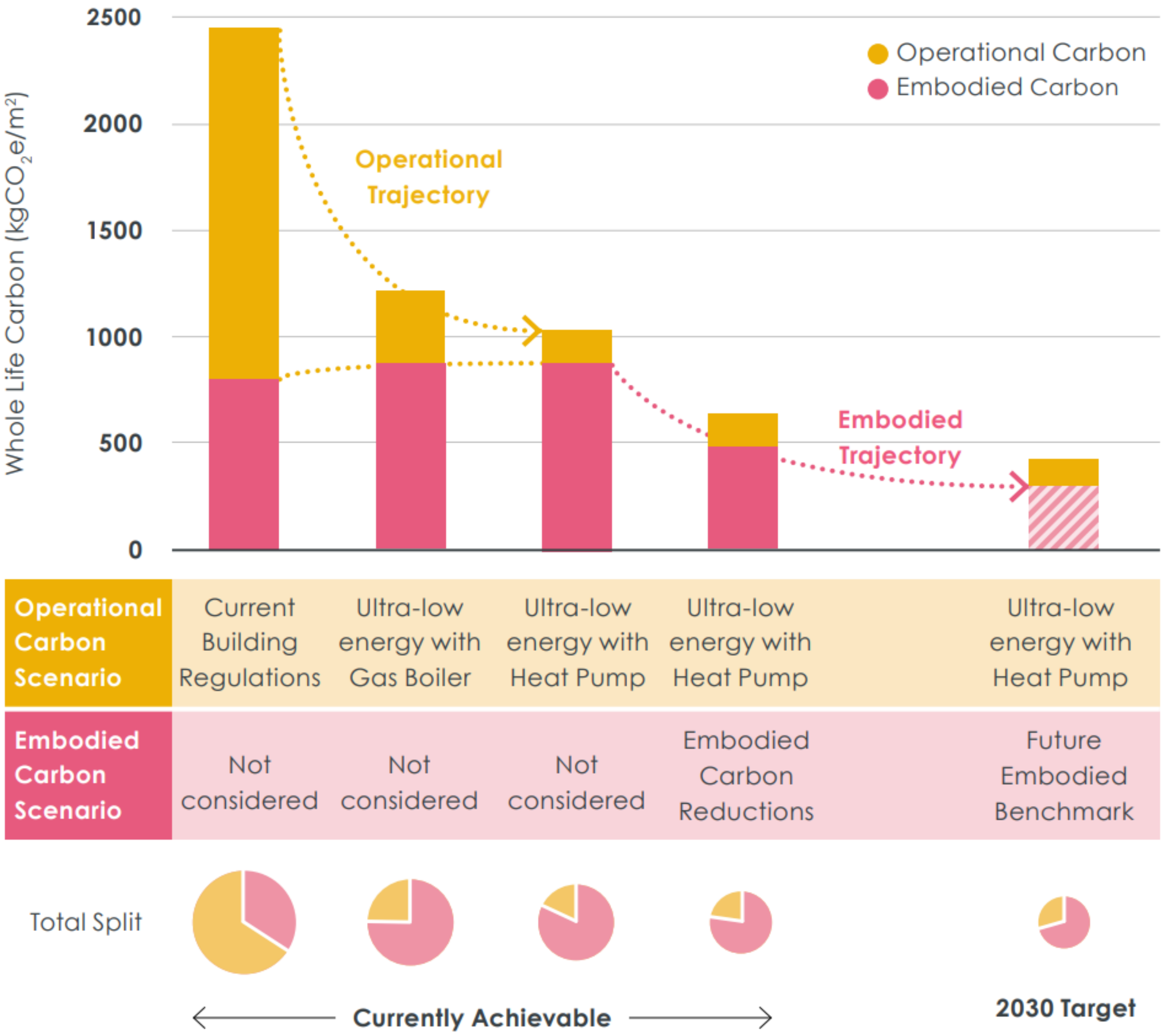


Figure 10 - Diagram showing operational and embodied carbon and trajectories

According to Brizzi and Viero (2021) a crucial step in the efforts to reduce the impact of the climate generated by construction was made with the 2015 Paris Agreement, an international treaty signed by the member states of the United Nations Framework Convention on Climate Change. Under this agreement, governments committed to limiting the global average temperature increase to well below 2°C above pre-industrial levels, with continued efforts to limit it to 1.5°C.

Another example that moves towards improved energy performance in the construction sector is the 2018/844/EU EPBD Directive, which serves as the foundation for national regulations to be implemented by member states. Specifically, this regulation stipulates that by the end of 2020, all new buildings will be Nearly-Zero Energy Buildings (nZEB), defined as buildings with very high energy efficiency.

Michelucci's (2022-2023) analyses demonstrated that, through the improvement of building energy performance and the simultaneous increase in the share of renewable energy supplied to the grid, lead to a reduction in energy consumption during the building's operational phase, i.e., a progressive reduction in what is defined as Operational Carbon. However, they do not address the reduction or containment of emissions related to embodied energy throughout the entire life cycle of the building, which also includes raw material extraction, production of construction materials, transportation to site, demolition, and waste disposal. Therefore, it is becoming increasingly important to focus on reducing the embodied emissions in buildings (Embodied Carbon).

In this regard, the joint efforts of industrialized countries have mainly focused on optimizing operational energy in buildings, direct energy used during construction, prefabrication, transport, and maintenance, and particularly the energy required to maintain comfort conditions inside buildings. However, there is still much work to be done in terms of embodied energy, which refers to the energy required for the production process of materials, as previously mentioned.

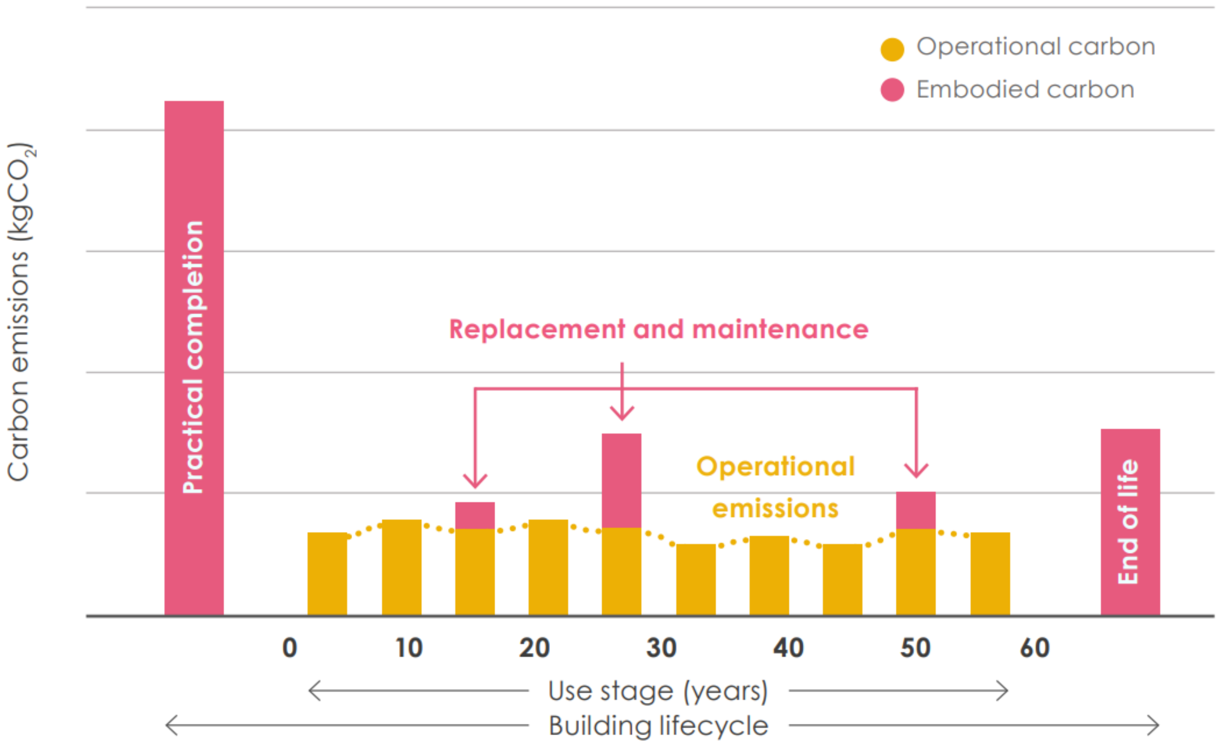


Figure 11. Breakdown of a building's emissions during its lifecycle - division of embodied carbon and carbon in the usage phase

As the construction industry increasingly moves toward the adoption of Nearly-Zero Energy Buildings (nZEB), the relevance of embodied carbon emissions within the broader emissions profile of buildings has become more pronounced. Traditionally, energy performance indicators have focused primarily on operational energy use; however, the introduction of supplementary metrics, such as carbon dioxide equivalent (CO_2eq), marks a critical shift in building assessment practices. This evolution serves not only to enhance awareness and transparency but also to support more informed decision-making and improved professional competencies across the sector. The development and application of such metrics enable the creation of standardized, comparable datasets, laying the groundwork for more effective policy and design interventions.

The long-term objective at the European level is to implement comprehensive Whole Life Carbon (WLC) performance frameworks. These would involve mandatory reporting, benchmarking, and carbon accounting across the entire building life cycle. However, this ambition depends on the progressive establishment of sufficient data infrastructure and industry-wide expertise. In the meantime, voluntary tools and standards continue to play a leading role. The Life Cycle Assessment (LCA) methodology, standardized in EN 15978:2011, provides a structured approach for calculating the environmental performance of buildings. This method uses carbon dioxide equivalent (expressed in $kgCO_2eq/m^2/year$) as the primary indicator, allowing a consolidated assessment of greenhouse gas (GHG) emissions throughout a building's life cycle. The use of CO_2eq facilitates the conversion and aggregation of various greenhouse gas emissions according to their respective Global Warming Potentials (GWP), enabling meaningful comparisons and clearer impact evaluations. This form of analysis is already embedded within several voluntary environmental certification schemes operating in the Italian construction market, notably LEED and BREEAM, which incorporate LCA-based metrics as part of their assessment protocols.

Despite these advancements, the construction sector continues to face significant challenges related to the lack of harmonized benchmarks and consistent methodologies at the European scale. Current targets, such as those developed by the Green Construction Board and the RIBA Sustainable Futures Group, represent interim guidance aimed at reducing upfront carbon emissions, which correspond to the embodied carbon generated during the initial construction phase. These benchmarks, however, often exclude emissions associated with later stages of the building life cycle, such as maintenance and decommissioning, due to the complexity involved in quantifying such impacts. Nonetheless, the growing emphasis on upfront carbon underscores the urgency of addressing embodied emissions early in the design and construction process to meet broader climate objectives.

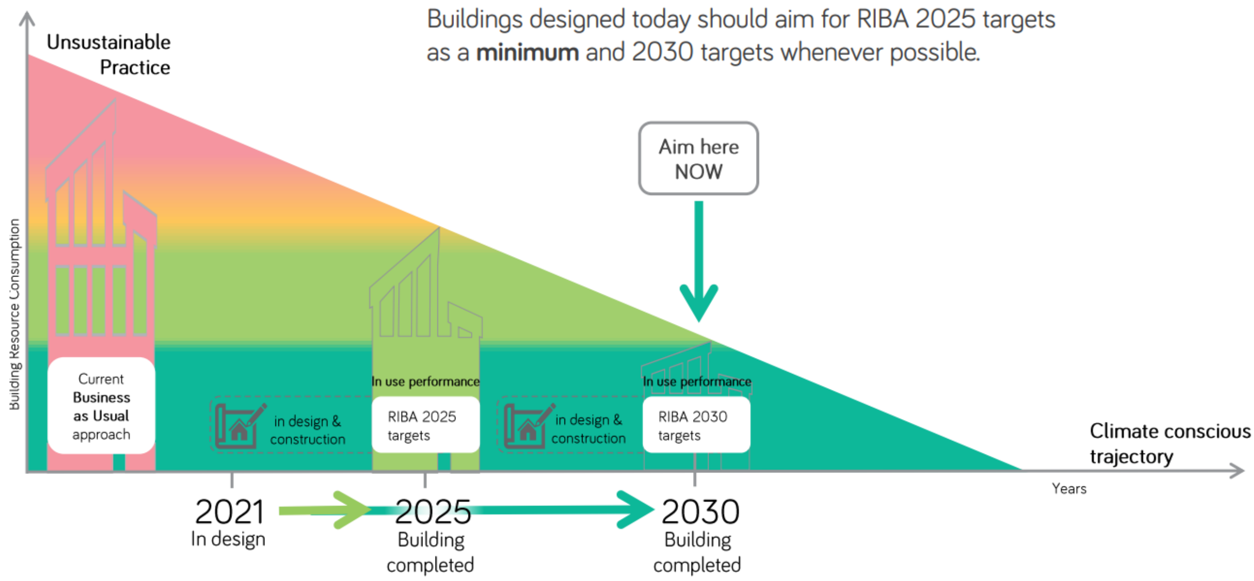


Figure 12. RIBA 2030 Climate Challenge as built target trajectories

2. Methodologies

2.1. What is Life Cycle Assessment (LCA)

Following the overview of the construction sector’s environmental impact and associated challenges, it is essential to introduce the methodological tool that enables a comprehensive evaluation of these impacts: Life Cycle Assessment (LCA). Originally developed in the 1960s within industrial settings, LCA was initially used to analyze the environmental implications of production processes. Its application outside the industrial domain began to take shape in the 1970s. However, by the end of the 1980s, the lack of methodological consistency led to divergent and often contradictory results across LCA studies, even when assessing identical products. This inconsistency stemmed from variations in data sources, methodological choices, and terminological definitions, underscoring the urgent need for a standardized framework.

In response to this need, the Society of Environmental Toxicology and Chemistry (SETAC), based in Vermont, Canada, introduced a comprehensive framework in 1993 that remains foundational in the field. According to this internationally recognized definition, a Life Cycle Assessment is “an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, and to assess the impact of those energy and material uses and releases” (Cabeza et al., 2014). LCA considers the full life span of a product—from raw material extraction and manufacturing to use, reuse, maintenance, recycling, and final disposal—commonly referred to as the “cradle-to-grave” approach.

LCA seeks to quantify potential environmental impacts in key categories such as human health, resource depletion, and ecosystem quality. However, it is important to recognize that LCA operates as a scientific modeling tool—it simplifies complex physical systems and, therefore, cannot fully capture all real-world environmental interactions. Nonetheless, it remains one of the most robust methodologies for identifying critical stages within a product's life cycle where environmental impacts are concentrated and for assigning responsibilities to relevant stakeholders, such as manufacturers or end-users.

The core objectives of LCA can be summarized as follows:

- To provide a comprehensive overview of the interactions between a product, service, or activity and the environment, addressing both direct and indirect consequences.
- To foster a deeper understanding of the interconnectedness of environmental effects caused by human activity.
- To support decision-making by delivering detailed information on environmental impacts and highlighting opportunities for mitigation and sustainable improvement.

In accordance with the principles set forth in ISO 14040 – Life Cycle Assessment: Principles and Framework, the LCA process is structured around four key phases, which will be outlined in the following section.

The LCA process, according to ISO 14040 - Life Cycle Assessment - Principles and Framework, involves four stages:

1. **Goal and Scope Definition Phase**: This phase includes defining the system boundaries (ISO 14041).
2. **Life Cycle Inventory (LCI) Phase**: This involves inventorying the input and output data of the system being studied, necessary to achieve the objectives of the study (ISO 14041).
3. **Impact Assessment (LCIA) Phase**: This phase evaluates the potential environmental impact associated with the inventory of inputs and outputs of a specific system, aiming to provide additional information for better understanding the environmental results (ISO 14042).
4. **Interpretation Phase**: The results of the LCI and/or LCIA are summarized and discussed (ISO 14043).

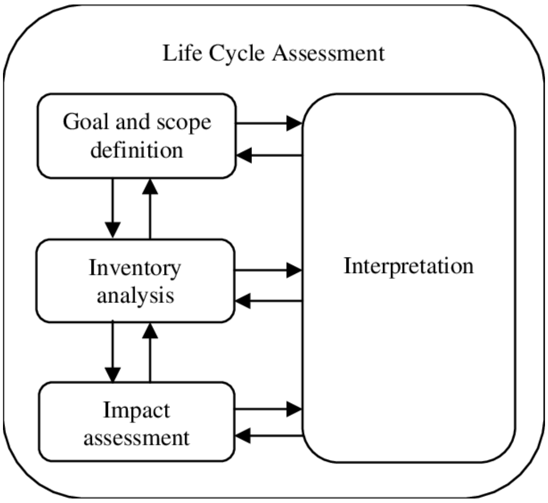


Figure 13. Phases of life cycle assessment (ISO 14040, 2006)

The goal and scope definition is the foundational phase of a Life Cycle Assessment (LCA), in which the purpose of the study is articulated, and the functional unit is established. For carbon-based evaluations, this functional unit is commonly expressed as kilograms of CO_2-equivalent per square meter per year (kg CO_2eq/m^2/year). This phase also involves the delineation of system boundaries, typically defined as cradle-to-grave, to determine which life cycle stages will be included in the assessment. Tailoring the scope to meet specific sustainability objectives, such as compliance with frameworks like LETI, ensures that the study remains aligned with its intended purpose (Cabeza et al., 2014).

The Life Cycle Inventory (LCI) phase involves compiling a comprehensive dataset of all inputs (e.g., raw materials, energy sources) and outputs (e.g., emissions, waste) associated with the product or process under study. These data are frequently sourced from established databases such as *Ecoinvent*. However, Cabeza et al. (2014) emphasize the importance of geographic specificity, as production processes and energy mixes can vary significantly across regions, potentially skewing results if local conditions are not adequately reflected.

In the Life Cycle Impact Assessment (LCIA) phase, the inventory data are translated into potential environmental impacts. Among the various impact indicators, Global Warming Potential (GWP) is particularly crucial for carbon-focused analyses. GWP quantifies the effect of greenhouse gas emissions in terms of their CO_2-equivalent values, thereby facilitating comparisons across different gases and identifying major contributors to climate change. A typical finding in LCIA studies is the significant impact of materials such as concrete, which is consistently highlighted as a primary emissions hotspot (Cabeza et al., 2014).

The interpretation phase synthesizes the results of the LCI and LCIA, drawing conclusions and providing recommendations. This stage identifies critical processes and materials that contribute disproportionately to the environmental impact, supporting more informed decision-making.

The growing adoption of LCA can be attributed to several converging trends. Firstly, there is a broadening recognition that environmental challenges, ranging from air and water pollution to soil degradation, cannot be addressed in isolation but require integrated and systemic evaluation methods. Secondly, there has been a policy shift toward product-centered environmental strategies, reflecting the importance of life cycle thinking in regulatory frameworks. Finally, public awareness has surged, with consumers increasingly demanding transparency and favoring products and services that meet environmental quality criteria.

LCA methodology relies on synthetic, quantitative indicators that represent various categories of environmental impact. These include the consumption of natural resources and emissions to environmental matrices such as air, water, and soil. The versatility of LCA makes it applicable at multiple levels: from individual businesses seeking to optimize operations, to national policymakers aiming to implement sustainable economic strategies. Thus, beyond its environmental function, LCA serves as a strategic tool for cost control, competitiveness, and market differentiation.

Despite its strengths, LCA faces several challenges. Data availability for novel and emerging materials is often limited, and inconsistencies in methodology across LCA software tools can lead to comparability issues. Hossain and Ng (2020) point out that expanding the coverage of Environmental Product Declarations (EPDs) and harmonizing databases are crucial steps toward improving the precision and reliability of assessments. Moreover, LCA's integration into voluntary certification systems such as BREEAM and LEED further reinforces its relevance in both regulatory compliance and market-driven sustainability efforts.

Ultimately, the results of an LCA should not be interpreted in isolation. Rather, they should be incorporated into broader, multi-dimensional decision-making processes that account for global environmental exchanges and systemic trade-offs.

2.2. Whole Life Carbon, Operational Carbon, and Embodied Carbon

Whole Life Carbon (WLC) refers to the total carbon emissions associated with a building throughout its entire life cycle, encompassing both embodied carbon, emissions from the extraction, manufacturing, transport, and installation of construction materials, and operational carbon, which includes emissions resulting from the building's energy use during its occupancy phase (WorldGBC, 2019). This comprehensive, cradle-to-grave approach provides a more accurate representation of a building's environmental impact and helps identify potential trade-offs. For example, a building that incorporates advanced energy-saving systems may reduce operational emissions significantly, yet these benefits could be offset by the high embodied carbon associated with the production and installation of such systems.

Recognizing these complexities, the World Green Building Council (WorldGBC, 2019) strongly advocates for Whole Life Carbon assessments as a foundational design tool. The organization emphasizes the importance of early-stage interventions, which can yield the most significant reductions in both embodied and operational emissions. One example is the Passive House model: while it excels in minimizing energy demand and operational emissions, it often relies on high-performance materials that may have a higher carbon footprint, underscoring the need for balanced and informed decision-making.

In response to growing climate imperatives, regulatory frameworks are increasingly incorporating WLC considerations. Notably, the European Commission's Level(s) framework promotes consistent reporting of life cycle emissions, offering a common language and structure for sustainability performance across the EU (European Commission, 2020). This initiative aims to improve transparency and enable meaningful comparisons across projects, supporting the broader decarbonization goals of the European Green Deal.

However, practical implementation remains challenging. Data inconsistencies, limited access to reliable environmental product declarations (EPDs), and a general lack of stakeholder expertise in life cycle methodologies often hinder the effective use of WLC assessments. Overcoming these barriers requires expanded data harmonization efforts and capacity-building initiatives within the industry.

As shown by the analyses in Michelucci (2022-2023) both embodied and operational carbon metrics, Whole Life Carbon assessments offer a robust framework that aligns with emerging standards such as LETI. This approach not only facilitates comprehensive environmental evaluation but also serves as a critical driver for achieving net-zero carbon targets across the built environment.

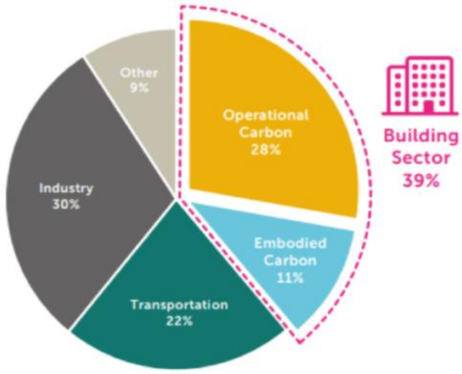


Figure 14. Global carbon emissions divided by sector

2.2.1 Embodied Carbon

According to Brizzi and Viero (2021), embodied carbon encapsulates emissions from a building's life cycle, including material extraction, manufacturing, transportation, construction, maintenance, and end-of-life stages (WorldGBC, 2019). Unlike operational carbon, it is largely fixed upon construction completion, making early design decisions pivotal. WorldGBC (2019) highlights that embodied carbon accounts for 11% of global emissions, with "Upfront Carbon" (emissions from material production and construction) being particularly critical due to its immediate environmental impact. For example, concrete production, driven by energy-intensive cement clinker, contributes significantly to global emissions, while steel's smelting processes add to its high carbon footprint.

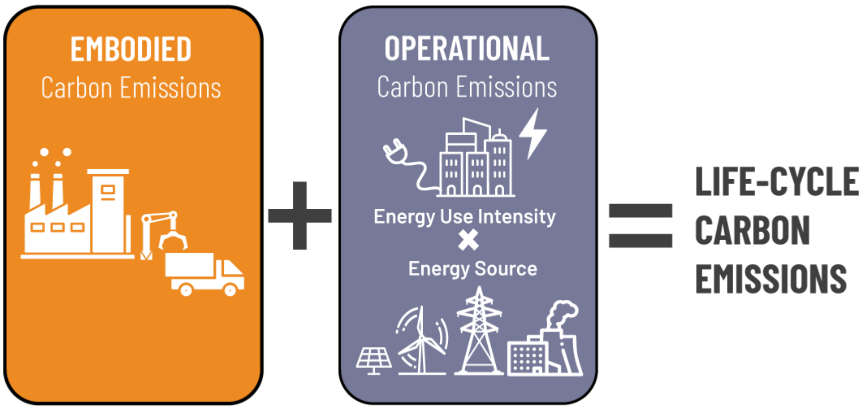


Figure 15. A building's carbon footprint over its lifespan is the sum of its embodied plus operational emissions. Adapted from Magwood et al. 2021

Timber presents a compelling alternative, as demonstrated by Gagnon and Pirvu (2011), who found Cross Laminated Timber (CLT) structure buildings can reduce embodied carbon by up to 30% compared to concrete structures. Timber's ability to sequester carbon during growth further enhances its sustainability, though challenges like regional availability and fire resistance require careful consideration. Recycled materials, such as reclaimed aggregates, also mitigate embodied carbon by reducing virgin resource use, but their structural performance needs validation for widespread adoption. The complexity of embodied carbon accounting lies in data variability, Environmental Product Declarations (EPDs) offer standardized metrics, but gaps in coverage for novel materials hinder precision. Designers must navigate these uncertainties to prioritize low-carbon options, balancing immediate impacts with long-term sustainability goals.

2.2.2 Operational Carbon

Operational carbon arises from energy consumption during a building's use, encompassing heating, cooling, ventilation, lighting, and appliances (UNEP, 2022). It varies based on climate, occupant behavior, and energy sources, making it dynamic and challenging to predict. UNEP (2022) notes that operational carbon historically dominated building emissions, prompting interventions like passive design and renewable energy adoption. The EU's push for Nearly-Zero Energy Buildings (nZEBs) has slashed operational emissions in some contexts, with buildings leveraging solar panels or heat pumps to approach net-zero energy use (European Commission, 2020).

However, operational carbon's variability complicates assessments. Occupant habits, such as excessive heating, can inflate emissions, while grid carbon intensity, higher in coal-reliant regions, further skews impacts. Over a building's lifespan, grid decarbonization (e.g., shifting to renewables) alters operational carbon projections, requiring dynamic modeling. Energy simulation tools like EnergyPlus help predict performance, but trade-offs emerge thick insulation reduces operational carbon but increases embodied carbon from material production. This interplay demands integrated strategies, ensuring operational efficiencies don't inadvertently inflate life cycle emissions. As operational carbon decreases, its relative contribution shrinks, elevating embodied carbon's importance in achieving net-zero targets.

2.2.3. Whole Life Carbon

In their 2021 work, Brizzi and Viero meticulously outline how the 'Whole Life Carbon' approach can serve as a robust design methodology to progressively reduce carbon emissions in buildings. Having previously mentioned the terms Whole Life Carbon, Operational Carbon, and Embodied Carbon, and needing to analyze their different contributions in the case study at hand, the following definitions are provided. Whole Life Carbon refers to the sum of two main contributions:

1. **Operational Carbon**: Emissions associated with the energy used to operate the building or manage the infrastructure (B6).
2. **Embodied Carbon**: Carbon emissions related to materials and construction processes throughout the entire life cycle of a building or infrastructure. This includes: material extraction (A1), transportation to the producer (A2), manufacturing at the factory (A3), transportation to the site (A4), building construction (A5), use phase (B1), maintenance (B2), repair (B3), replacement (B4), renovation (B5), decommissioning (C1), transportation at end-of-life (C2), processing (C3), and disposal (C4). Additionally,

benefits beyond the system boundary (D) should be reported separately from modules A-C.

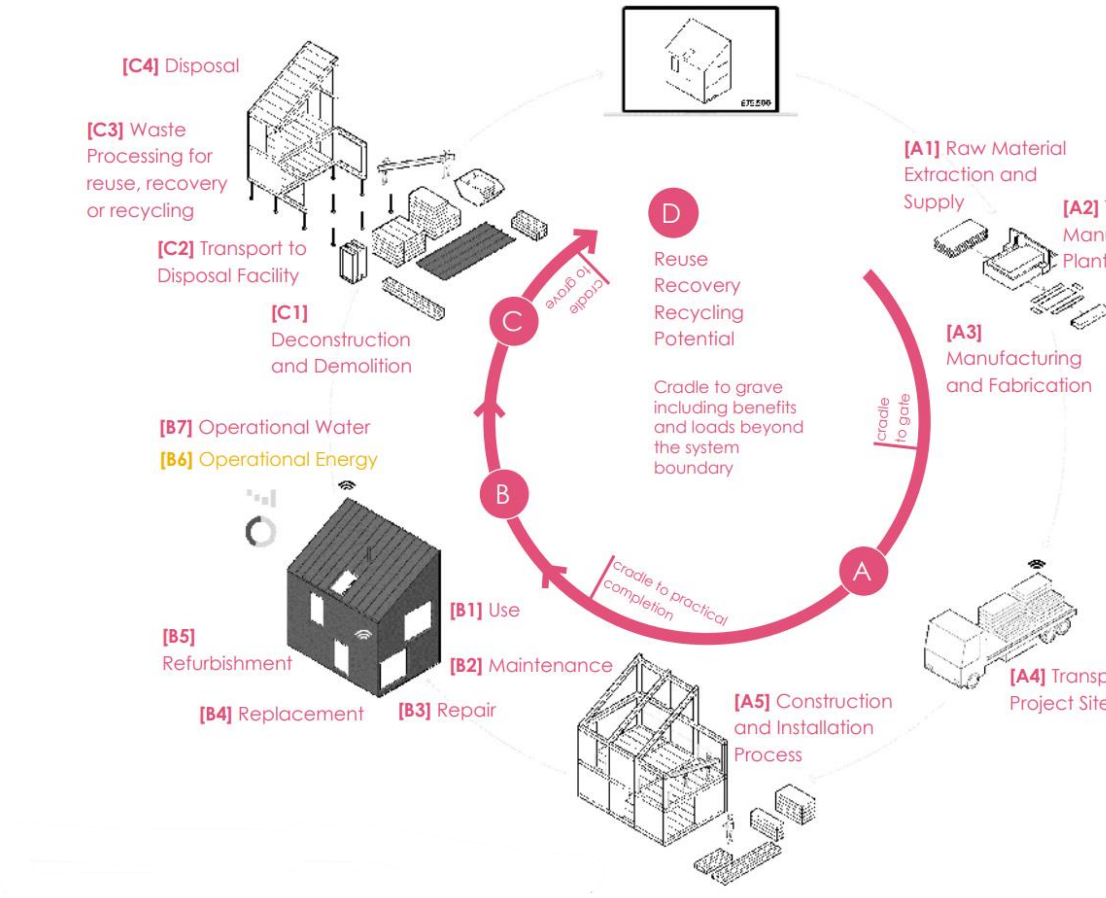


Figure 16. Life Cycle Assessment (LCA) Diagram adapted from Hawkins\Brown using illustrations from Open Systems Lab 2018 licensed under Creative Commons CC BY-N

Furthermore, the term Upfront Carbon refers to emissions caused during the material production and construction phases (A1-A5) before the building or infrastructure begins its use. Unlike other categories of emissions, these are released into the atmosphere before the building is occupied or the infrastructure becomes operational.

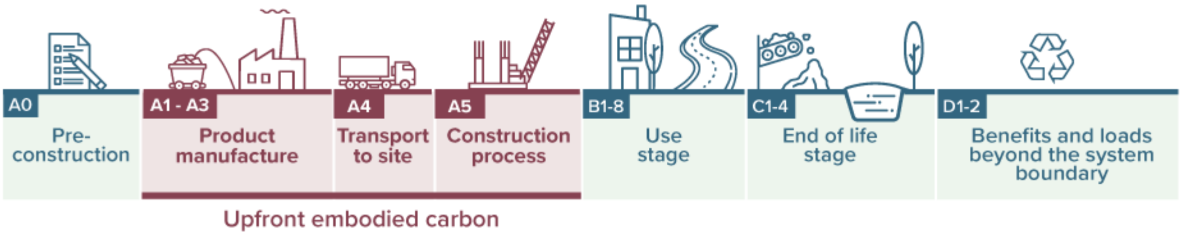


Figure 17. Breakdown of upfront carbon emissions

Life Cycle Assessment (LCA) enables the quantification of carbon equivalent emissions generated throughout the entire lifespan of a building, commonly considered to be 50 years.

This total emission is known as Whole Life Carbon and is composed of two main components: Embodied Carbon and Operational Carbon. The proportion of these two varies significantly depending on the building type.

An illustrative example is provided by the London Energy Transformation Initiative (LETI), which presents a breakdown of global carbon emissions for a typical office building designed according to current national regulations. As shown in the corresponding pie chart, Operational Carbon, referring to emissions generated during the building's use phase, constitutes the majority at approximately 66% of the Whole Life Carbon. The remaining 34% represents Embodied Carbon, which itself is further divided into several categories: 16% arises from materials used during initial construction, 15% from materials consumed during routine and extraordinary maintenance, and smaller shares of 1% each are attributed to construction activities, transportation, and the decommissioning phase.

A more detailed examination of Embodied Carbon reveals that structural elements—specifically the foundation and above-ground structures—account for roughly 65% of the total embodied emissions, as depicted in the second pie chart. Other contributors include the building façade (16%), building services such as mechanical and electrical systems (15%), and finishes (4%).

Given this distribution, it becomes clear that focusing carbon reduction efforts on the structural components offers the greatest potential impact. Strategies such as promoting the reuse of existing building materials or adopting timber-based structural solutions can be particularly effective in reducing the embodied carbon footprint within the construction sector.

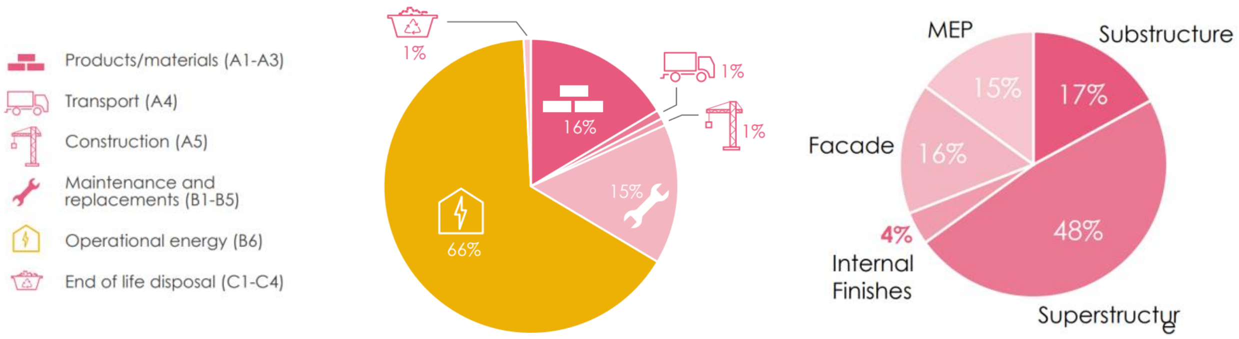


Figure 18. Breakdown of whole life carbon in further detail for typical office, and Embodied carbon per element (Cradle to Gate)

The emissions [kgCO2eq] resulting from energy consumption [kWh/m^{2}a] during the operational phase of a building are referred to as *Operational Carbon*.

To reduce Operational carbon, it is essential not only to minimize the building's energy demand through passive measures and design choices, but also to enhance the efficiency of the systems. However, the most significant impact comes from ensuring sustainable energy generation, which can be either on-site (such as rooftop photovoltaic systems) or off-site (by purchasing energy from renewable sources, contributing to national sustainability).

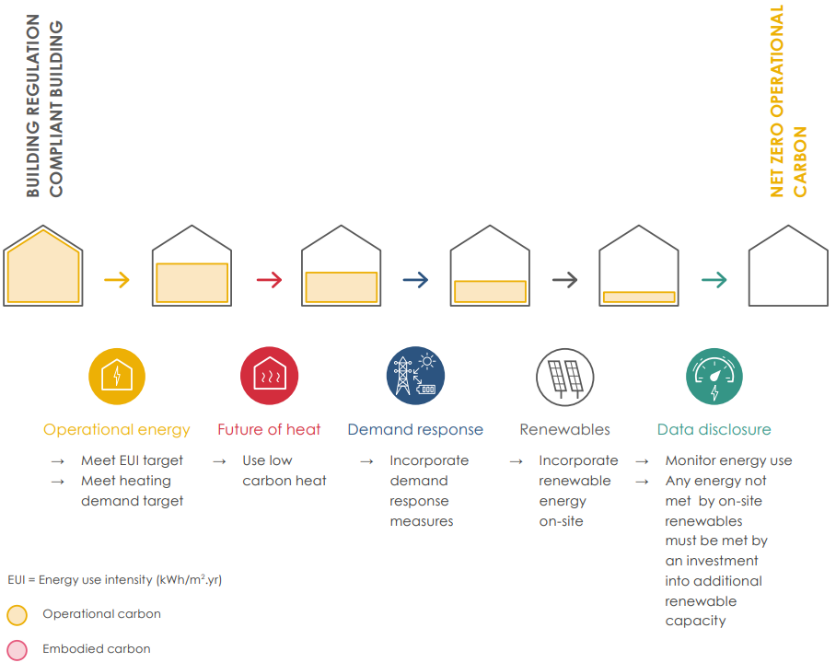


Figure 19. The operational carbon reduction stages on the left, and the embodied carbon reduction stages on the right.

The Energy Use Intensity (EUI) is a key metric used to evaluate a building's annual energy consumption relative to a defined functional unit, typically the Gross Internal Area (GIA). Expressed as energy per square meter per year (e.g., kWh/m^2/year), EUI provides a standardized basis for comparing energy performance across different buildings or design scenarios. This metric plays a crucial role in assessing the operational efficiency of buildings and identifying opportunities for energy savings.

Energy consumption within the EUI framework is generally divided into two categories: regulated energy and unregulated energy. Regulated energy includes consumption directly controlled by building systems and subject to regulatory standards; this encompasses energy used for heating and cooling to maintain indoor thermal comfort during both summer and winter, domestic hot water production, ventilation, and lighting. These elements are typically the focus of building codes and energy performance certifications, as they represent predictable and controllable energy demands.

In contrast, unregulated energy refers to energy use that is largely dependent on occupant behavior and operational patterns, making it more variable and harder to predict. This category includes electricity consumed by personal devices such as computers, televisions, kitchen appliances, elevators, and other plug loads. Because user habits strongly influence unregulated energy consumption, its management often requires occupant engagement and behavioral interventions alongside technological solutions.

Understanding and accurately measuring both regulated and unregulated energy use is essential for comprehensive energy performance analysis. This holistic view supports the development of effective energy reduction strategies, which can contribute to achieving sustainability goals such as Nearly-Zero Energy Building (nZEB) standards and net-zero carbon targets.

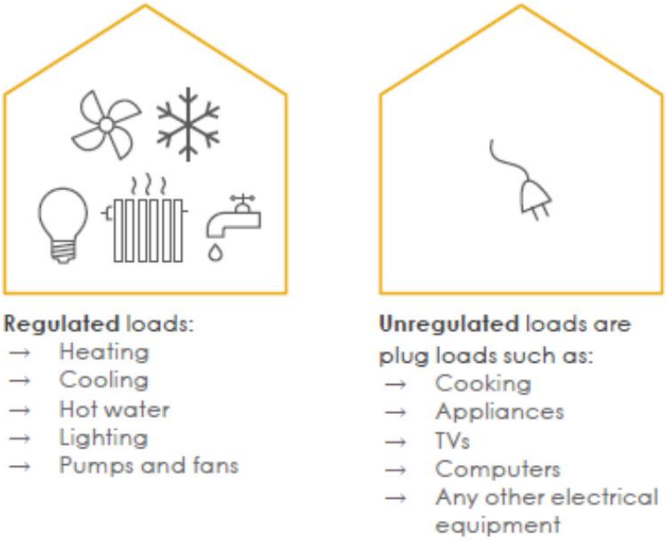


Figure 20. Different MEP parts contributing operational carbon.

The energy consumed by a building, expressed in kWh/year for the entire building, can be converted into greenhouse gas emissions, making it possible to compare and place embodied and operational emissions on the same level using the same unit of measurement.

The method (Commissione Europea, 2024) involves converting kWh/year into CO2 emissions through conversion factors. The calculation method can be:

- **Location-based**: This approach calculates the average CO2 emissions per kWh of electricity in Italy. The electrical grid contains electricity produced from various sources, such as gas, coal, and photovoltaics. Since all electricity flows into the same grid, it is impossible to distinguish whether the electrons come from renewable sources or not. Therefore, the location-based approach considers the average emissions of energy present in the grid.
- **Market-based**: This method calculates the average CO2 emissions per kWh of electricity from the specific provider. Guarantees of Origin (GO) are the mechanism upon which this calculation method is based. A GO is a certificate issued by the Gestore dei Servizi Energetici (GSE) for each MWh produced from renewable sources. By purchasing a GO, it's as if you are buying renewable energy from the grid. Additionally,

many companies install renewable energy systems on their premises. By generating electricity on-site, they reduce withdrawals from the grid, ensuring that the kWh of electricity consumed has emitted zero CO2.

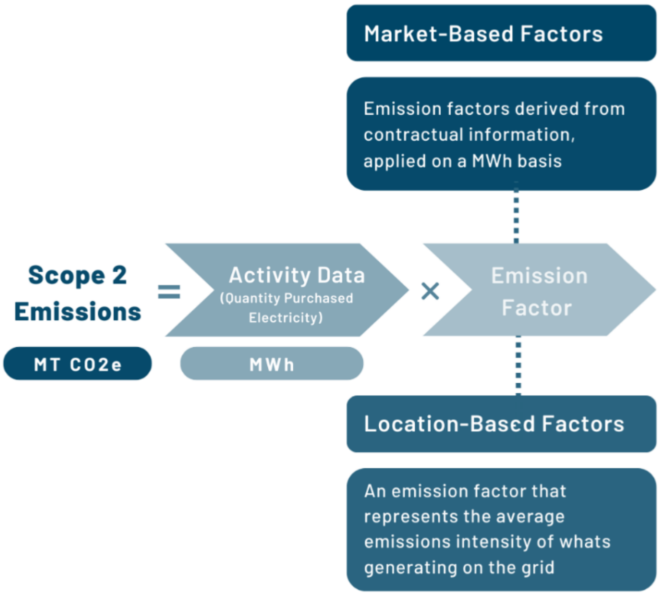


Figure 21. Calculating scope 2 emissions

The accuracy of carbon emissions calculations fundamentally relies on the emission factors applied to the energy consumed. In Italy, the location-based emission factors are published annually by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). For example, in 2022, the carbon intensity for electricity consumption in Italy was reported as 0.309 kg of CO_2 per kilowatt-hour (kWh). These location-based factors reflect the average emissions associated with the regional electricity grid mix.

On the other hand, market-based emission factors require a nuanced understanding of the energy procurement sources. Excluding Guarantees of Origin (GOs)—which certify renewable energy generation and are assigned a carbon factor of zero kg CO_2 per kWh—the residual energy mix must be carefully evaluated. In Europe, the Association of Issuing Bodies (AIB) annually publishes the emission factors corresponding to this residual mix. For Italy in 2022, the residual mix exhibited a higher carbon intensity of 0.457 kg CO_2 per kWh according to AIB data, reflecting the combined emissions from non-renewable and unspecified energy sources.

Reducing energy consumption through design optimizations remains a critical strategy in lowering associated carbon emissions. The London Energy Transformation Initiative (LETI) employed shoebox parametric models to identify key design parameters that influence a building's energy demand. Although developed for the UK context, these passive design principles are broadly applicable. Key parameters include building orientation, which can dramatically affect heating loads. For instance, simply rotating the shoebox model led to an increase in heating demand from 13 kWh/m^2·year to 24 kWh/m^2·year for winter climate control.

Another important factor is the window-to-wall ratio, or the percentage of transparent to opaque surfaces. Adjusting this ratio according to the local climate can substantially reduce both heating and cooling loads by optimizing solar gain and natural daylight. Additionally, the form factor, which measures the ratio between the external surface area and internal floor area, influences heat loss and gain; more compact forms generally perform better energetically.

By strategically optimizing these parameters, orientation, window-to-wall ratio, and form factor, designers can effectively reduce energy demand through intelligent architectural choices, thereby contributing to the overall reduction of operational carbon emissions (Ferrari, A., 2023/2024).

2.3. Environmental Certification Tools for Products: Labeling I, II, III; EPD

Based on the analyses conducted by Benini (2022), it has been shown that recently, there has been a disorganized and continuous proliferation of certifications, markings, labels, logos, and tags, each of which follows its own "private" protocols or international standards (ISO or EN) and focuses on one or more aspects for evaluating sustainability and the impacts of a product. In this context, it is challenging to monitor eco-efficiency parameters, which is why, to make consumers more informed, environmental communication tools called ecological labels have been developed.

In order to establish the guidelines and principles for the development and application of environmental labels, the UNI EN ISO 14020:2002 standard has defined three different types:

- **UNI EN ISO 14024:2001** - Type I Environmental Labeling
- **UNI EN ISO 14021:2002** - Type II Environmental Labeling
- **UNI EN ISO 14025:2010** - Type III Environmental Labeling

Type I Environmental Labeling

Type I labeling (e.g., NaturePlus, Anab Icea, etc.) is a voluntary environmental marking method for products that certifies reduced environmental impact. It is considered reliable because it is awarded by external organizations, which can be public or private entities independent of the producer (such as the European ECOLABEL). These labels are based on indicators that take into account all stages of the product's life cycle and set specific performance thresholds to be met. The product can be labeled once it satisfies all the minimum requirements listed in the checklist.

Type II Environmental Labeling

Type II environmental labeling consists of ecological labels that feature self-declarations made by producers, importers, or distributors of products, without the involvement of an independent certification body. Type II labels can cover various aspects, such as the use of recycled materials, the use of energy from renewable sources, or other environmental claims. Since these declarations are made directly by the producers or distributors, they do not undergo third-party verification, which can sometimes lead to questions regarding the accuracy or reliability of the claims. However, these labels provide useful information for consumers and can help them make more sustainable purchasing decisions.

Type III Environmental Labeling - EPD (Environmental Product Declaration)

Type III environmental labeling, also known as Environmental Product Declaration (EPD) in English, involves declarations based on established parameters that quantify the environmental impacts associated with the product's life cycle. This is calculated through a Life Cycle Assessment (LCA) conducted according to rules and requirements outlined in PCR (Product Category Rules), which are discussed and agreed upon by various stakeholders.

Specifically, the Product Category Rules (PCR) that different manufacturers must follow allow the market to make a consistent comparison of the environmental impacts of a given product category. These rules must be created while adhering to specific and rigorous methodological requirements, as they serve as the basis for third-party verification of the LCA study for the Environmental Product Declaration (EPD).

The Environmental Product Declaration (EPD) is a document that communicates objective, comparable, and credible information regarding the environmental performance of products and services. These details are purely informational and do not involve evaluation criteria, minimum performance levels, or preferences.

Furthermore, the certification system for EPDs is managed by international Program Operators (such as Environdec, IBU, AENOR, Norge, EPDItaly, etc.), and the LCA assessment underpinning the EPD is subjected to third-party verification.

In the previously described complex context, manufacturers perceive EPD as the only reliable, objective, and transparent tool to communicate the environmental performance of a product to architects and design firms in a technical, standardized, and comprehensive manner. This reliability comes from the use of standards (such as ISO 14025 and EN 15804) and the LCA methodology (defined in ISO 14040-44), which are foundational to the EPD.

To facilitate the use of verified and verifiable environmental information, the CAM (Criteri Ambientali Minimi) related to the procurement of design services and works for new construction, renovation, and maintenance of public buildings encourage the use of environmental labels of Types I, II, and III (particularly the EPD). These labels allow contracting authorities to easily verify compliance with minimum environmental criteria. As a result, manufacturers have increasingly turned to EPD certification and the development of LCA studies for their products.

Moreover, in the context of Green Public Procurement (GPP), contracting authorities often include in tender criteria the requirement for environmental certifications (e.g., LEED, BREEAM), which encompass LCA studies.

2.3. EUROPEAN AND ITALIAN REGULATORY LANDSCAPE

Benini's 2022 thesis on Life Cycle Assessment highlights that buildings in Europe represent a critical nexus in the region's efforts to combat climate change and improve energy efficiency. They account for roughly 40% of the European Union's total energy consumption and contribute over one-third of its carbon dioxide (CO_2) emissions. This significant share stems largely from the age and inefficiency of the existing building stock, with most buildings constructed before 1980. These older buildings generally lack modern energy-saving technologies and often rely on outdated heating, cooling, and insulation systems, which results in high energy demands and emissions.

To meet the ambitious climate targets set by the European Green Deal, particularly the goal of climate neutrality by 2050, the EU faces a monumental challenge: the vast majority of buildings will require deep renovations to drastically reduce their energy consumption and carbon footprint. Yet, despite this urgent need, the current annual renovation rate is only around 1%. This rate is insufficient to achieve the scale of change needed within the next three decades, highlighting a critical gap between policy aspirations and practical implementation.

Improving energy performance in buildings offers multiple benefits beyond emission reductions. Upgrading insulation, ventilation, and heating systems enhances indoor environmental quality, which supports occupant health and wellbeing. Improved thermal comfort reduces health risks related to cold or heat exposure, while better air quality mitigates respiratory problems. Furthermore, energy-efficient buildings can reduce energy poverty by lowering utility costs for residents, making housing more affordable and equitable.

Modern buildings are no longer passive energy consumers but are evolving into active components of a smart energy ecosystem. Technologies such as photovoltaic panels, battery storage, demand-response systems, and integration with electric vehicle (EV) charging infrastructure enable buildings to generate, store, and manage energy dynamically. These capabilities improve grid resilience, support renewable energy integration, and empower occupants to participate in energy markets. However, unlocking this potential requires substantial investment in modernizing the building stock and deploying smart technologies at scale.

In response to these challenges and opportunities, the European Union has made building modernization a cornerstone of its climate and energy policies. The EU's Climate Law, proposed in 2020 as part of the broader European Green Deal, sets legally binding targets for reducing greenhouse gas emissions and promotes a large-scale "renovation wave." This initiative aims to accelerate the renovation of public and private buildings across Europe, making them more energy-efficient, sustainable, healthier, and more affordable.

The renovation wave is designed not only as a climate action but also as an economic stimulus. It is expected to drive growth in the construction and renovation sectors, create millions of jobs locally, and foster innovation in green building technologies. By investing in sustainable building practices, the EU seeks to stimulate economic recovery while advancing its decarbonization agenda.

Over the past two decades, the EU has developed extensive experience in building energy policy, ranging from mandatory energy performance standards to voluntary certification schemes like BREEAM and LEED. These policies and frameworks provide a robust foundation for accelerating sustainable building practices and offer valuable lessons for other regions with similar goals. The EU's integrated approach combines regulatory measures, financial incentives, and technical support to promote market transformation toward nearly zero-energy buildings (nZEBs) and beyond.

In summary, transforming Europe's building stock is pivotal for achieving the continent's climate goals. It requires addressing technical, economic, and social challenges through coordinated policy frameworks, innovation, and stakeholder engagement. By advancing deep renovations and embracing smart building technologies, Europe aims to create a sustainable, resilient, and equitable built environment for future generations.

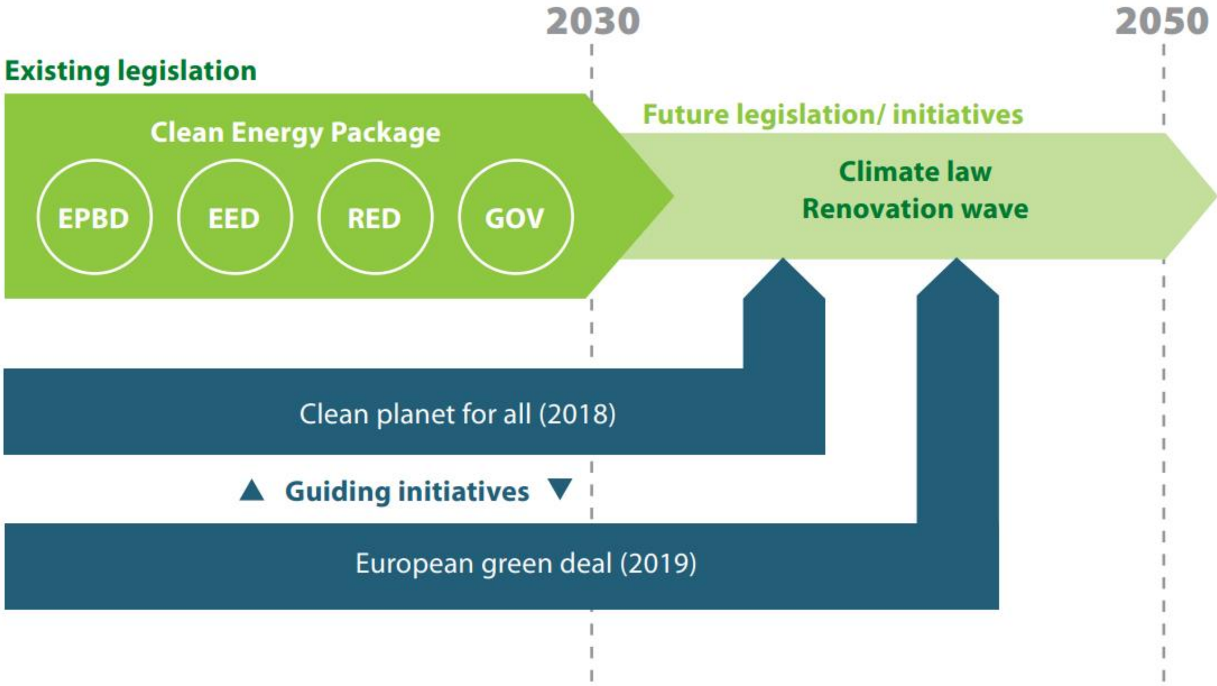


Figure 22. European Climate and Energy Legislation and Initiatives (Source: BPIE)

2.3.1. Clean Energy Package

At the heart of the European Union's strategy to decarbonize the building sector is the Clean Energy Package, a comprehensive set of legislative measures introduced after 2020. This package plays a pivotal role in steering Europe towards a low-carbon economy by addressing key areas such as energy efficiency, the deployment of renewable energy sources, the advancement of smart building technologies, and the enhancement of consumer rights. A central focus of the package is to make buildings not only greener but also more integrated into the broader energy system, enabling them to act as active participants rather than passive energy consumers.

The Clean Energy Package fills significant regulatory gaps that previously hindered progress in building decarbonization and supports the EU's commitments under the Paris Agreement. It explicitly recognizes the vital role buildings play within the energy system, emphasizing their potential to generate, store, and manage electricity on-site. This legislative framework provides member states and stakeholders with the tools and incentives necessary to accelerate the renovation and modernization of Europe's vast building stock, thereby facilitating the transition to smart, flexible, and sustainable built environments.

Complementing EU policy initiatives, the World Green Building Council (WorldGBC) has emerged as a leading voice advocating for transformative action within the construction sector. In its influential report, *From Thousands to Billions*, the WorldGBC establishes ambitious, clear milestones to guide the industry's carbon reduction efforts. The report calls for all new buildings to achieve net-zero operational carbon emissions by 2030, while extending this target to cover the entire building stock—including existing buildings—by 2050. Meeting these goals will demand coordinated efforts that combine robust public policies, market incentives, and active engagement from construction industry professionals, designers, and developers.

To support this transition, governments are encouraged to develop long-term strategies that gradually implement regulations targeting both operational and embodied carbon emissions. This comprehensive approach acknowledges the importance of measuring and reducing emissions throughout a building's entire life cycle—from the extraction and processing of raw materials, through construction and operation, to eventual demolition or reuse. By embedding life cycle thinking into policy and practice, regulators can promote cleaner construction technologies, sustainable materials, and innovative design solutions that collectively drive down carbon footprints.

Achieving such ambitious objectives requires an aligned policy framework, informed by evolving scientific understanding and supported by market transformation initiatives. The integration of life cycle carbon accounting methods, such as Life Cycle Assessment (LCA) and frameworks like the London Energy Transformation Initiative (LETI), provides essential methodologies for quantifying and managing emissions. These tools empower designers, builders, and policymakers to identify carbon hotspots, evaluate trade-offs, and prioritize effective interventions in both new construction and renovation projects.

Ultimately, the Clean Energy Package, combined with global advocacy from organizations like the WorldGBC, sets the stage for a resilient and sustainable European building sector. This dual approach not only advances Europe's climate goals but also catalyzes innovation, economic growth, and improved quality of life through healthier, more energy-efficient, and future-ready buildings.

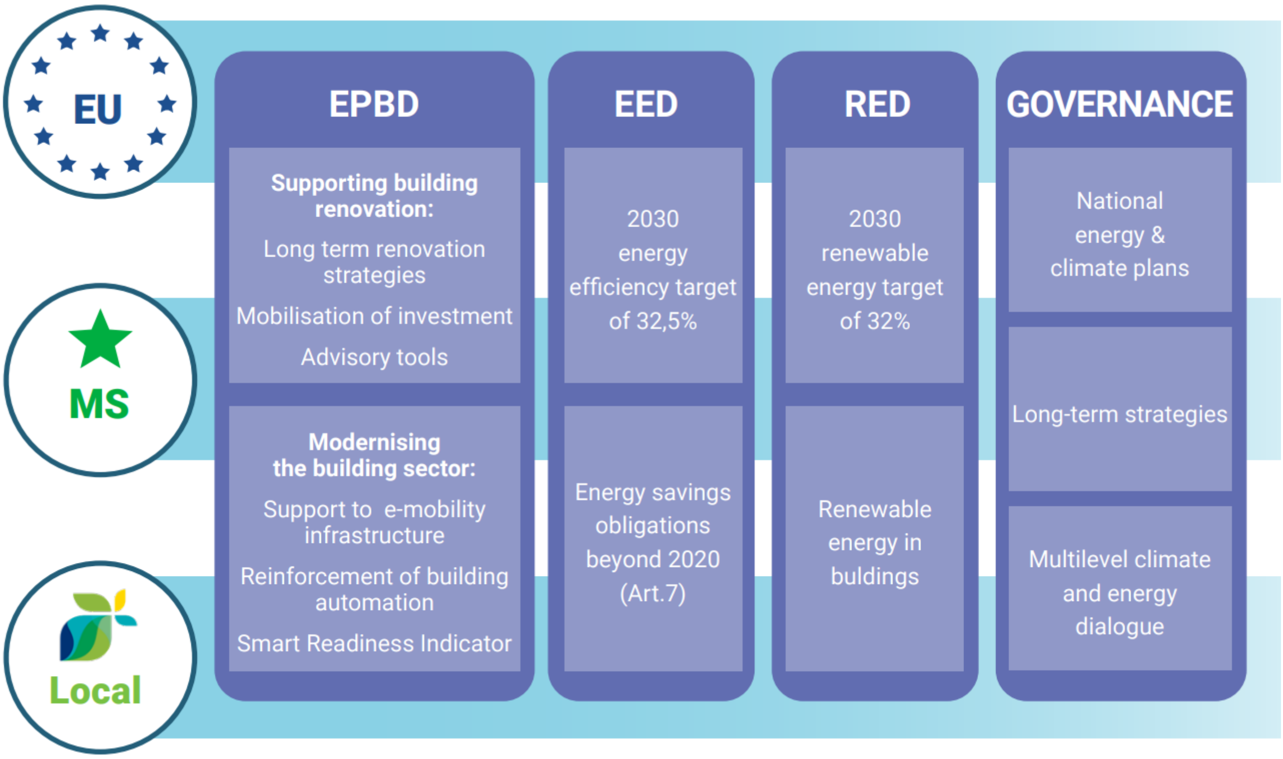


Figure 23. Clean Energy Package elements related to buildings (Source: BPIE)

2.3.2. Life Cycle Thinking in Policy and Standards

One of the most powerful tools shaping sustainable construction today is Life Cycle Assessment, or LCA. This method takes a full-picture view of a building's environmental impact, from the extraction of raw materials, through construction and use, all the way to demolition or recycling. Over the years, LCA has become a cornerstone in European Union strategies aimed at greening the construction sector.

Based on the analyses conducted (Benini 2022), it has been shown that the European Commission has embedded LCA into key policy frameworks such as the Integrated Product Policy, while regulations like EMAS (Eco-Management and Audit Scheme) and the EU Ecolabel actively encourage its use to boost sustainability across industries. On the standards front, international bodies like ISO and the European Committee for Standardization (CEN) have developed rigorous guidelines that bring clarity and consistency to environmental assessments in construction.

Standards such as ISO 15392 and EN 15804 serve as critical reference points for incorporating environmental, social, and economic factors into building practices. These frameworks underpin the creation of Environmental Product Declarations (EPDs), which transparently report the environmental footprint of construction materials. Across Europe, LCA and EPDs have gained widespread acceptance, helping architects, builders, and policymakers make smarter, data-driven decisions.

By offering a clear, science-backed way to measure and compare the sustainability of buildings and materials, LCA has become indispensable in the push for greener construction — ensuring transparency and driving the industry toward a low-carbon future.

2.3.3. Italy and the National CAM Criteria

In step with broader European ambitions, Italy has taken decisive action to green its construction sector through the adoption of key sustainability frameworks. Central to this effort is the CAM — *Criteri Ambientali Minimi* or Minimum Environmental Criteria — a set of mandatory guidelines for public works and procurement aimed at embedding environmental responsibility throughout the lifecycle of building projects.

The CAM underwent a significant update in 2022, strengthening its commitment to sustainability by fully integrating Life Cycle Assessment (LCA) principles. This means that public construction projects are now required to rigorously evaluate the environmental impacts of their materials and designs from cradle to grave — considering everything from raw material extraction, manufacturing, and construction to use, maintenance, and eventual disposal.

By tying public project awards to these stringent environmental benchmarks, the CAM fosters sustainable procurement practices that go beyond simple cost considerations. It aligns closely with European standards such as EN 15804, which defines the rules for environmental product declarations in construction, and EN 15978, which guides the assessment of the overall environmental performance of buildings.

Furthermore, the CAM encourages the adoption of tools like Level(s), the EU's harmonized framework for measuring and reporting sustainability across building projects. This linkage not only promotes transparency and comparability but also drives innovation by pushing manufacturers and designers to develop greener solutions.

Through these measures, Italy is positioning itself at the forefront of sustainable construction in Europe, ensuring that public investments support climate targets, stimulate market transformation, and hold all stakeholders accountable to higher environmental standards.

2.3.4. EU Taxonomy and LEVEL(S)

The European Union's legislative journey toward a greener economy was significantly advanced with Regulation (EU) 2020/852, known as the EU Taxonomy Regulation, later supplemented by Regulation (EU) 2021/2139. Together, these regulations establish a comprehensive classification system designed to identify which economic activities can be legitimately considered environmentally sustainable. This classification hinges on their alignment with the EU's ambitious climate and environmental goals, while simultaneously ensuring compliance with essential social safeguards.

Central to the Taxonomy's framework is a set of delegated acts, developed in close consultation with the Platform on Sustainable Finance , an expert advisory group tasked with refining the technical criteria. These acts rigorously define when an economic activity makes a substantial positive contribution to at least one of six environmental objectives, including climate change mitigation and adaptation, sustainable use of water and marine resources, transition to a circular economy, pollution prevention, and biodiversity preservation. Critically, the framework mandates adherence to the "Do No Significant Harm" (DNSH) principle, preventing activities that might undermine progress in any other environmental domain.

Annex I to Regulation (EU) 2021/2139 lays out the detailed technical screening criteria that guide the assessment of whether an activity significantly contributes to climate change mitigation or adaptation, while ensuring no collateral environmental damage occurs. This annex functions as a vital reference for policymakers, investors, and businesses alike, offering precise benchmarks against which economic activities can be measured.

The taxonomy's design facilitates multi-stakeholder utility:

- **Businesses** leverage it to evaluate their operational footprint, align strategic planning with sustainability imperatives, and enhance transparency in environmental reporting, fostering comparability and accountability.
- **Investors** integrate taxonomy criteria to screen portfolios, thus embedding environmental risk management and aligning capital flows with the EU's green transition.

- **Public institutions** employ the taxonomy to refine policy instruments and funding mechanisms that accelerate the ecological transition across member states.

Under Article 8 of Regulation (EU) 2021/2139, organizations falling under the scope of the Non-Financial Reporting Directive (NFRD), soon to be expanded under the Corporate Sustainability Reporting Directive (CSRD), are mandated to disclose detailed information on their taxonomy alignment. This includes quantifiable data such as the share of revenue, capital expenditures (CapEx), and operational expenditures (OpEx) linked to sustainable activities, promoting a high degree of transparency.

Focus on Construction and Real Estate: Chapter 7

Chapter 7 of Regulation (EU) 2021/2139 specifically targets the construction and real estate sector, a critical arena for achieving EU climate ambitions given its substantial environmental footprint. This chapter addresses several core themes:

- Making a substantial contribution to climate change mitigation
- Upholding the DNSH principle
- Facilitating climate change adaptation
- Promoting sustainable water and marine resource use
- Driving the transition toward a circular economy
- Preventing and reducing pollution
- Protecting and restoring biodiversity and ecosystems

A key technical criterion underpinning climate mitigation effort is the calculation and disclosure of the Global Warming Potential (GWP) across a building's entire life cycle, in accordance with the EU's Level(s) framework, specifically Indicator 1.2. For buildings exceeding 5,000 square meters, the life cycle GWP, including emissions from material production, construction processes, use, and end-of-life, must be rigorously calculated and disclosed to investors and stakeholders upon request.

The GWP metric is expressed in kilograms of CO_2 equivalent per square meter of internal usable floor area per year (kg $CO_2e/m^2/yr$), averaged over a 50-year reference period. This standardization promotes comparability across projects and facilitates long-term environmental performance assessment. The methodology for this calculation adheres strictly to EN 15978 (BS EN 15978:2011), the internationally recognized standard for environmental performance assessment of buildings. EN 15978 outlines how to scope building elements and technical systems to ensure consistent embodied carbon accounting, an approach fully integrated within the Level(s) framework.

Level(s) represents the European Commission's voluntary, yet foundational, framework establishing harmonized sustainability indicators for residential and office buildings. It is explicitly designed to drive measurable improvements in environmental performance across the building sector at scale.

By defining clear, science-based sustainability metrics, Level(s) aims to foster a common understanding and reporting language among policymakers, developers, designers, and investors. Its indicators cover a comprehensive range of environmental and social dimensions, enabling stakeholders to holistically assess building impacts throughout their entire life cycle—from design and construction to operation and eventual deconstruction.

Level(s) thereby plays a pivotal role in aligning building practices with the EU Green Deal, Circular Economy Action Plan, and overarching climate targets. Its systematic approach supports market transformation by incentivizing sustainable design choices, material efficiency, and occupant well-being, ultimately embedding sustainability as a core value in European construction.

Level(s) provides a series of common indicators and parameters to measure the sustainability performance of buildings throughout their life cycle, evaluating the following aspects:

- Environmental performance: This includes the building's impact on the environment, such as energy consumption, resource use, water consumption, and emissions, particularly focusing on embodied carbon and operational energy efficiency.
- Health and well-being: This refers to the building's impact on the health, comfort, and overall well-being of its occupants, considering factors such as air quality, lighting, acoustics, and thermal comfort.
- Cost and life-cycle value: This refers to the total cost of a building over its entire life cycle, from construction to operation, maintenance, and end-of-life stages. It helps to evaluate the long-term financial impact and return on investment, considering the environmental savings and potential for energy efficiency.
- Potential risks for future performance: This aspect assesses the building's resilience to potential environmental, technological, and operational risks in the future. It ensures that the building remains sustainable and adaptable to evolving standards and conditions over time.

The Level(s) framework offers a structured approach to assessing building sustainability through six macro-objectives, each defined by specific performance indicators with clear units of measurement. The first macro-objective focuses on greenhouse gas and air pollutant emissions over a building's life cycle. It includes indicators like *use stage energy performance*, measured in kilowatt-hours per square meter per year (kWh/m^2/yr), which tracks how much energy a building consumes during operation. Alongside this, the *life cycle Global Warming Potential* (kg CO_2 equivalents per square meter per year) quantifies the total greenhouse gas emissions generated throughout the building's lifespan. These metrics provide a crucial baseline to reduce carbon footprints and comply with EU climate targets.

The second macro-objective centers on resource efficiency and circular material life cycles. It evaluates the amount and lifespan of materials used through a bill of quantities, considering unit quantities, mass, and years. Additionally, construction and demolition waste is quantified per square meter of usable floor area, helping to monitor and minimize waste generation. Two design-oriented indicators assess how well buildings accommodate adaptability for renovation and potential for deconstruction, reuse, and recycling, each scored to encourage circularity in building design and material use. This objective supports the EU's circular economy goals by promoting sustainable material management throughout the building's life.

Addressing water resource efficiency, the third macro-objective measures *use stage water consumption* in cubic meters per occupant annually. Efficient water use is critical given increasing water scarcity concerns across Europe. This objective is part of a broader full Life Cycle Assessment (LCA), which covers ten environmental impact categories related to energy, materials, and water use, offering a comprehensive view of a building's environmental footprint from construction to end-of-life.

The fourth macro-objective tackles healthy and comfortable indoor environments. It tracks indoor air quality by monitoring key parameters such as ventilation rates, CO_2 levels, humidity, and the presence of pollutants including total volatile organic compounds (TVOCs), formaldehyde, mold, benzene, and radon. Additionally, indicators assess thermal comfort by measuring the percentage of time temperatures fall outside comfort ranges during heating and cooling seasons. Lighting and acoustics are also evaluated through checklist-based assessments, ensuring that buildings provide occupants with safe, comfortable, and productive environments.

Recognizing the increasing risks posed by climate change, the fifth macro-objective evaluates adaptation and resilience. It projects future occupant health and thermal comfort risks by estimating the percentage of time temperatures may be outside comfortable ranges by 2030 and 2050. Emerging checklists under development focus on the building's vulnerability to extreme weather events and flooding, enabling designers and planners to future-proof buildings against climate-related hazards and safeguard occupant well-being.

Finally, the sixth macro-objective emphasizes optimized life cycle costs and value creation. It quantifies the economic dimension by calculating life cycle costs in euros per square meter per year, allowing stakeholders to understand long-term financial implications. A complementary checklist addresses value creation and risk exposure, encouraging balanced decision-making that integrates environmental, social, and economic considerations to maximize sustainable investment returns.

Together, these six macro-objectives, backed by a detailed set of indicators, form a comprehensive toolkit for evaluating the sustainability performance of buildings throughout their entire life cycle. This holistic approach supports the EU's ambition to promote greener, healthier, and more resilient buildings while fostering circularity and economic viability in the construction sector.

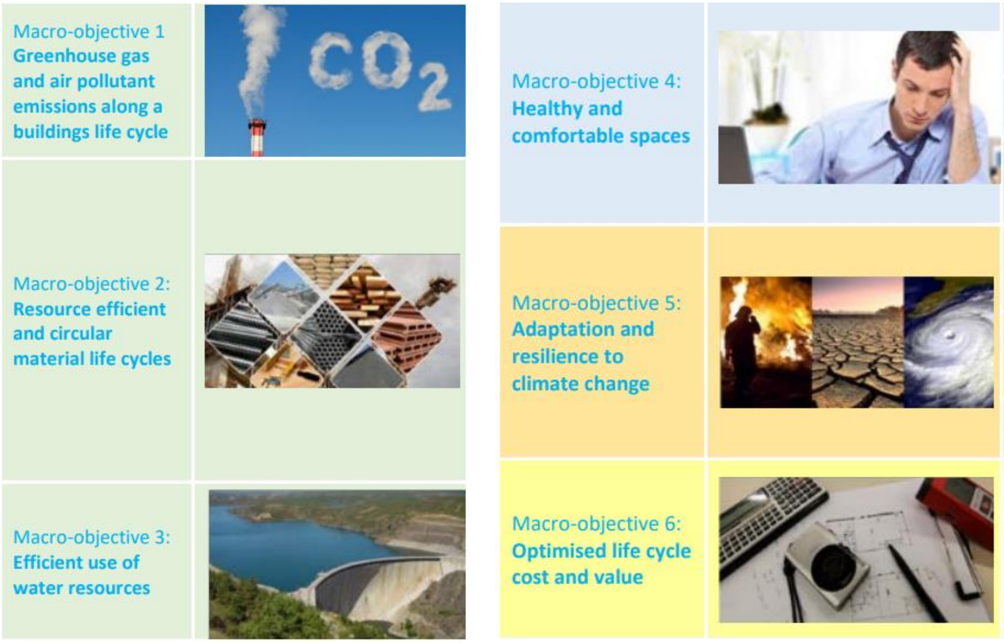


Figure 24. The six macro-objectives of Level(s)

Each indicator has specific metrics and guidelines for calculation, ensuring that the sustainability of buildings is measured consistently and transparently. By using these indicators, stakeholders can assess the environmental impact of buildings at various stages of their lifecycle, from design to operation and deconstruction, contributing to more sustainable construction practices across Europe.

Macro-objective	Indicators	Unit of measurement
1: Greenhouse gas and air pollutant emissions along a building's life cycle	1.1 Use stage energy performance	kilowatt hours per square meter per year (kWh/m2 /yr
	1.2 Life cycle Global Warming Potential	kg CO2 equivalents per square meter per year (kg CO2 eq./m2/yr
2. Resource efficient and circular material life cycles	2.1 Bill of quantities, materials and lifespans	Unit quantities, mass and years
	2.2 Construction & demolition waste and material	kg of waste and materials per m2 total useful floor area
	2.3 Design for adaptability and renovation	Adaptability score
	2.4 Design for deconstruction, reuse and recycling	Deconstruction score
3. Efficient use of water resources	3.1 Use stage water consumption	m3/yr of water per occupant
1-3. Full LCA	n/a	10 impact categories
4. Healthy and comfortable spaces	4.1 Indoor air quality	Parameters for ventilation, CO2 and humidity Target list of pollutants: TVOC, formaldehyde, CMR VOC, LCI ratio, mold, benzene, particulates, radon
	4.2 Time outside of thermal comfort range	% of the time out of range during the heating and cooling seasons
	4.3 Lighting and visual comfort	Level 1 checklist
	4.4 Acoustics and protection against noise	Level 1 checklist
5. Adaptation and resilience to climate change	5.1 Protection of occupier health and thermal comfort	Projected % time out of range in the years 2030 and 2050 (see also indicator 4.2)
	5.2 Increased risk of extreme weather events	Level 1 checklist (under development)
	5.3 Increased risk of flood events	Level 1 checklist (under development)
6. Optimized life cycle cost and value	6.1 Life cycle costs	Euro per square meter per year (€/m2/yr)
	6.2 Value creation and risk exposure	Level 1 checklist

Table1. Overview of the macro-objectives and their corresponding indicators and units of measurement

Level(s) adopts a sustainability approach to buildings based on the entire lifecycle. To fully support this approach, the main indicators for macro-objectives 1, 2, and 3 are integrated with a global environmental impact assessment of a building, which means a complete Life Cycle Assessment (LCA) of a building. Developing an LCA allows for quantifying the environmental impacts associated with a building and identifying and leveraging the most significant areas, commonly referred to as "critical points," as a starting point for improving performance.

To ensure consistency in assessing the environmental impact of buildings, Level(s) defines a standardized scope of building components. This system outlines the parts of a building that must be considered during performance assessment. Crucially, it excludes any construction products installed directly by occupiers, keeping the focus on structural and service-related elements integrated during the construction phase. The building is broken down into key parts such as the Shell, Core, and External Works. Each part contains associated elements that contribute to the overall environmental footprint, from foundational piles and facade systems to heating, ventilation, and lighting systems.

Building Part	Related Building Elements
Shell (Substructure and Superstructure)	**Foundations (Substructure):** Piles, basements, retaining walls **Load-bearing Frame:** Columns, beams, slabs, upper floors, external walls, balconies **Non-load-bearing Elements:** Ground floor slab, internal walls/partitions/doors, stairs and ramps **Facades:** External wall systems, cladding, shading devices, facade openings (windows, external doors), external paints and coatings **Roof:** Structure and weatherproofing **Parking Facilities:** Above-ground and underground within building curtilage
Core (Fittings, Furnishings, Services)	**Fittings and Furnishings:** Sanitary fittings, cupboards, wardrobes, worktops (in residential settings) Ceilings, wall/ceiling finishes, floor coverings **Lighting System:** In-built light fittings, sensors, control systems **Energy Systems:** Heating/cooling plants and distribution, electricity generation/distribution **Ventilation System:** Air handling units, ductwork **Water Systems:** Cold/hot water distribution, water treatment, drainage **Other Systems:** Lifts, escalators, fire safety systems, telecoms, data, security and communication systems
External Works	Utility connections and diversions, substations and equipment, landscaping, paving and hard surfaces, fencing, railings, walls, drainage systems

Table2. Scope of Building Parts and Related Elements

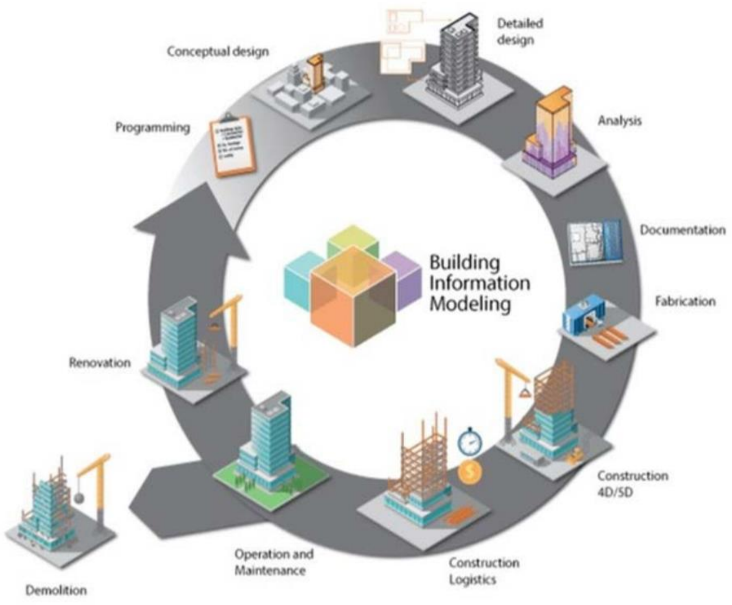
Macro-objectives 1-3: **Full Life Cycle Assessment (LCA)**	**Cradle to grave Life Cycle Assessment (LCA): Impact categories**
	– Climate change – Ozone depletion – Acidification – Eutrophication aquatic freshwater – Eutrophication aquatic marine – Eutrophication terrestrial – Photochemical ozone formation – Depletion of abiotic resources - minerals and metals – Depletion of abiotic resources – fossil fuels – Water use

Figure 26. Environmental macro-objectives and the Life Cycle Assessment (LCA) indicators

The conventional approach to (LCA), which involves compiling Environmental Product Declarations (EPDs) for all materials, is hampered by inconsistencies in data completeness. Indeed, as evidenced by Michelucci's (2022-2023) extensive analyses and findings from other researchers, the aspiration for comprehensive LCA results remains challenged by current EPD limitations. For instance, a thesis by Del Rosario (2020), specifically examining EPD utilization in office building LCA, identified significant informational gaps. Out of roughly 30 labels sampled, indicators for product use conditions were often missing (appearing in only 30% of EPDs), with similar deficiencies for phase C1 data (also 30%). Moreover, only 70% of the EPDs analyzed provided more phases than the standard cradle-to-gate requirement. Consequently, the Ministero dell'Ambiente e della Sicurezza Energetica (2021) points out, "The obvious consequence is that the ability to obtain a complete LCA through LCA-based environmental labels is still a distant goal."

Figure 27. Circular Economy vs Linear Economy

Michelucci's (2022-2023) analysis of circular economy principles highlights a fundamental paradigm shift from product ownership to service provision. This perspective posits that the core inquiry for both consumers and producers should be reframed: rather than seeking to acquire a physical product (e.g., a bedside lamp), the focus ought to be on fulfilling the underlying need (e.g., requiring illumination). This reorientation encourages manufacturers to develop and offer durable, long-term services, thereby extending product utility and lifespan, in contrast to the prevailing model of producing short-lived goods.

To operationalize this vision and align material procurement with circular economy tenets, several established recommendations can be followed (The Plan, 2023):

- **Buy-Sell Back Systems:** This model involves the original producer repurchasing a product from the consumer at the end of its initial use phase. For instance, a computer manufacturer might evaluate and buy back a used device, facilitating its reintegration into the value chain.
- **Buy-Resell Systems:** In this scenario, a third-party entity acquires the used product and subsequently reintroduces it to the market, thereby extending its useful life through reuse. The second-hand clothing market provides a clear illustration of this model.
- **Product Service Systems (PSS):** This business model retains product ownership with the manufacturer, who then "rents" or leases the product to the consumer. This incentivizes the producer to design for durability, maintenance, and eventual recovery, as the product's ongoing performance generates revenue.

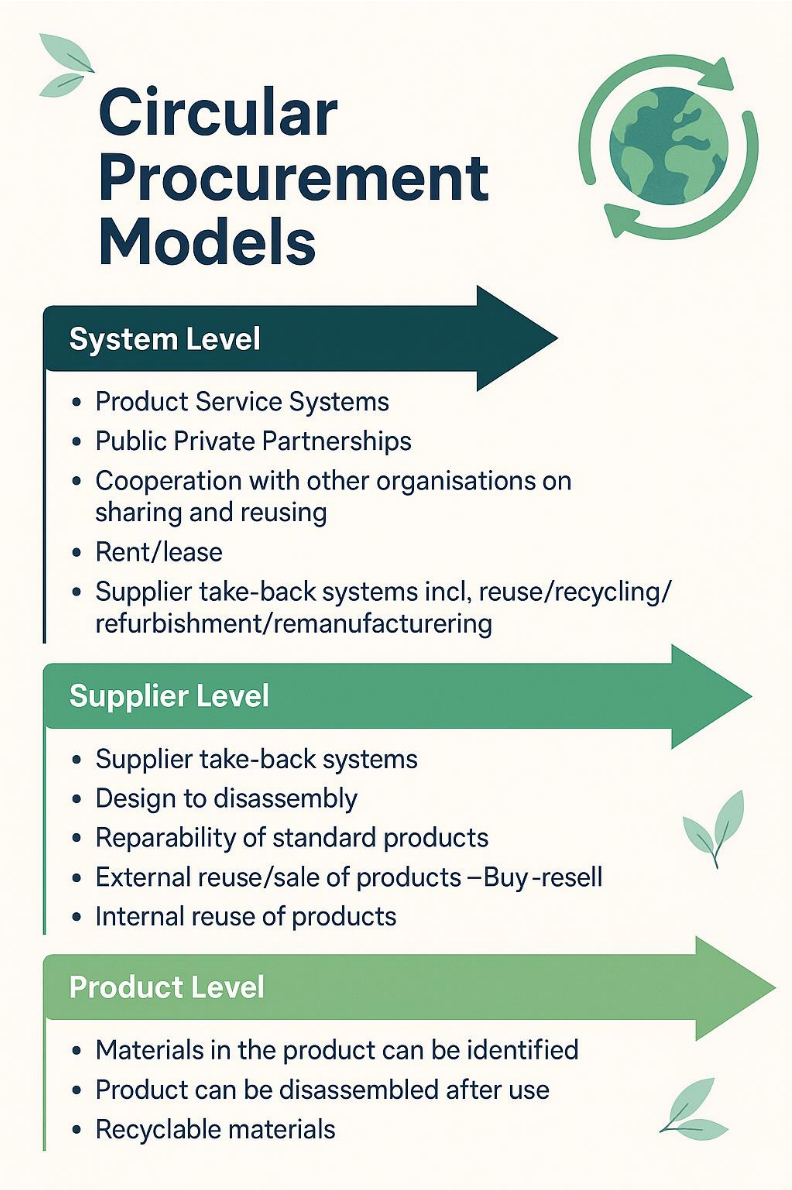


Figure 28. Procurement and various levels of intervention

This virtuous cycle can significantly reduce the embodied carbon emissions of materials in the A1-A3 phase. However, the key is to promote recycling and the recovery of products at the end of their life. Italy is not too negative on this issue, as highlighted by the analysis conducted by the Foundation for Sustainable Development.

2.4. Compensation strategies

The complex landscape of climate change mitigation necessitates a dual approach: direct emission reductions paired with strategic compensation efforts. In her comprehensive analysis, Michelucci (2022-2023) delves into these crucial aspects, revealing both the potential and pitfalls of current strategies.

Michelucci's findings highlight that while tree planting is vital in the fight against climate change, acting as natural carbon sinks, absorbing CO_2, and fostering biodiversity, it isn't a standalone solution. Forests undeniably purify air and stabilize ecosystems, yet reforestation alone cannot fully counteract the broader environmental consequences of human activity.

Her research also underscores the environmental benefits of using timber as a building material. Trees capture carbon during their lifetime, and this carbon remains stored even after harvesting and use in construction. When sourced from responsibly managed forests, wood significantly contributes to both sustainable architecture and long-term carbon storage. However, Michelucci emphasizes that true progress depends on broader systemic change: improving energy efficiency, rethinking industrial processes, embracing circular economy principles, and managing resources more sustainably.

This integrated approach, becomes particularly relevant within the framework of international agreements like the Kyoto Protocol. Signed in 1997, the Protocol introduced mechanisms such as the Clean Development Mechanism (CDM). This allowed countries and companies to offset emissions by investing in certified environmental projects that generated tradable carbon credits. This system effectively enabled the "balancing" of emissions through initiatives like reforestation or renewable energy development. A particularly radical idea of the CDM, as noted by Michelucci, was the notion that carbon emissions and reductions don't need to occur in the same place; the global outcome is what truly matters. This opened new avenues for international cooperation, for instance, a European company offsetting emissions by funding a solar power project in Africa.

Beyond trees, Michelucci's analysis confirms that compensation strategies are diverse. They include restoring degraded ecosystems, modernizing farming and livestock practices, developing carbon capture technologies that convert CO_2 into useful materials, and investing in cleaner energy systems. Together, these efforts aim to reduce humanity's environmental footprint and foster global collaboration towards a low-carbon future.

However,it is also critically examined concerns regarding the implementation of these compensation mechanisms. While they can contribute to climate action, they are not a substitute for deeper, structural reforms. As various sustainability experts confirm (ArchDaily, ARPA Lombardia, BREEAM, 2024), genuine transformation demands a fundamental re-evaluation of how we produce, consume, and build. Compensation might buy time, but it doesn't address the root causes of the problem.

One of the significant flaws in carbon markets, according to Michelucci, is that the price of CO_2 is determined by market demand rather than the actual cost of mitigating emissions. It often proves more economical for companies to purchase carbon credits than to invest in cleaner technologies or halt polluting operations. This economic logic was part of the CDM's rationale: facilitating a green transition without triggering major economic shocks, especially in emerging economies. The idea was that lower-income nations could reduce emissions more affordably, benefiting both the environment and global equity.

Nevertheless, critics like Professor Kevin Anderson from the University of Manchester, warn that this model can backfire. As long as polluters can effectively "neutralize" their emissions by paying for offsets, they may lack sufficient incentive to reduce them directly. This reliance on offsets risks solidifying the status quo instead of promoting meaningful change.

Furthermore, report highlights the persistent issue of accountability. The promised environmental benefits of carbon offset projects are frequently theoretical until measured post-implementation, and all too often, the actual results fall short. A major controversy in early 2023, where an investigation revealed that approximately 94% of rainforest offsets certified by Verra were essentially worthless, starkly illustrates this point; many projects failed to deliver promised reductions.

Michelucci's comprehensive assessment underscores a broader truth: the world of carbon offsets is still maturing, lacking consistent standards, effective regulation, and full transparency. While compensation initiatives offer potential pathways to lower net emissions, they cannot replace the urgent need for direct, structural reductions in carbon output. The ultimate solution, she concludes, lies in a strategic combination of immediate emission cuts and thoughtful, genuinely verified programs that contribute to restoring the planet’s balance.

2.5. The Future of Whole Life Carbon

While a building's operational energy demand remains substantial, ongoing advancements in energy efficiency and the projected decarbonization of national grids have led the Green Building Council to predict a significant rebalancing of carbon footprints. Between 2020 and 2050, over 50% of the total carbon emissions from all new buildings globally are anticipated to be attributable to embodied carbon.

There's a clear trend towards reducing embodied carbon, but its rate of decrease lags behind that of operational energy consumption, which has benefited from more extensive study and mitigation strategies. Consequently, an increasing percentage of a building's total emissions is now associated with its materials and construction processes. This phenomenon is vividly depicted in comparative analyses, such as the breakdown of emissions for a baseline office versus its near-future counterpart (as illustrated in a hypothetical "graph below" or "Figure X" in the original thesis). This trend underscores the growing importance of addressing embodied carbon, as improvements in energy efficiency alone may prove insufficient for long-term, significant emissions reductions.

Therefore, meticulous attention to all phases of a building's life cycle, extending beyond just energy-related aspects, is paramount. This necessitates intelligent decisions from the initial design stage, particularly concerning the selection of low-impact materials. These deliberate choices are crucial steps in the transition towards a more sustainable built environment. Further emphasizing this point (referencing a "Figure 25" in the original thesis), for office buildings, embodied carbon constitutes the largest share of overall emissions.

These collective insights highlight the increasing significance of addressing embodied carbon in tandem with operational carbon, with the ultimate objective being a comprehensive approach that effectively reduces both forms of emissions throughout the entire building lifecycle.

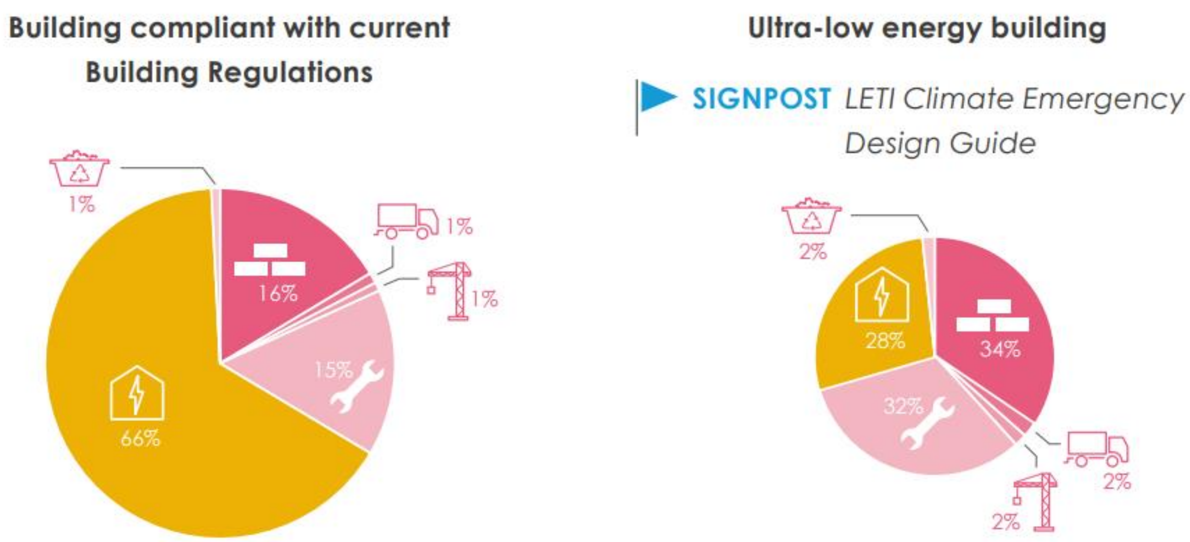


Figure 29. Breakdown of whole life carbon in further detail for typical office

The substantial efforts dedicated to understanding and optimizing emissions linked to a building's energy consumption have been highly effective. Consequently, this thesis shifts its focus to investigating strategies for reducing embodied carbon, the emissions associated with a building's materials, construction processes, and end-of-life phases.

Unlike operational carbon, which has been a primary target for mitigation, embodied carbon often presents greater challenges in both quantification and reduction. This complexity stems from the diverse range of materials involved and the intricate nature of modern construction methods. By thoroughly examining these aspects, this research aims to identify practical strategies and innovative solutions. The ultimate goal is to effectively lower the embodied carbon footprint, thereby contributing significantly to a building's overall environmental performance across its entire lifecycle.

2.5.1. Embodied Carbon Emissions: Goals and Benchmarks

One of the most significant challenges the construction industry faces is the lack of precise information regarding product emissions (EPD - Environmental Product Declaration) and the difficulty in adopting uniform methodologies for measuring embodied carbon emissions. The absence of standardized benchmarks and design goals at the European level makes it difficult for industry professionals to make informed decisions about material selection and construction processes.

While buildings are recognized as key elements for energy flexibility through production, control, and storage of energy, it is equally important that energy efficiency and the adoption of smart technologies are promoted as crucial measures for creating a decarbonized energy system. However, despite progress in optimizing the energy efficiency of buildings, the construction sector must also tackle the challenge of reducing carbon emissions related to materials and construction processes, as these are becoming a growing part of global emissions.

A key fact is that to meet decarbonization goals by 2050, it is essential to renovate and modernize the existing building stock, given that only 1% of buildings are renewed annually. Although Italian regulations have already introduced measures to reduce operational emissions, such as requiring a minimum percentage of renewable energy in Legislative Decree 8 November 2021, n. 199, there are still no defined constraints on embodied emissions.

This scenario highlights the need for a paradigm shift towards a "green building" approach with high performance. Leading certifications for high-energy efficiency buildings, such as LEED, BREEAM, and WELL, focus mainly on transparency regarding the materials used through the implementation of LCA (Life Cycle Assessment) analyses. However, these certifications do not set concrete goals for reducing embodied emissions, instead only requiring detailed reporting.

To achieve carbon neutrality, it is necessary to go a step further. One of the most advanced certifications in this regard is the Zero Carbon certification from the International Living Future Institute (ILFI), which sets a maximum limit for embodied emissions and requires them to be offset to reach zero emissions. This is currently the only viable path toward truly sustainable construction.

Moreover, steps are being taken towards the concept of regenerative architecture. This approach involves a conception of architecture that not only respects the environment but is also capable of regenerating and healing itself. It goes beyond merely not consuming material resources; it actively contributes to creating new resources, taking construction to a much more advanced level of sustainability (Michelucci, 2022-2023).

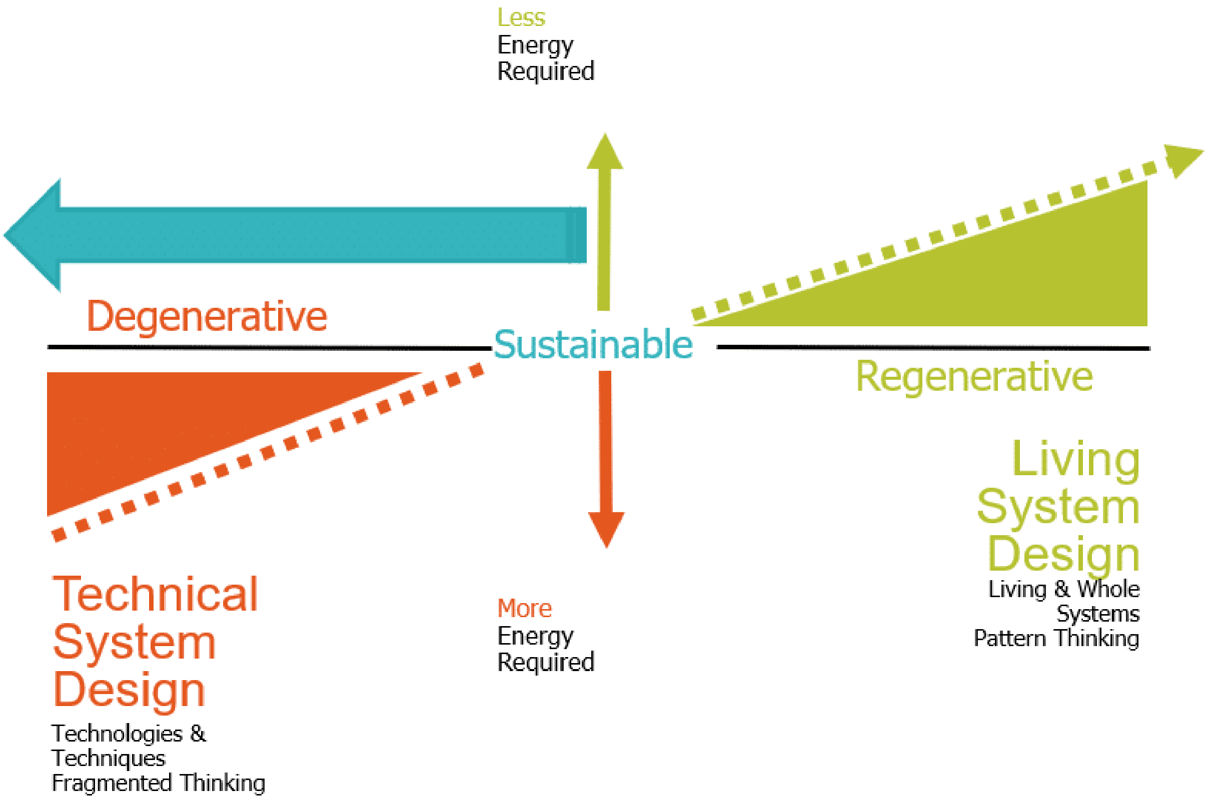


Figure 30. Regenerative design diagram

Regenerative buildings are designed and managed to reverse ecological damage and have a net positive impact on the natural environment. Interventions can include biomimicry to mimic nature, building envelopes that purify the air, structures that purify water, or architecture that captures carbon.

Shifting the focus from sustainable architecture to regenerative architecture will represent a better strategy for addressing the climate and biodiversity emergency facing today's society.

Regenerative architecture will allow the construction industry to "do good" rather than simply "do less harm."

Before analyzing the certifications that guide designers in the green direction, it's important to understand where we stand today in terms of embodied emissions and the technologies associated with them that shape the Italian baseline. Since the case study to be developed is for commercial and office buildings, the values for these types of buildings will be specifically provided. (Ferrari, A.2023/2024)

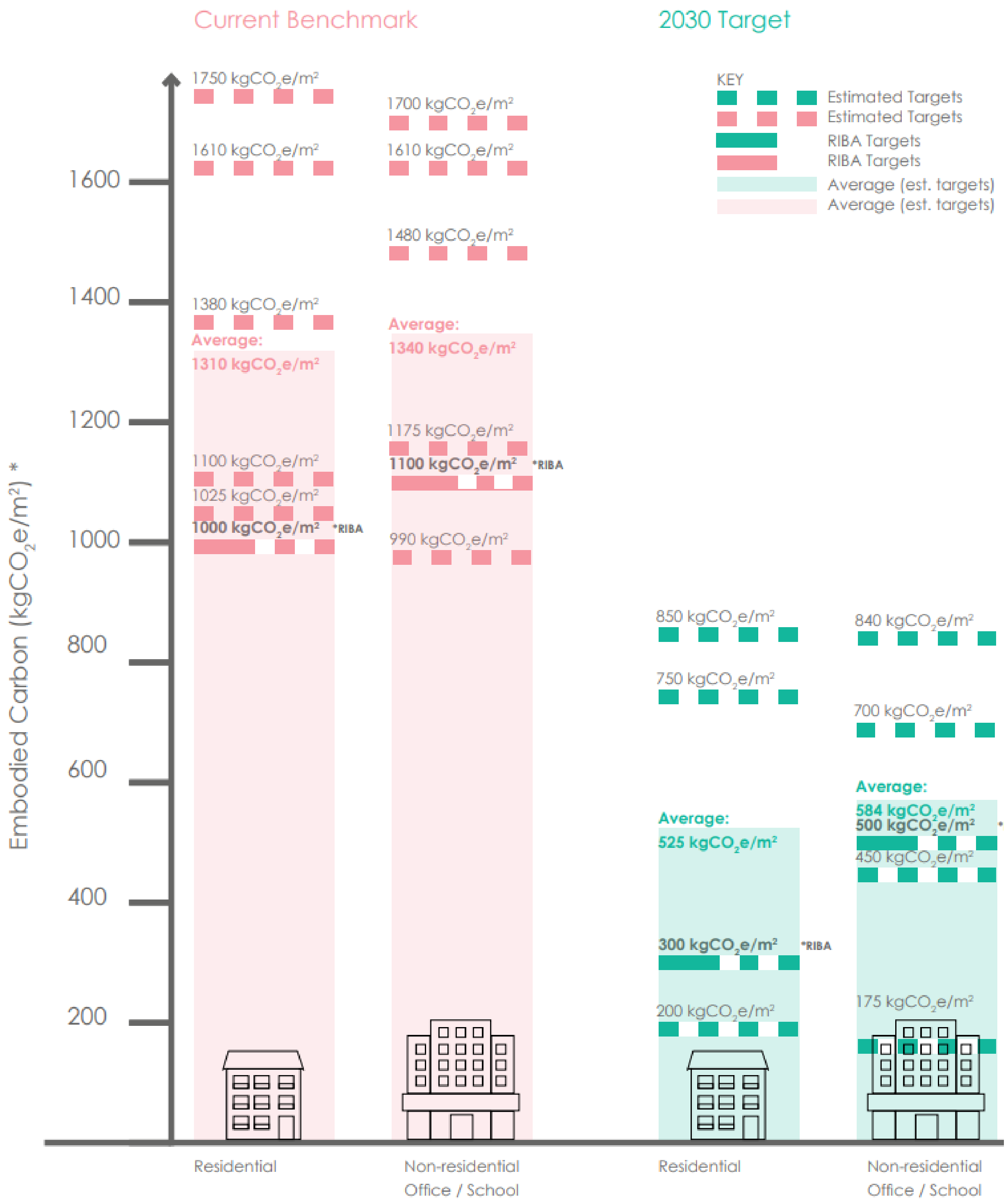


Figure 31. RIBA 2030 Climate Challenge Target benchmarks review

If we consider emissions over the entire lifecycle, the targets found by the Greater London Authority (GLA) should be cited, which set the maximum value at 850 kgCO2/m2 for the building's entire useful life (Divisare, 2021).

RIBA Sustainable Outcome Metrics	Business as usual (new build, compliance approach)	2025 Targets	2030 Targets	Notes
Operational Energy kWh/m²/y	130 kWh/m²/y DEC D (90)	< 75 kWh/m²/y DEC B (50) and/or NABERS Base build 5	< 55 kWh/m²/y DEC B (40) and/or NABERS Base build 6	Targets based on GIA. Figures include regulated & unregulated energy consumption irrespective of source (grid/renewables). 1. Use a 'Fabric First' approach 2. Minimise energy demand. Use efficient services and low carbon heat 3. Maximise onsite renewables
Embodied Carbon $kgCO_2e/m^2$	1400 $kgCO_2e/m^2$	< 970 $kgCO_2e/m^2$	< 750 $kgCO_2e/m^2$	Use RICS Whole Life Carbon (modules A1-A5, B1-B5, C1-C4 incl sequestration). Analysis should include minimum of 95% of cost, include substructure, superstructure, finishes, fixed FF&E, building services and associated refrigerant leakage. 1. Whole Life Carbon Analysis 2. Use circular economy strategies 3. Minimise offsetting & use as last resort. Use accredited, verifiable schemes (see checklist). BAU aligned with LETI band E; 2025 target aligned with LETI band C and 2030 target aligned with LETI band B.
Potable Water Use Litres/person/day	16 l/p/day (CIRA W11 benchmark)	< 13 l/p/day	< 10 l/p/day	CIBSE Guide G.

Figure 32. RIBA 2030 Climate Challenge target metrics for non-domestic (new build offices)

Finally, the very stringent targets outlined by LETI and RIBA to reach the 2030 objectives are summarized as follows:

Upfront Embodied Carbon, A1-5 (exc. sequestration)

	Band	Office	Residential (6+ storeys)	Education	Retail
	A++	<100	<100	<100	<100
	A+	<225	<200	<200	<200
LETI 2030 Design Target	A	<350	<300	<300	<300
	B	<475	<400	<400	<425
LETI 2020 Design Target	C	<600	<500	<500	<550
	D	<775	<675	<625	<700
	E	<950	<850	<750	<850
	F	<1100	<1000	<875	<1000
	G	<1300	<1200	<1100	<1200

Life Cycle Embodied Carbon, A1-5, B1-5, C1-4

	Band	Office	Residential (6+ storeys)	Education	Retail
	A++	<150	<150	<125	<125
	A+	<345	<300	<260	<250
	A	<530	<450	<400	<380
RIBA 2030 Design Target	B	<750	<625	<540	<535
	C	<970	<800	<675	<690
	D	<1180	<1000	<835	<870
	E	<1400	<1200	<1000	<1050
	F	<1625	<1400	<1175	<1250
	G	<1900	<1600	<1350	<1450

Figure 33. LETI 2030 Carbon Labelling System and Comparison with LETI 2020 and RIBA 2030 Design Targets ($kgCO_{2e}/m^2$)

These emissions have been analyzed in more detail, outlining the influence of each individual building element.

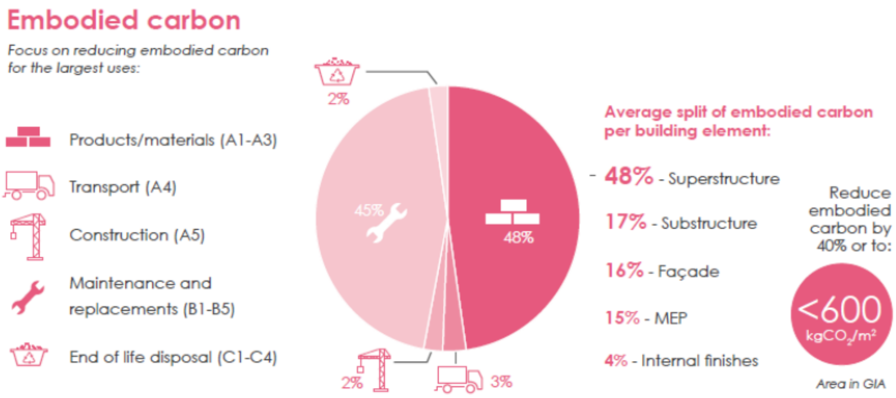


Figure 34. Embodied carbon in different phases of building life

It is interesting to see how LETI identifies the material production phases (A1-A3) and the replacement and maintenance phases (B1-B5) as the most problematic in terms of emissions. This could be related to the fact that replacement in a building open to the public occurs more frequently than in other types of buildings (for example, compared to a small single-family house), where emissions during the operational phase are significantly lower. It is also important to note that almost 65% of emissions typically come from the structures, making their optimization a primary focus. Another category to analyze and optimize will be the facade, which accounts for 16% of the up-front carbon, a "big ticket item." These values are derived from an international European average, and not specifically for the Italian context, but they help outline an indicative starting point.

This research evaluates a real-world case study office building across four design scenarios: Baseline, CAM-compliant, CLT-integrated.

Each scenario is assessed for its total embodied carbon emissions, with detailed breakdowns of building elements such as structure, envelopes, MEP systems, and finishes. The results are benchmarked against industry-leading standards, with particular attention to the **RIBA 2030 Climate Challenge target for offices (≤530 $kgCO_2e/m^2$).** This emphasis on holistic assessment aligns with the methodology proposed by Brizzi and Viero (2021) for net-zero carbon buildings.

3. Case study and tools

3.1. One Click LCA: Calculation Software

To conduct the Life Cycle Assessment (LCA) for the selected case study, the One Click LCA software was employed as the primary analytical tool. This platform is specifically designed to assess and minimize the environmental impact of buildings, infrastructure, construction materials, and products. It is widely used by architects, designers, manufacturers, consultants, and investors throughout all stages of design, construction, and production.

Figure 35. One Click LCA tool

One Click LCA supports over 80 international and regional green building certification systems aimed at achieving net-zero environmental impact. Among these are prominent frameworks such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and GRESB (Global Real Estate Sustainability Benchmark), among many others. Furthermore, the software adheres to a range of both international and national standards, including the Minimum Environmental Criteria (CAM), Level(s) the EU's sustainability reporting framework for buildings, and the EN 15978 standard for assessing the environmental performance of buildings.

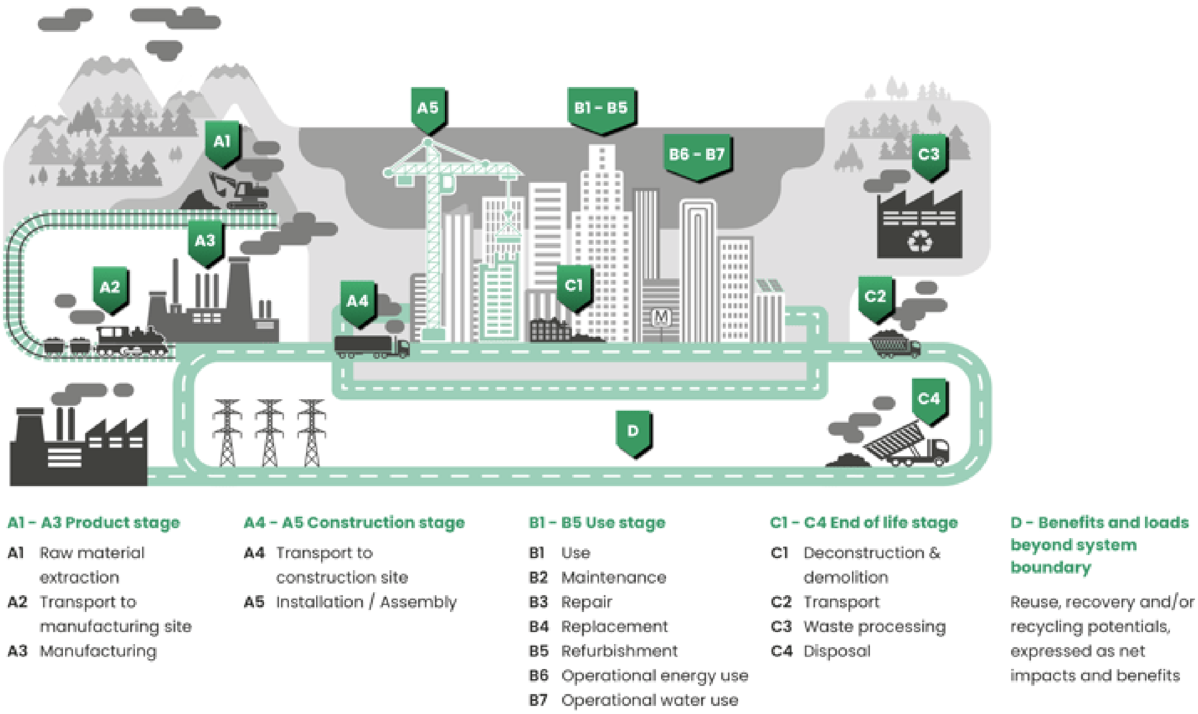


Figure 36. Phases that are covered in One click LCA

The software can address nearly all of the macro-objectives outlined in the Level(s) framework.

These objectives include:

- Reducing greenhouse gas emissions and atmospheric pollutants
- Promoting circular material life cycles and resource efficiency
- Ensuring efficient water usage
- Enhancing indoor environmental quality for health and comfort
- Supporting climate change adaptation and resilience
- Optimizing life cycle cost and value

With access to a certified database containing over 200,000 globally verified and up-to-date LCA (Life Cycle Assessment) and EPD (Environmental Product Declaration) records, One Click LCA serves as a comprehensive and credible resource. It integrates data from nearly all recognized EPD platforms worldwide.

For this thesis, the tool specifically employed was "Level(s) Life-Cycle Assessment (+A1 only)", which is suitable for Level(s) assessment levels 2 and 3. This tool enables detailed emissions calculations following the Level(s) guidelines through a series of procedural steps, including:

- Material Input: Quantities of materials were entered based on the project's bill of quantities (BoQ), referencing environmental data from the integrated EPD database or through manual input when necessary.
- Energy Consumption: Operational energy use figures were input into the system.
- Reference Period Setting: The time span for the life cycle assessment was defined as 50 years.
- Reference Floor Area: The gross floor area of the assessed building was entered to normalize impact values per unit area. here there are different type of area for buildings, we consider GIFA (Gross Internal Floor Area).

It is important to note that now there are EN 15804+A2 EPDs available in software but construction and architecture companies prefer to use +A1 only because:

- *"Due to the broader availability of EPDs and LCI datasets aligned with EN 15804+A1, this standard provides a more practical foundation for comprehensive and comparable product assessments in academic research."*
- *"To enable alignment with existing benchmarks and building certification systems, EN 15804+A1 offers a more suitable framework for comparative assessment."*
- *"The more concise indicator set of EN 15804+A1 allows for a focused and interpretable impact assessment that aligns with the scope of this academic research."*

- *"For continuity with existing academic literature and comparative purposes, the use of EN 15804+A1 maintains methodological alignment."*
- *"The practical implementation of EN 15804+A1 in major LCA tools ensures a stable and well-supported framework for data collection and analysis."*

The table outlines the categorization of building parts and their related building elements as used in One Click LCA tools for life cycle assessment (LCA) in construction projects. It organizes elements into key functional groups such as the shell (including both substructure and superstructure), core components, and external works. This classification supports accurate material and resource quantification by aligning with standardized construction frameworks. By systematically grouping structural, architectural, and technical systems, such as foundations, facades, MEP systems, and finishes, the table enables comprehensive environmental impact analysis and streamlines the LCA process within the One Click LCA software. This structured approach ensures consistency in data input and improves comparability across different building projects.

Building Part	Related Building Elements
Shell (Substructure & Superstructure)	
- Foundations (Substructure)	Piles, Basements, Retaining walls
- Load Bearing Structural Frame	Frame (beams, columns, slabs), Upper floors, External walls, Balconies
- Non-load Bearing Elements	Ground floor slab, Internal walls, Partitions and doors, Stairs and ramps
- Facades	External wall systems, Cladding, Shading devices, Façade openings (windows and external doors), External paints, coatings and renders
- Roof Structure	Weatherproofing
- Parking Facilities	Above ground and underground (within the curtilage of the building and servicing the building occupiers)
Core (Fittings, Furnishings and Services)	
- Fittings and Furnishings	Sanitary fittings, Cupboards, Wardrobes, Worktops (residential only)
- Finishes	Ceilings, Wall and ceiling finishes, Floor coverings and finishes
- Lighting System	In-built light fittings, Control systems, Sensors
- Energy System	Heating plants and distribution, Cooling plant and distribution, Electricity generation and distribution
- Ventilation System	Air handling units, Ductwork and distribution
- Sanitary Systems	Cold water distribution, Hot water distribution, Water treatment systems, Drainage system
- Other Systems	Lifts and escalators, Firefighting installations, Communication and security installations, Telecoms and data installations
External Works	
- Utilities	Connections and diversions, Substations and equipment
- Landscaping	Landscaping, Paving and other hard surfacing, Fencing, Railings and walls
- Drainage Systems	External drainage systems

Table 3. Level(s) minimum scope of building parts and elements

3.2. Case Study: Office Building

In this section, the selected case study is introduced to support the comparative analysis of structural material scenarios within a sustainability and environmental impact framework. The project has been chosen due to its representative characteristics as a mid-rise office building and its suitability for adaptation under varying structural design criteria.

The case study has been modeled as a commercial office building with five floors above ground and two underground levels, resulting in a total of seven stories. A rectangular footprint, regular column spacing, and efficient vertical circulation have been applied. Key characteristics of the building are summarized in Table 4.

Feature	**Specification**
Building Type	Office building
Total Floors	7 (5 above ground, 2 underground)
Gross Floor Area (GFA)	5,000 m^2
Gross Internal Floor Area (GIFA)	4,150 m^2
Building Height (Above Ground)	18 m
Internal Floor Height	3.3 m
Footprint Dimensions	44 m (width) × 18 m (depth)
Structural System	Beams, slabs, columns (CLT in final scenario)
Façade Type	Glass curtain wall
Assessment Period	50 years

Table 4. Summary of Building Characteristics

The design has been visualized in 3D using a sectional cutaway representation to depict all key architectural and technical systems. The façade has been modeled as a fully glazed curtain wall, and the internal components—such as partitions, vertical circulation, and service cores—have been carefully represented. A pile foundation system has been applied to support the substructure and two underground levels.

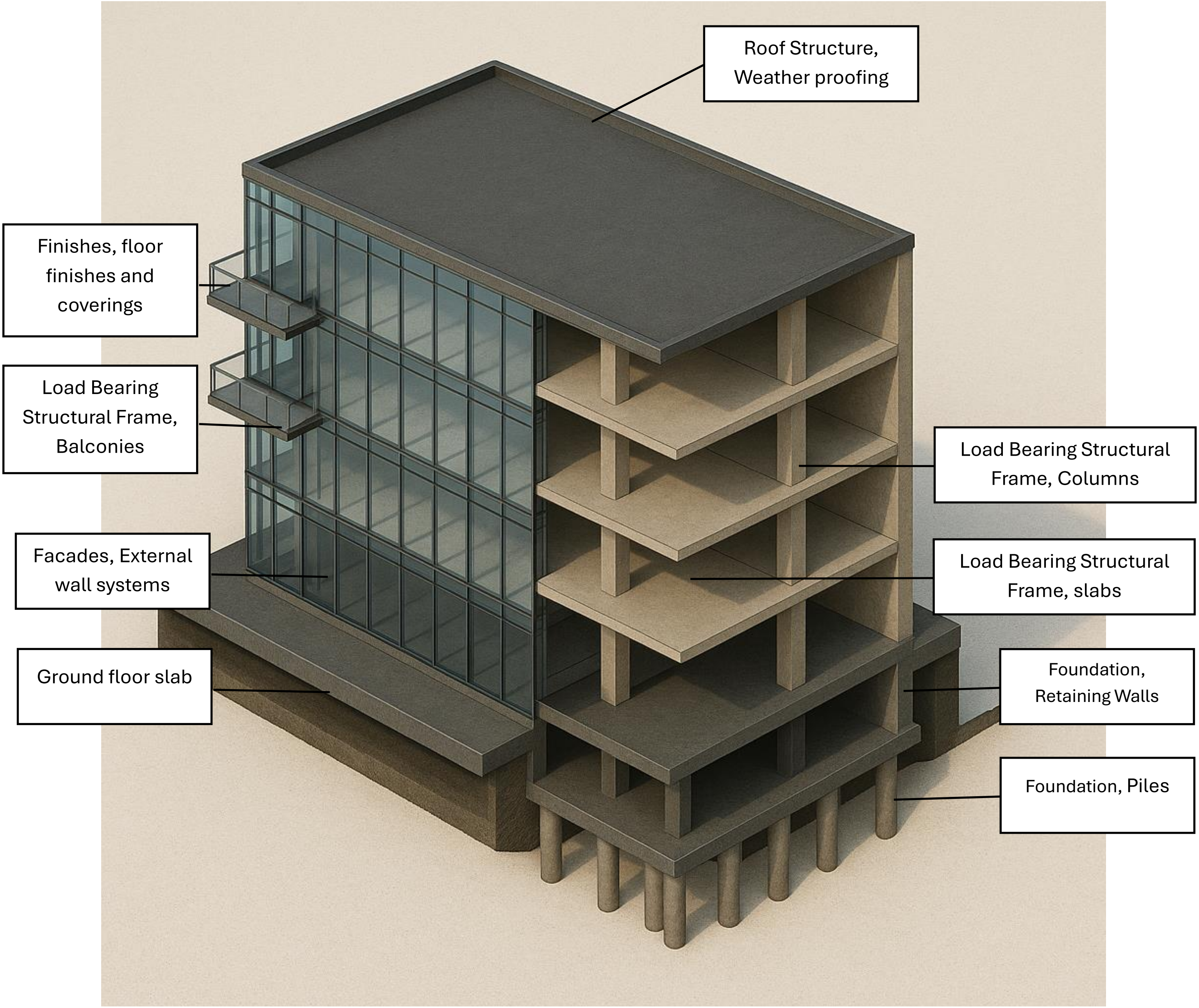


Figure 37. 3D Model of the building parts used in one click

3.2.1 Objective of the Comparative Analysis

To evaluate the environmental and structural performance of alternative material configurations, the case study has been modeled in three distinct design scenarios:

1. **Business-as-Usual (BAU):**

   A conventional structural configuration with concrete columns, slabs, and steel reinforcements, modeled without specific sustainability criteria.

2. **CAM-Compliant (Italy):**

   A version adapted to meet the **Minimum Environmental Criteria (CAM)**, as required by Italian procurement law. Recycled content and certified materials have been prioritized in the design of concrete and steel components.

3. **CLT Integration Scenario:**

   A timber-based version, where **Cross-Laminated Timber (CLT)** is introduced for the structural framework wherever feasible, primarily replacing concrete columns and internal elements.

Throughout all three scenarios, the geometry and spatial configuration of the building have been maintained consistently. This approach allows for an isolated analysis of material impact, particularly focusing on embodied carbon, regulatory compliance, and lifecycle performance.

3.2.2. Structural Scenarios Definition and Differentiation

To evaluate the environmental and material impacts of different structural strategies, the selected case study has been modeled across three distinct scenarios. These include a standard business-as-usual configuration, a model compliant with the Criteri Ambientali Minimi (CAM) as defined under Italian procurement legislation, and a low-carbon alternative that incorporates Cross-Laminated Timber (CLT) wherever feasible. The purpose of these scenarios is to enable a comparative analysis that emphasizes material composition, recycling content, and embodied carbon.

Each scenario retains the same architectural geometry and spatial distribution. All structural variations have been limited to foundations, vertical load-bearing elements, floor assemblies, and reinforcement specifications. As examined by Ferrari (2023-2024) detailed overview of material choices and specifications across the three scenarios is provided below.

Building Component	BAU	CAM-Compliant
Foundation – Retaining Walls	C30/37 concrete	C30/37 concrete, > 10% recycled
Foundation – Unreinforced Sub-foundations	C16/20 concrete	C16/20 concrete, >10% recycled
Foundation – Reinforced	C25/30 concrete	C25/30 concrete, >10% recycled
Steel Reinforcement (Foundations)	60% recycled	>80% recycled
Beams and Columns	C40/50 concrete	C40/50 concrete, >10% recycled
Reinforced Walls (e.g., stairwell)	C32/40 concrete	C32/40 concrete, >10% recycled
Steel Reinforcement (Superstructure)	60% recycled	>80% recycled
Floor Joists	C30/37 concrete	C30/37 concrete, >10% recycled
Floor Fill (Blocks)	Lightweight clay blocks	>10% recycled clay blocks
Façade Structure	Glass curtain wall	Glass curtain wall
Column Material	Reinforced concrete	Reinforced concrete
Recyclability and Environmental Credits	Limited	Optimized per CAM

Table 5. Structural Material Definition per Scenario

Key Scenario Highlights

- **BAU (Business-as-Usual)**

  A traditional reinforced concrete structure has been modeled, using standard European concrete classes and moderate levels of recycled steel (60%). This serves as a benchmark for environmental performance.

- **CAM-Compliant Scenario**

  All concrete types have been replaced with alternatives containing 10% recycled aggregates, in accordance with the Criteri Ambientali Minimi (CAM). Recycled steel reinforcement content has been increased to >80% and building blocks for floors have been partially replaced with >10% recycled material. This scenario reflects a real-world procurement-driven sustainability standard under Italian law.

- **CLT Scenario**

  In this configuration, all non-core vertical and horizontal load-bearing elements have been substituted with Cross-Laminated Timber (CLT) panels and columns where structurally viable. Reinforced concrete is still used for core walls (e.g., stairwells) and underground structures. This scenario prioritizes carbon sequestration and material renewability.

3.3. CLT Integration Strategy for the Case Study

In the third scenario investigated in this thesis, a hybrid concrete–CLT structural system was introduced as a potential alternative to the fully concrete configuration of the case study building. The use of Cross-Laminated Timber (CLT) was proposed where feasible, considering Italian seismic codes (NTC 2018), fire safety regulations, and structural performance requirements.

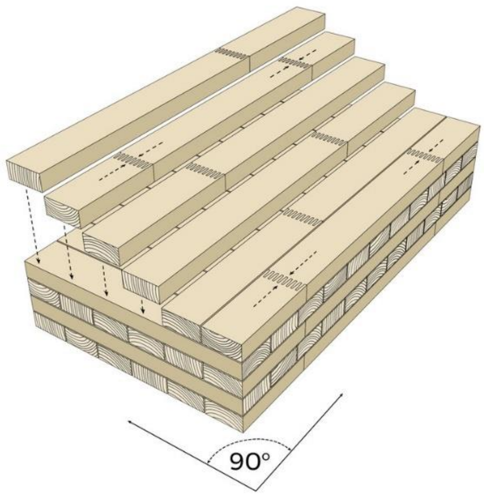


Figure 38. Cross-Laminated Timber (CLT)

The intervention was developed with the aim of minimizing the building's embodied carbon footprint while maintaining its original spatial configuration and functional use. Substitutions were proposed selectively—only where technical and regulatory conditions allowed for a safe and compliant replacement of reinforced concrete with engineered timber elements.

The selection of (CLT) as the primary structural material for the proposed office building is grounded in both environmental and technical performance considerations, particularly within the framework of Life Cycle Assessment (LCA) and Whole Life Carbon (WLC) evaluation. As the construction industry confronts increasing pressure to reduce embodied carbon and align with targets outlined in frameworks such as LETI, RIBA 2030, and Level(s), CLT emerges as a strategically appropriate material choice for achieving significant carbon reductions without compromising structural efficiency or design flexibility.

CLT, as a mass timber product, offers substantial advantages over conventional materials such as reinforced concrete, especially in terms of embodied carbon (A1–A3). Timber sequesters carbon during the growth phase of trees, and when harvested from sustainably managed forests, this carbon remains stored throughout the building's life cycle.

Numerous studies (e.g., Gagnon & Pirvu, 2011) have shown that substituting concrete with CLT can result in up to 30–50% reductions in embodied emissions. This is particularly relevant given that embodied carbon constitutes a growing share of total emissions in Nearly Zero Energy Buildings (nZEBs), where operational emissions are significantly minimized.

From a life cycle perspective, CLT also performs well in the construction (A5) and end-of-life (C1–C4) phases. It is lightweight, reducing transport emissions and construction energy demand, and offers high potential for reuse, recycling, or energy recovery, supporting circular economy principles emphasized in the EU Taxonomy and EN 15978. Additionally, the high prefabrication potential of CLT contributes to waste minimization and construction speed, aligning with low-impact construction goals.

Figure 39. Archdaily.com E2E Offices / 57STUDIO. Image © Roland Halbe

In terms of indoor environmental quality, CLT contributes to biophilic design and can positively influence occupant well-being—an aspect indirectly relevant to the social sustainability component outlined in EN 15643. Structurally, modern CLT assemblies meet fire, seismic, and acoustic performance requirements when properly detailed, making them viable for mid-rise office construction.

Given the emphasis of this thesis on embodied carbon reduction through LCA, and the critical role that material choices play in achieving climate targets, the use of CLT not only reflects a low-carbon design strategy but also reinforces the alignment of the project with both voluntary sustainability benchmarks and regulatory trajectories. Thus, the integration of CLT in the proposed design serves as a robust and forward-thinking solution in the transition toward carbon-neutral and regenerative architecture.

3.3.1. Elements Retained in Reinforced Concrete

Certain structural components were retained in concrete due to their critical roles in load-bearing stability, fire resistance, and exposure to moisture or aggressive conditions. These included:

- **Floor slabs**, which were maintained in concrete based on structural continuity and fire compartmentation needs.
- **Foundations**, where direct soil contact and bearing capacity requirements dictated the use of reinforced concrete.
- **Stairwells and elevator shafts**, where core stiffness and fire rating compliance necessitated concrete construction.
- **Exposed balconies**, typically retained for waterproofing and thermal bridging considerations.
- **Structural beams**, which were left in concrete for load transfer continuity and to reduce complexity in the redesign.

These retained elements continued to represent the majority of the overall structural volume, particularly in the case of slabs and foundations.

3.3.2. Elements Converted to CLT

CLT was introduced selectively in the following building components:

- **Internal load-bearing walls** were replaced with CLT panels of sufficient thickness to meet fire and acoustic requirements, offering both vertical support and bracing capacity.
- **Shear walls**, where feasible, were redesigned using CLT to contribute to lateral load resistance while respecting seismic performance criteria.
- **Non-core columns**, particularly those in open plan or edge zones, were substituted with CLT columns to reduce embodied emissions while maintaining stiffness and fire safety standards.
- **Slabs**, in part, were redesigned as hybrid systems combining CLT panels with a thin concrete topping, allowing for integration of services and enhancing fire resistance.

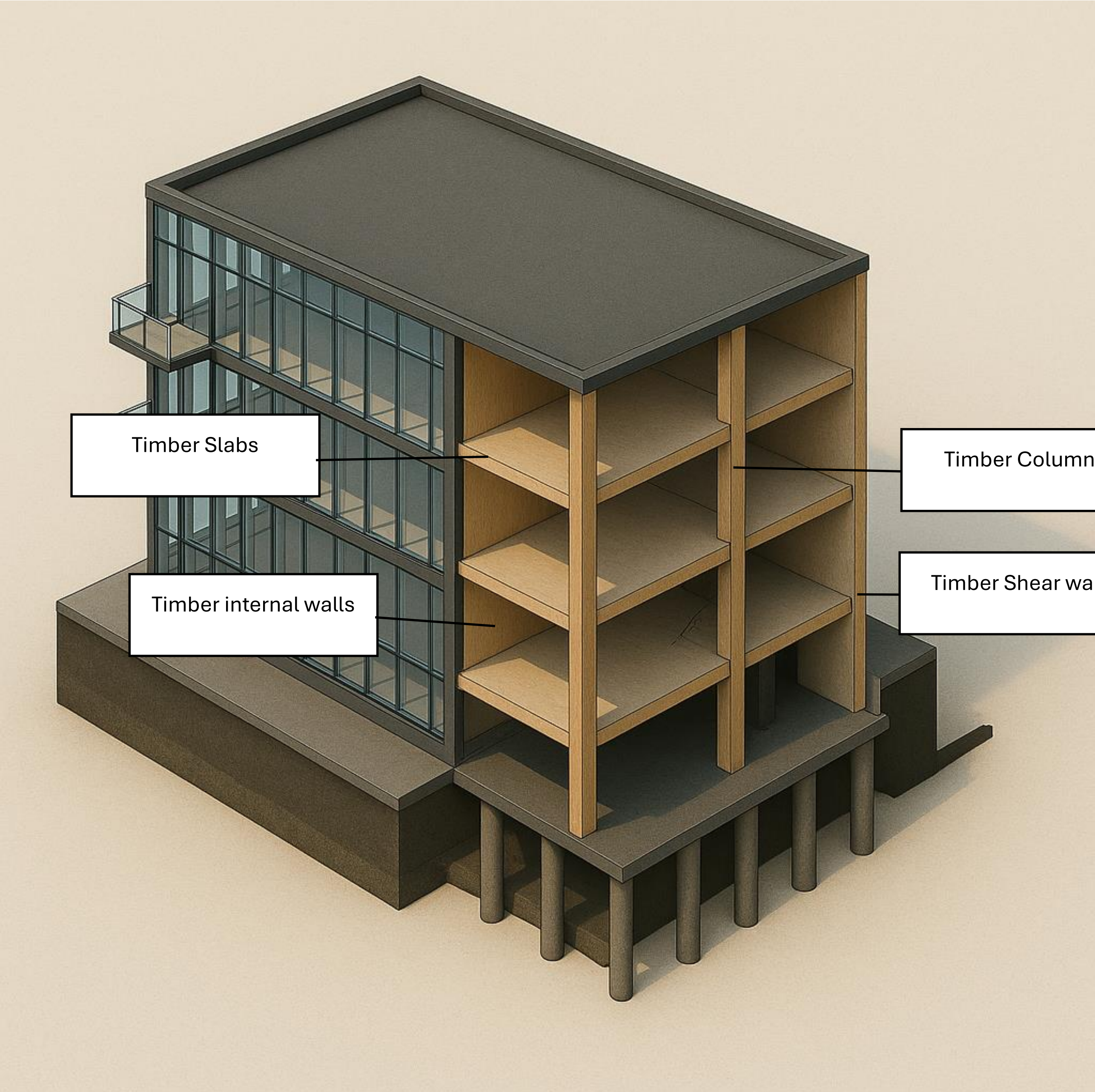


Figure 40. 3D Model of the building parts used in CLT Scenario

Overall, a substantial portion of internal vertical structural elements was successfully converted to CLT, with a portion of the slab system also modified to incorporate timber in a hybrid configuration. These interventions enabled a meaningful reduction in the use of reinforced concrete, while maintaining the functional and regulatory performance of the original design.

3.3.3. Benefits and Strategic Rationale

The integration of CLT was guided by three primary considerations:

- Environmental performance, as CLT offers a lower embodied carbon profile compared to conventional concrete.
- Structural viability, ensured by maintaining concrete where needed for sheer, stiffness, or exposure resistance.
- Regulatory compliance

by adhering to national codes governing seismic safety and fire protection.

Through this strategy, a balanced material substitution was achieved, demonstrating the potential of CLT as a viable material in mid-rise, mixed-use buildings in seismic zones such as Italy. While concrete remained essential for core stability and long-span floor structures, significant reductions in its use were realized through targeted CLT adoption.

3.4. Scenarios Calculations

In this part the calculations and the results of the analysis with the One click LCA are covered. Then input data is based on the “bill of the quantity” which was provided by experts to reach the best simulation with the real-world condition. First, it is notable to understand what has been considered in the calculations. In general, we should remember that this analysis was based on the Level(s) framework, so we need to refer to the building parts and the input data that is predicted in this framework and One click LCA is comprehensively working with these criteria.

As this research is made in the early stages of the building design, which is called conceptual design, its impact on the process of design would be vitally important. Also, it should be noticed that the data provided as input materials are not complete in this stage but that would be improved in the next phases, where the more detailed designs are achievable and more realistic quantities based on the as built drawings could be accessible.

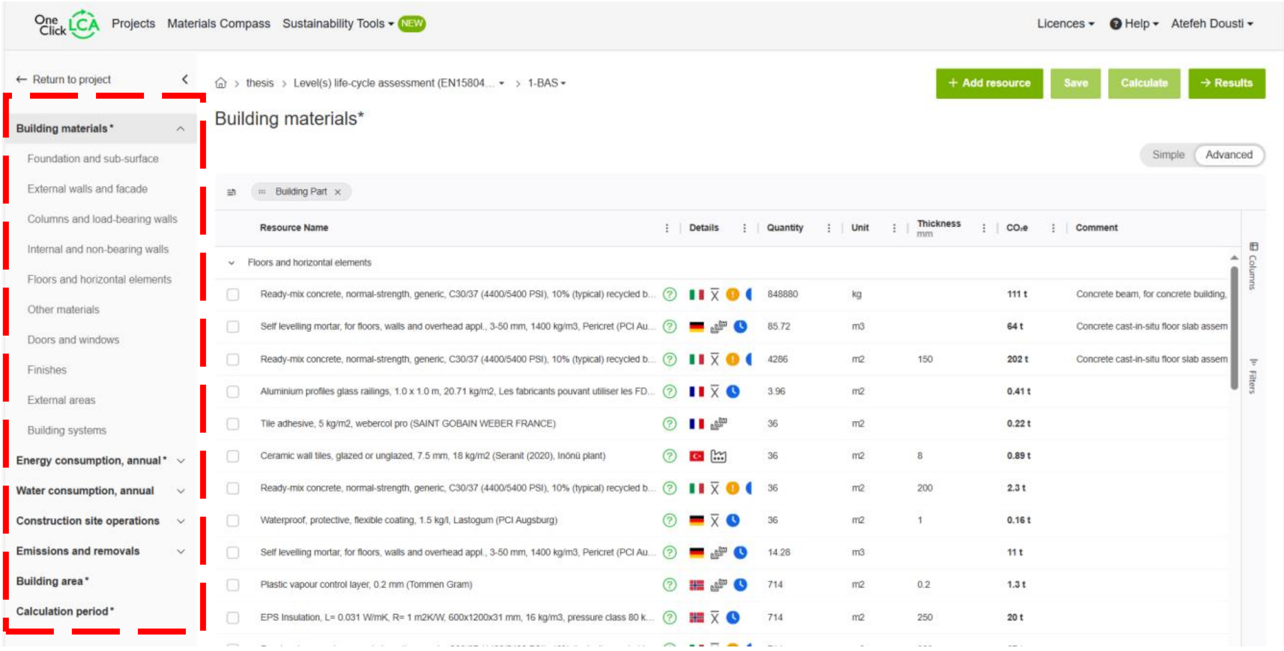


Figure 41. One Click LCA main input material page

The One Click LCA tool, to analyze the all life stages of the building life, provided specific parts as input data, from building materials production, which based on the EPD provided for each item, calculates the life stages A1-A3, for the stages related to the construction and the use and end of life scenarios, it consider the A4-A5, B1-B5, C1-C4 stages, where we have specific parts to insert them as, Energy consumption, annual, Water consumption, annual (which in this project are not important as we are thinking about embodied carbon in early stages). All the calculations by the One Click LCA are just based on the EPDs, if there is no specific data from factories, generic EPDs are professionally predicted by the software itself.

The other input data parts which are important for us are Emissions and removals where we consider the type and quantity of the Refrigerant that is used in HVAC systems. And building area is important for normalizing the impact of materials in each square meters of the building area. At the end we considered the 50 years to analyze the whole life building impacts.

The research started with considering all the contributing materials for each scenario, and at the end the results were compared with each other to check how much the total Whole Life Building Carbon, Embodied Carbon and Upfront Carbon.

The main results and general material analysis are just shown for the first scenario and for the others just a comparison has been made by analyzing the carbon-related graphs.

3.4.1. First scenario: BAS

Here are the main graphs to show how the contributing materials, and their life stages has an impact on the life cycle of the building.

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1 885 387,28	27 309,77	0,25	8 290,65	7 863,4	724,67	283,71	19 254 353,69
A4	Transportation to site	48 032,18		0,01	102,18	21,48	6,28	76,38	793 424,79
A5	Construction/installation process	146 780,16		0,01	575,27	903,43	39,68	19,28	2 193 140,68
B1	Use phase	3 265,61		0	12,46	0,82	0,8	0,29	62 498,21
B3	Repair	0		0	0	0	0	0	0
B4-B5	Material replacement and refurbishment	631 938,39		0,34	4 126,39	935,25	292,38	334,22	8 774 136,07
B6	Energy consumption	11 251 065		0,87	46 316,07	9 101,57	1 855,55	34,53	160 889 275
B7	Water use								
C1-C4	End of life	87 988,03		0,01	246,9	60,51	10,35	248,41	1 426 618,91
D	External impacts (not included in totals)	−714 002,35		−0,03	−2 281,61	−345,82	−332,86	−2,96	−7 820 994,58
	Total	**14 054 456,66**	**27 309,77**	**1,5**	**59 669,93**	**18 886,46**	**2 929,71**	**996,81**	**193 393 447,36**
	Results per denominator								
	Per gross internal floor area m2 / year	67,73	0,13	0	0,29	0,09	0,01	0	932,02
	Per gross internal floor area m2	3 386,62	6,58	0	14,38	4,55	0,71	0,24	46 600,83

Figure 42. One Click LCA result page, Life-Cycle Assessment for Level(s) in compliance with EN 15978 in BAS scenario

This table refers to an environmental assessment of a building project using the Level(s) framework (an EU sustainability tool) and following the EN 15978 standard, which outlines how to evaluate a building's environmental performance throughout its life cycle, from raw material extraction to demolition.

It ensures that the assessment results (like carbon footprint or resource use) are calculated in a standardized, comparable way, supporting EU green building goals and certifications.

Here are the main environmental impacts that have been calculated by the One Click LCA, that are explained below:

Global Warming (kg CO_2e) measures the total climate impact of a product or building over its life cycle, expressed in kilograms of CO_2 equivalent (kg CO_2e). It includes carbon dioxide and other greenhouse gases (like methane and nitrous oxide), converted to the equivalent amount of CO_2 based on their global warming potential. The result shows how much the assessed item contributes to global warming.

Biogenic Carbon Storage (kg CO_2e bio) indicates the amount of carbon dioxide (CO_2) that is absorbed and stored in biological materials like wood during a building’s life cycle. It's shown in kilograms of biogenic CO_2 equivalent (kg CO_2e bio).

Ozone Depletion (kg CFC-11e) measures the potential of emissions to destroy the ozone layer, which protects Earth from harmful UV rays. Expressed in kg of CFC-11 equivalents, a standard for comparing ozone-depleting substances.

Acidification (kg SO_2e) represents emissions that can cause acid rain, harming soil, water bodies, and ecosystems. Expressed in kg of sulfur dioxide equivalents (SO_2e).

Eutrophication (kg PO_4e) indicates the potential for nutrient pollution (like phosphorus or nitrogen) to over-enrich water bodies, leading to algae blooms and oxygen depletion. Expressed in kg of phosphate equivalents (PO_4e).

Formation of Ozone in Lower Atmosphere (kg Ethene e) measures emissions that contribute to ground-level (tropospheric) ozone, a harmful air pollutant and greenhouse gas. Expressed in kg of ethene equivalents.

Abiotic Depletion Potential – Elements (kg Sbe) refers to the use of non-fossil, non-renewable resources (like metals and minerals). Expressed in kg of antimony equivalents (Sbe), used as a benchmark for resource depletion.

Abiotic Depletion Potential – Fossil Fuels (MJ) quantifies the depletion of fossil energy resources (coal, oil, gas). Expressed in megajoules (MJ), indicating the energy content of fossil fuels consumed.

In the scope of this research for calculating the carbon footprint of the building we refer to use the column **Global Warming (kg CO_2e)** so the main item for us in whole life building carbon is the total GWP Per gross internal floor area m^2.

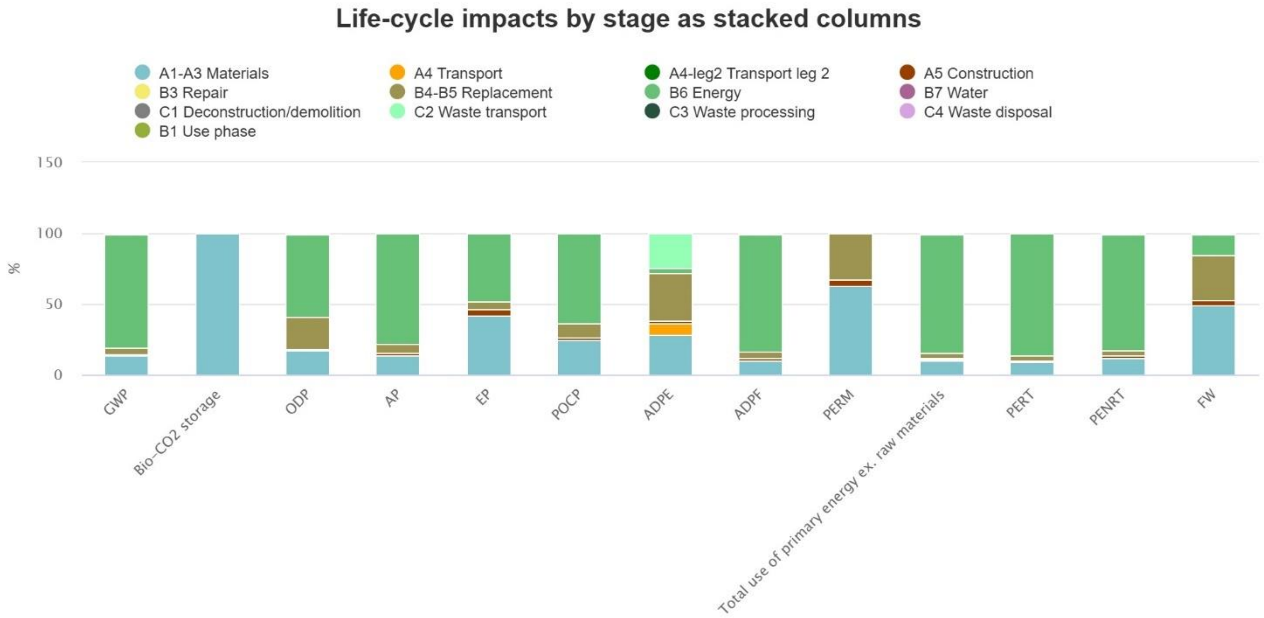


Figure 43. Life cycle impacts by stages

The "Lifecycle impacts by stage as stacked columns" graph visually represents the total environmental impact of the building, broken down by life-cycle stages according to EN 15978. Each column typically corresponds to an impact category (e.g., global warming potential), while the stacked segments within each column show how much each life-cycle stage (A1–A3, A4, A5, B1–B5, C1–C4, D if included) contributes to the total impact.

In the context of carbon emissions (kgCO_2e), the lower portion of each column often represents upfront emissions (A1–A5), including material production, transport, and construction. These are usually the largest contributors, particularly from A1–A3 (product stage). The middle segments reflect use-stage emissions (B1–B5), which may include refrigerant leakages or maintenance-related impacts. The top segments represent end-of-life emissions (C1–C4), such as demolition, transport, and waste processing.

This graph format clearly highlights which stages are most carbon-intensive and supports comparative analysis. For example, a tall lower segment indicates high upfront impact, typical in concrete-heavy structures. The stacked design helps decision-makers identify where emission reductions are most effective, whether through low-carbon materials (A1–A3), efficient maintenance strategies (B-stage), or improved end-of-life planning (C-stage).

As is obvious in the most impacts categories provided by the one click LCA, the energy B6 is the main polluting item in the life cycle of the building, after this the product stage A1-A3 is the second most contributing stage to climate change.

Another useful graph in the result page is the Sankey diagram, The Sankey diagram of Global Warming Potential (GWP) provides a visual representation of carbon flows throughout the life cycle of a building, measured in kg CO_2 equivalent (kgCO_2e). In this diagram, wider flows represent higher emissions, allowing users to intuitively see which building components and life-cycle stages contribute most to the overall carbon footprint.

The diagram typically starts from the building elements or material groups (such as foundations, superstructure, MEP systems, etc.) and traces their carbon contributions across life-cycle stages—production (A1–A3), transport (A4), construction (A5), use (B1–B5), and end-of-life (C1–C4). In many cases, the thickest flows emerge from structural elements like concrete and steel components, especially in A1–A3, emphasizing the high carbon intensity of material production. It is important to say that the Energy use B6 part is omitted from the diagram to show the relation between embodied carbon and stages.

This format helps clearly identify "carbon hotspots", areas with the highest emissions, making it an effective tool for targeting reductions. For instance, a large flow from the superstructure to A1–A3 highlights the impact of heavy construction materials, while thinner flows from finishes or partitions may indicate lower relative contributions.

Overall, the Sankey diagram enhances understanding of where emissions are concentrated and supports data-driven decisions for reducing embodied carbon in buildings.

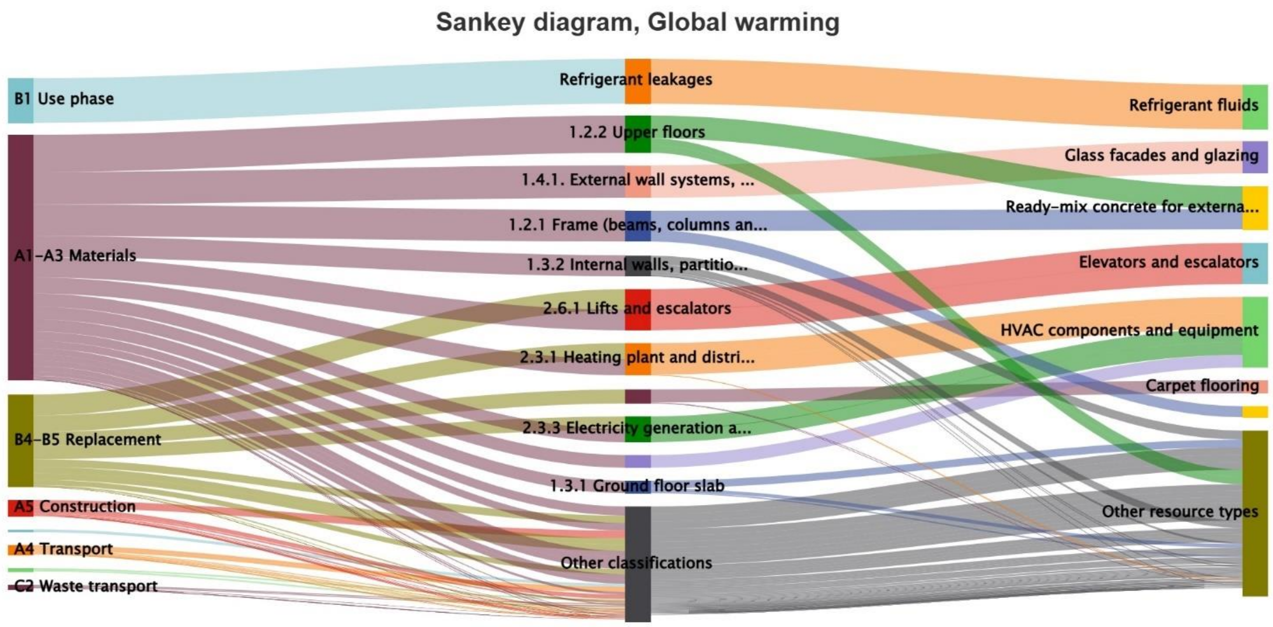


Figure 44. Sankey diagram of GWP

By analyzing the results and categories which can be downloaded as an excel file from one click LCA, we can reach this table to compare the data in different stages by normalizing them per square meters of area:

Building Parts	A1-A3	A4	A5	Upfront carbon [kgCO2e/m2]	B1-B5	C1-C4	Embodied carbon [kgCO2e/m2]
Foundation (substructure)	32.4	1.4	1.6	35	0.0	2.2	37
Superstructure	265.1	8.7	11.0	285	0.5	7.8	293
Envelope	14.0	0.1	0.1	14	14.8	0.3	29
Partitions	39.8	0.7	3.5	44	10.2	0.7	55
Finishes	12.7	0.1	1.7	14	26.8	3.0	44
MEP	90.4	0.5	0.9	92	100.0	0.7	193
External works	0	0	0	0	0	0	0
Construction impacts (A4)	0	16.8	0	17	0	0	17
Refrigerant Leakages (B1)	0	0	0	0	0.8	0	1
Demolitions (C1)	0	0	0	0	0	6.5	7
Total [kgCO2e/m2]	**454**	**28**	**19**	**501**	**153**	**21**	**676**

Table 6. Carbon impact breakdown BAS scenario

To understand better the performance of business-as-usual buildings the graphs are used to make the comparison easier.

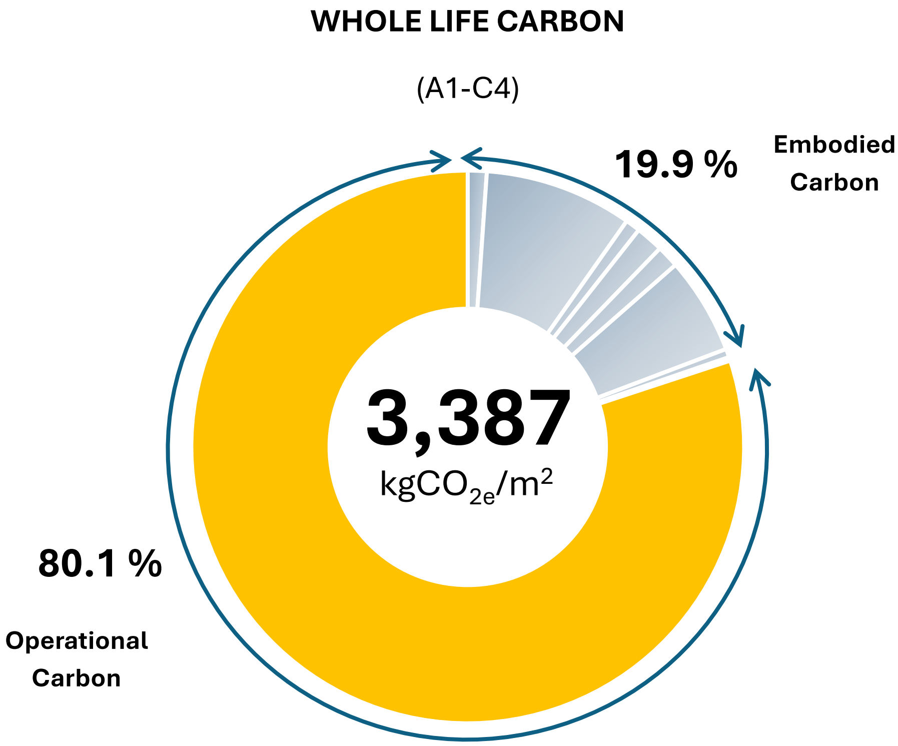
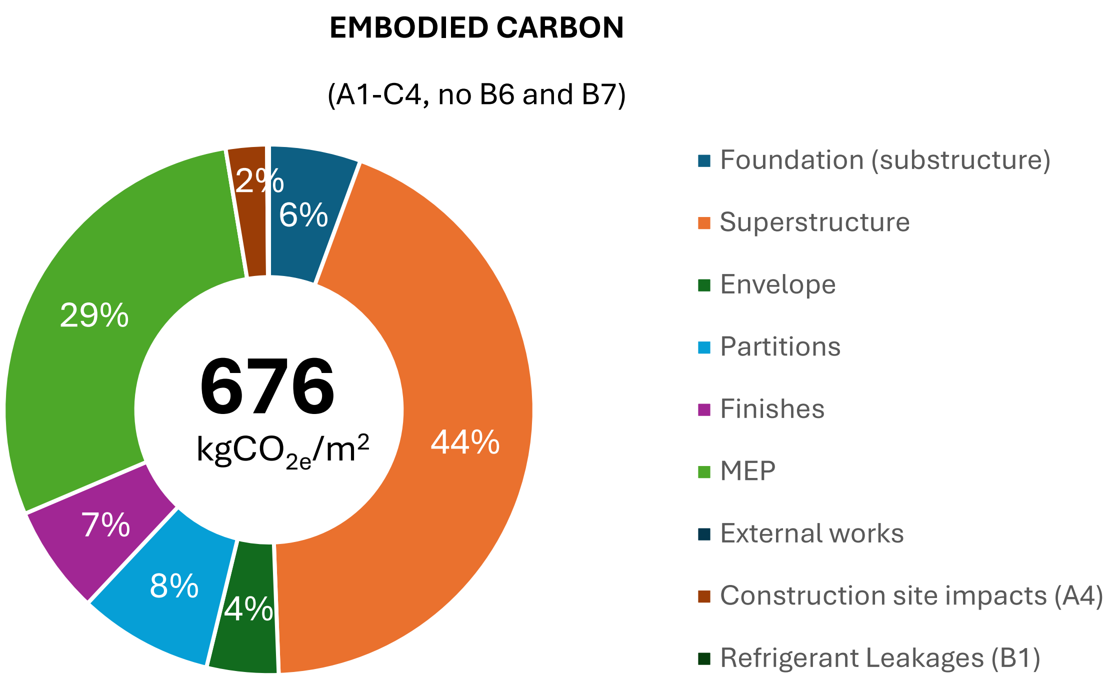


Figure 45. Operational vs Embodied Carbon BAS

In general, the B6 stage as the energy consumption stage is the most contributing part of building life, which is overall related to the lifestyle of the occupants and the energy production strategies in the urban planning. In this stage the main source of energy is defined as Electricity generated in Italy, provided with One Click LCA, as major contributor to energy consumption. As LCA expert or Architect the most effective impact that we can decrease is the embodied carbon which could be enhanced in design and the material selection phases.

To describe the situation of the building and all the contributing building parts it is better to focus more on the embodied carbon and upfront carbon which could be more interesting for analyzing the carbon emissions.



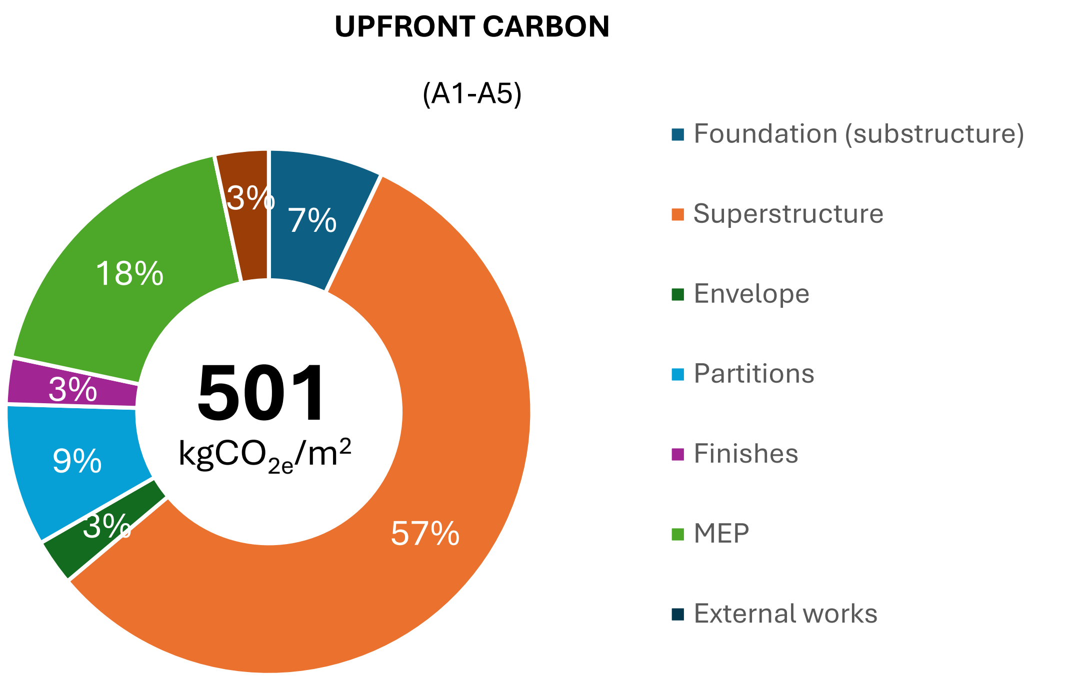


Figure 46. Upfront and Embodied Carbon for scenario BAS

The table presents the life-cycle carbon emissions (kgCO_2e/m^2) for key building elements. The total embodied carbon of the building is 676 kgCO_2e/m^2. Among all elements, the superstructure is the dominant source of emissions, contributing 293 kgCO_2e/m^2, which represents approximately 43.3% of the total. This high impact is primarily due to the intensive use of concrete and steel in structural components. The foundation (substructure), also heavily reliant on concrete, contributes 37 $kgCO_2e/m^2$, or about 5.5% of the total embodied emissions. Combined, these two concrete related elements account for 48.8% of the building's total embodied carbon. In contrast, MEP systems contribute 193 $kgCO_2e/m^2$ (approximately 28.5%), with a significant portion arising during the use stage. Other elements such as partitions (8.1%), finishes (6.5%), and the envelope (4.3%) have lower overall impacts but show higher use-phase emissions. These figures underline the crucial role of structural and material choices, particularly for concrete-intensive elements, in reducing a building's carbon footprint.

Also from the main page of the result part these graphs can give us a general view of the relations and the percentage of the contributing stages, classifications, resource types and the mass quantity per classification in the building life cycle.

Figure 47. Life-cycle overview of Global warming graphs for scenario BAS

3.4.2. Second scenario: CAM

As was mentioned before, for the rest of the scenarios just the results tables and figures are provided, and the general descriptions will be made at the conclusion.

Building Parts	**A1-A3**	**A4**	**A5**	**Upfront carbon [kgCO2e/m2]**	**B1-B5**	**C1-C4**	**Embodied carbon [kgCO2e/m2]**
Foundation (substructure)	42.6	2.8	2.0	47	0.0	2.7	50
Superstructure	170.7	9.3	9.3	189	0.5	7.5	197
Envelope	42.4	0.3	0.1	43	14.8	0.7	58
Partitions	40.1	0.8	3.5	44	10.2	0.7	55
Finishes	12.7	0.1	1.7	14	26.8	3.0	44
MEP	90.4	0.5	0.9	92	100.0	0.7	193
External works	0	0	0	0	0	0	0
Construction site impacts (A4)	0	16.8	0	17	0	0	17
Refrigerant Leakages (B1)	0	0	0	0	0.8	0	1
Demolitions (C1)	0	0	0	0	0	6.5	7
Total [kgCO2e/m2]	**399**	**30**	**17**	**447**	**153**	**22**	**622**

Table 7. Carbon impact breakdown CAM

By calculating the data downloaded from the One Click LCA as excel file the whole life carbon, embodied carbon and upfront carbon graphs are provided as below.

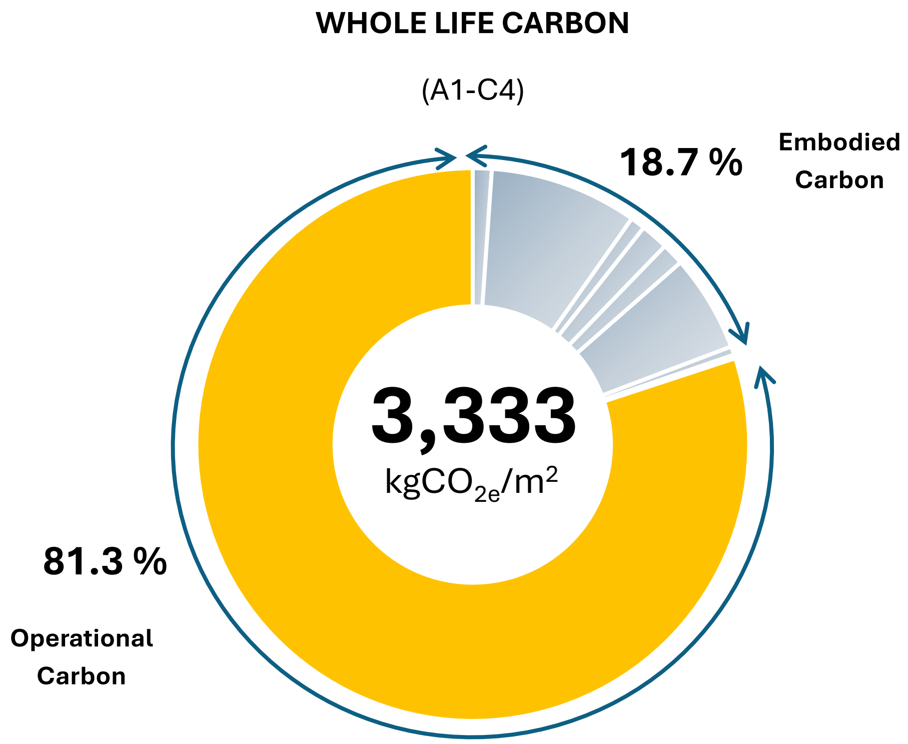
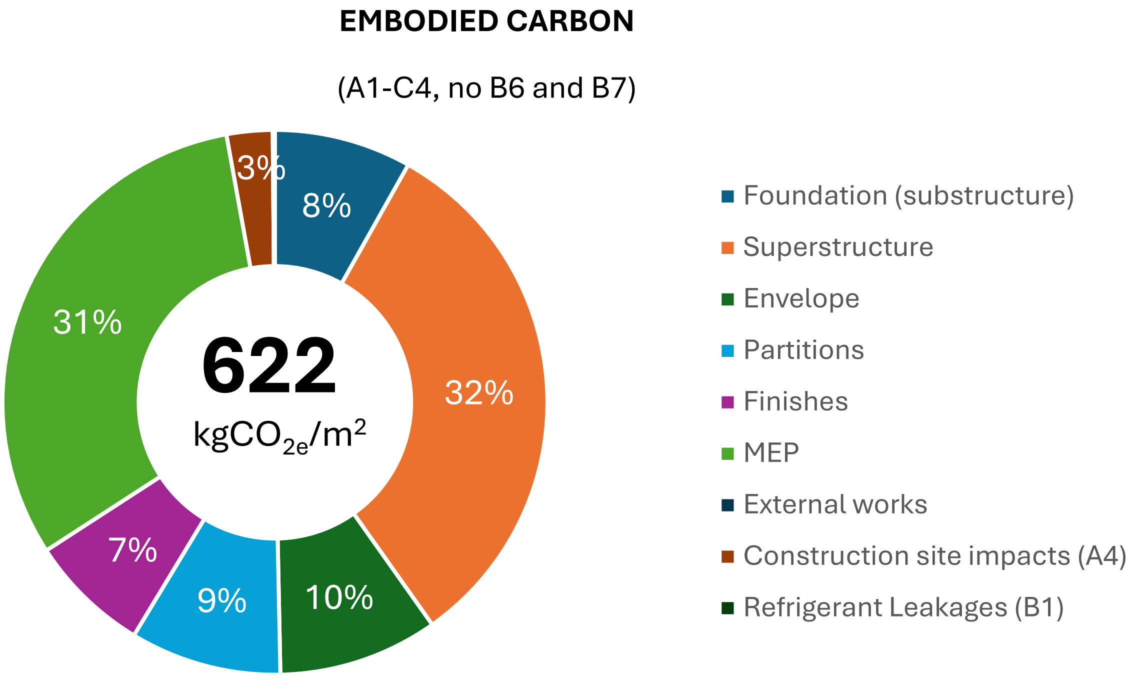


Figure 48. Operational vs Embodied Carbon CAM



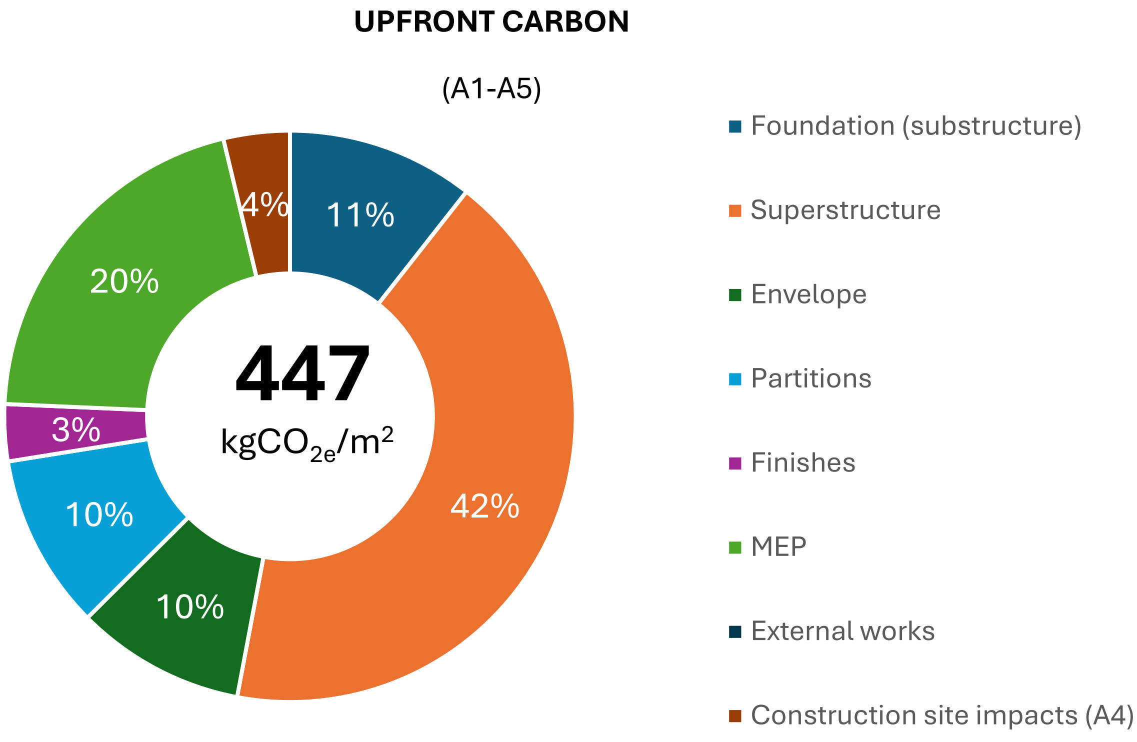


Figure 49. Upfront and Embodied Carbon for scenario CAM

The graphs represent the life-cycle carbon emissions ($kgCO_2e/m^2$) of the building under the CAM scenario, where material choices have been optimized, particularly through increased recycled content in concrete and steel rebars, to reduce the building's environmental impact. The total embodied carbon under this scenario is 622 $kgCO_2e/m^2$, representing a reduction of approximately 8% compared to the original value of 676 $kgCO_2e/m^2$. The superstructure remains the largest single contributor, with 197 $kgCO_2e/m^2$, or 31.7% of the total, despite a significant decrease from its original 293 $kgCO_2e/m^2$. This reduction clearly reflects the positive impact of using recycled steel and concrete in the load-bearing structure. Similarly, the foundation shows an increase in emissions compared to the original scenario (from 37 to 50 $kgCO_2e/m^2$), likely due to a redistribution of material volumes or increased reinforcement needs, yet it still represents only 8% of the total. Other elements such as MEP systems (193 $kgCO_2e/m^2$, 31%), partitions (55 $kgCO_2e/m^2$, 8.8%), and finishes (44 $kgCO_2e/m^2$, 7%) remain unchanged, indicating that the CAM scenario primarily targeted structural components for decarbonization. Notably, upfront emissions (A1–A5) have dropped from 501 to 447 $kgCO_2e/m^2$, reinforcing the significance of material selection in reducing early-stage environmental impacts. Overall, this analysis demonstrates the effectiveness of CAM-based strategies in lowering embodied carbon, particularly through improvements in concrete and steel sustainability.

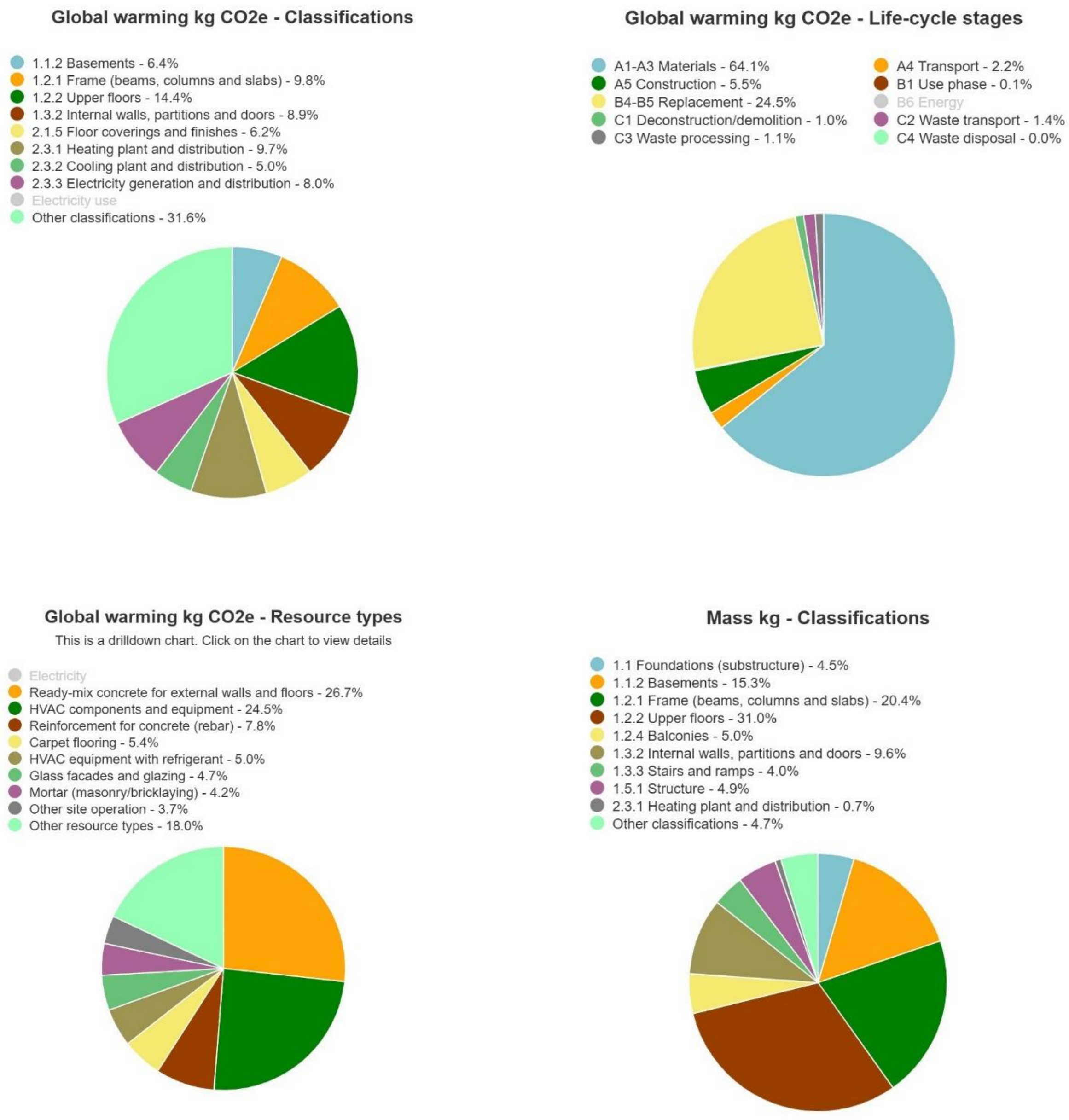


Figure 50. Life-cycle overview of Global warming graphs for scenario CAM

3.4.3. Third scenario: CLT

As it mentioned before, for this scenario just the results tables and figures are provided, and the general descriptions will be made at the conclusion.

Building Parts	**A1-A3**	**A4**	**A5**	**Upfront carbon [kgCO2e/m2]**	**B1-B5**	**C1-C4**	**Embodied carbon [kgCO2e/m2]**
Foundation (substructure)	42.6	2.8	2.0	47	0.0	2.7	50
Superstructure	150.0	8.2	8.7	167	0.5	6.7	174
Envelope	42.4	0.3	0.1	43	14.8	0.7	58
Partitions	36.0	0.5	3.5	40	10.2	0.6	51
Finishes	12.7	0.1	1.7	14	26.8	3.0	44
MEP	90.4	0.5	0.9	92	100.0	0.7	193
External works	0	0	0	0	0	0	0
Construction site impacts (A4)	0	16.8	0	17	0	0	17
Refrigerant Leakages (B1)	0	0	0	0	0.8	0	1
Demolitions (C1)	0	0	0	0	0	0.0	0
Total [kgCO2e/m2]	**374**	**29**	**17**	**420**	**153**	**15**	**588**

Table 8. Carbon impact breakdown CLT

By calculating the data downloaded from the One Click LCA as excel file the whole life carbon, embodied carbon and upfront carbon graphs are provided as below.

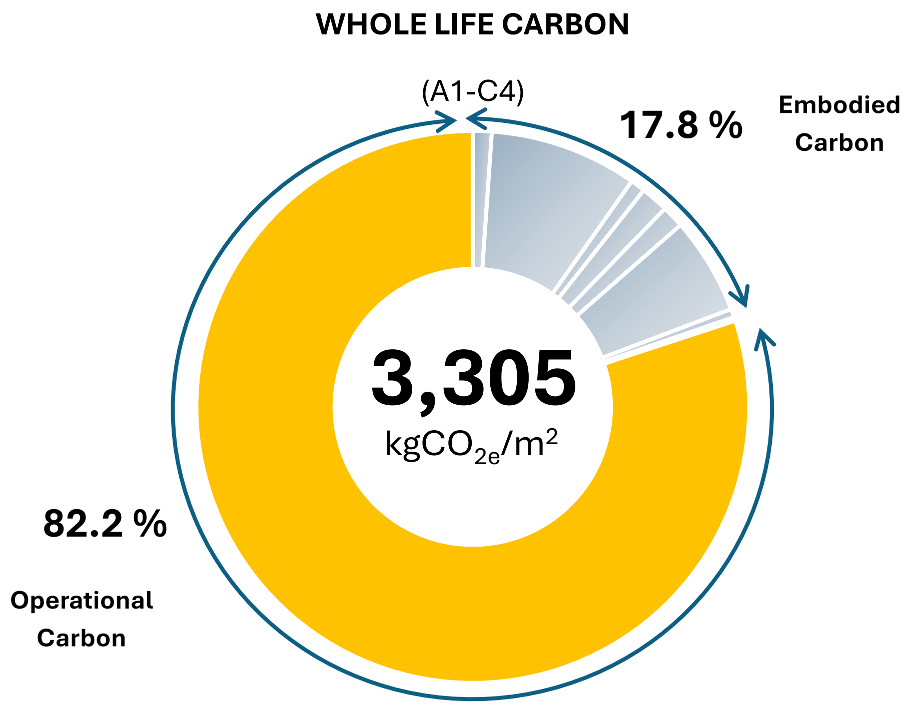
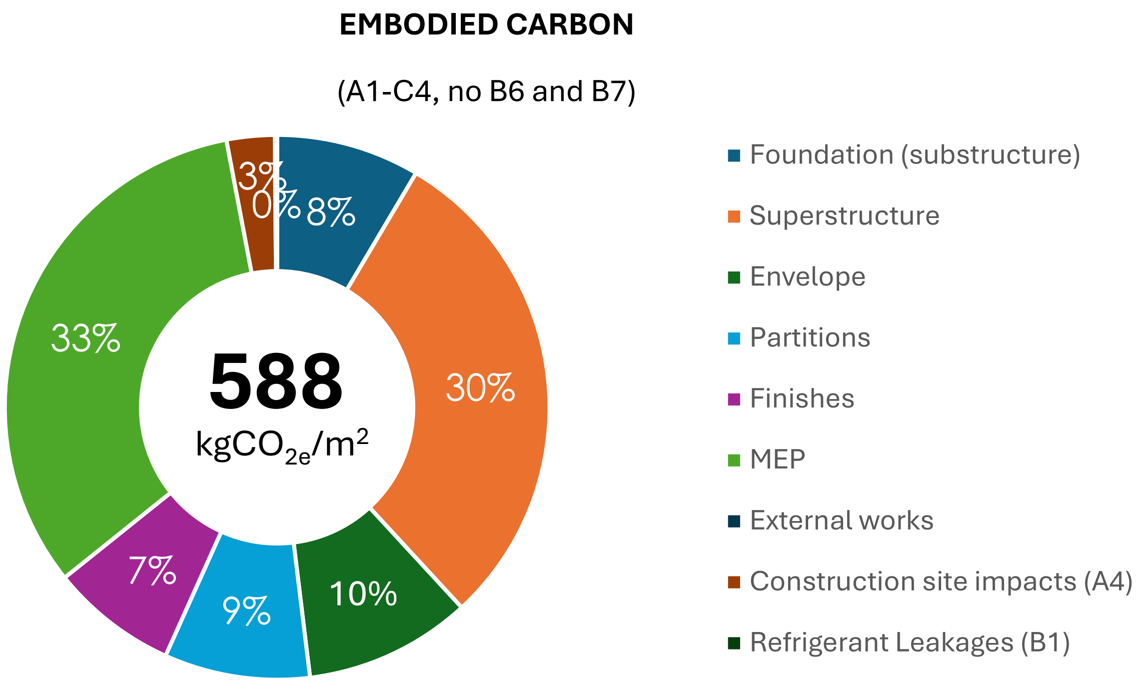


Figure 51. Operational vs Embodied Carbon for CLT scenario



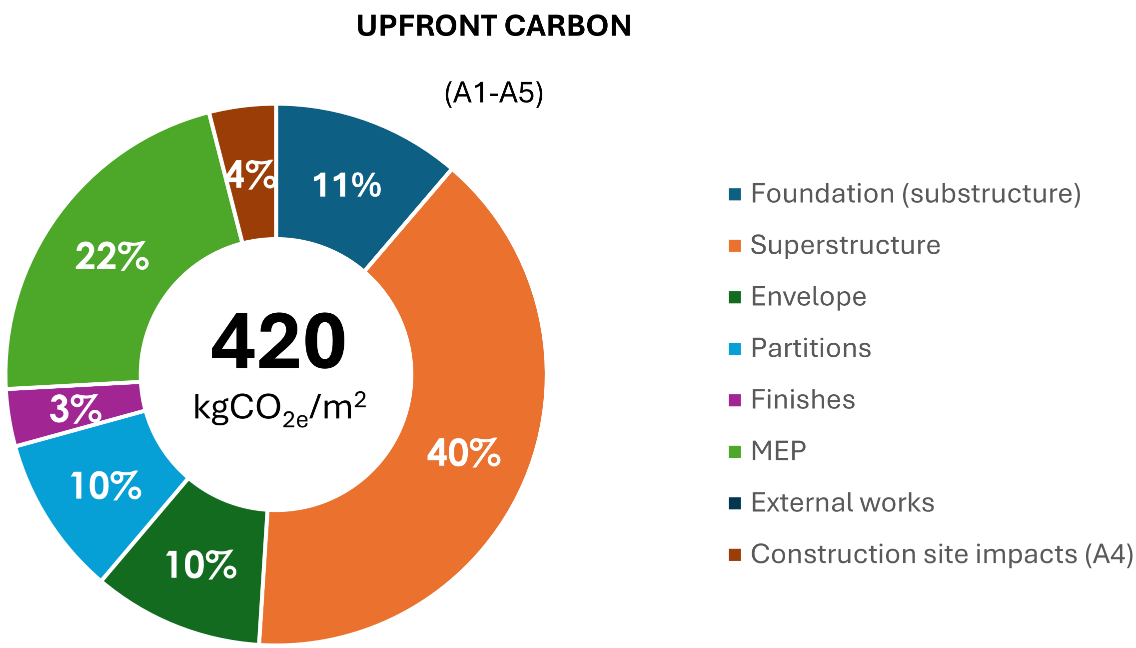


Figure 52. Upfront and Embodied Carbon for scenario CLT

These graphs present the life-cycle carbon emissions of a building design using CLT (Cross-Laminated Timber) in the superstructure, compared to the baseline scenario which relies on conventional concrete and steel. The total embodied carbon in the CLT scenario is 588 kgCO_2e/m^2, reflecting a 13% reduction from the baseline value of 676 kgCO_2e/m^2. The most significant change occurs in the superstructure, where emissions drop from 293 kgCO_2e/m^2 to 174 kgCO_2e/m^2, a 41% reduction. This outcome demonstrates the substantial carbon-saving potential of replacing conventional structural materials with timber, which requires less energy-intensive processing and can store biogenic carbon (although biogenic carbon is typically reported separately).

Despite similar emissions in other elements such as MEP systems (193 $kgCO_2e/m^2$) and finishes (44 $kgCO_2e/m^2$), the reduction in the superstructure alone contributes most to the overall improvement. Upfront carbon (A1–A5) decreases from 501 $kgCO_2e/m^2$ to 420 $kgCO_2e/m^2$, a reduction of 16%, showing the influence of material production on early-stage emissions. Other parts such as the foundation and envelope remain relatively stable across both scenarios, as they are less affected by structural material changes. Notably, end-of-life emissions (C1–C4) are also reduced in the CLT scenario, from 21 to 15 $kgCO_2e/m^2$, likely due to easier dismantling and reduced waste treatment impacts for timber-based components. These findings suggest that a structural shift to CLT can significantly lower embodied carbon, particularly in the superstructure, and make a compelling case for the use of timber as a sustainable alternative in building design.

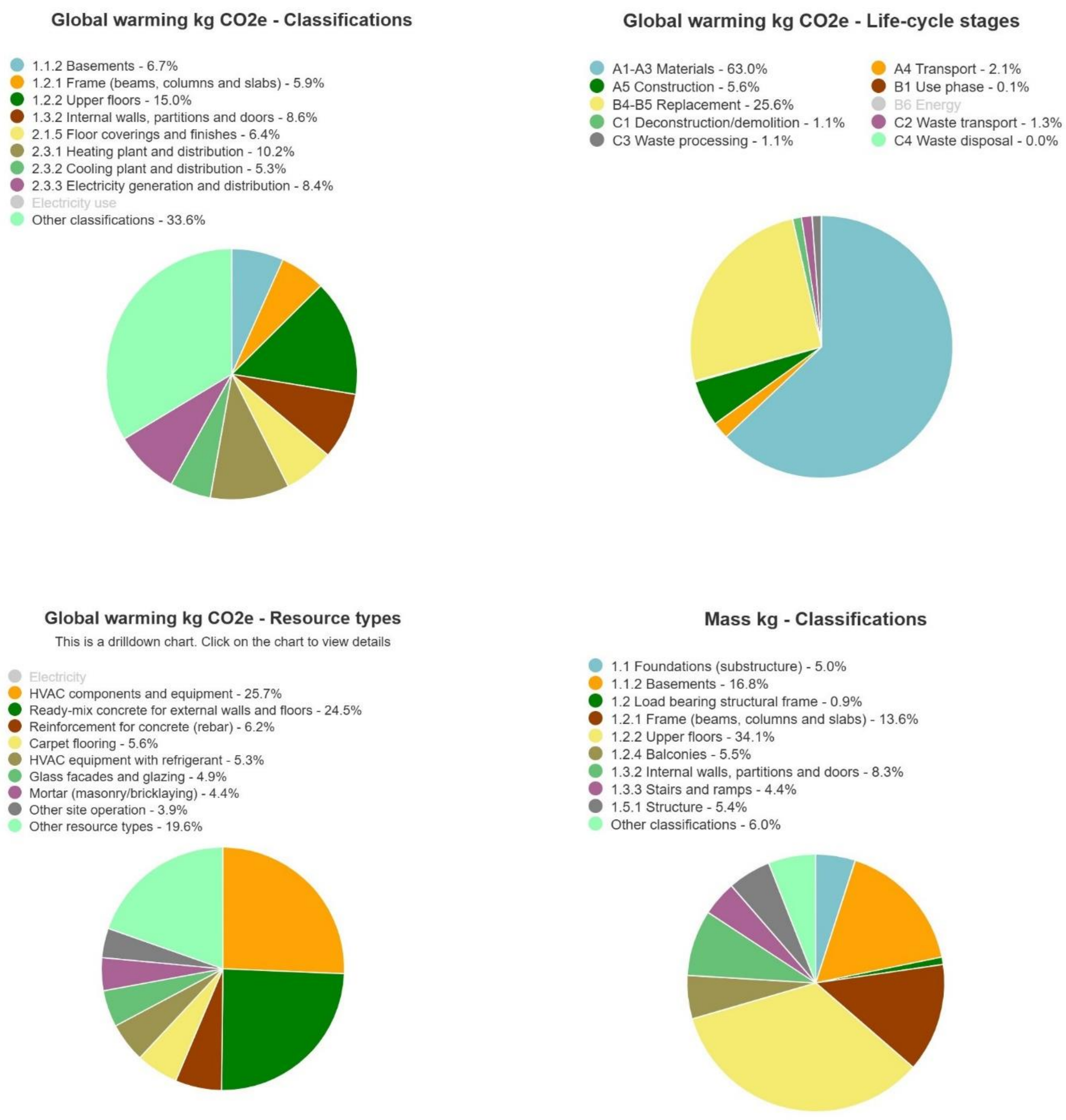


Figure 53. Life-cycle overview of Global warming graphs for scenario CLT

3.4.4. Comparison between scenarios

The comparative analysis of the three design scenarios, Baseline (BAS), CAM (with recycled concrete and steel), and CLT (Cross-Laminated Timber), demonstrates that while structural elements are the largest contributors to embodied carbon, non-structural components also present important opportunities for emission reductions. In all scenarios, the superstructure accounts for the highest share of total embodied carbon: 293 $kgCO_2e/m^2$ (43%) in BAS, 197 $kgCO_2e/m^2$ (32%) in CAM, and 174 $kgCO_2e/m^2$ (30%) in the CLT scenario. These reductions confirm the critical impact of material choices in structural systems. However, a closer look reveals that other elements, particularly the MEP systems, contribute consistently high emissions, 193 $kgCO_2e/m^2$ in all cases, representing approximately 29% to 33% of the total embodied carbon.

Similarly, the envelope, including glass façades and cladding, shows a marked increase in the CAM and CLT scenarios (58 $kgCO_2e/m^2$) compared to BAS (29 $kgCO_2e/m^2$), comprising up to 10% of total emissions. This increase may reflect material or design changes not offset by low-carbon alternatives. Partitions and finishes also make up around 8–9% of the total, suggesting that even interior components hold potential for further optimization.

These findings indicate that a holistic decarbonization strategy should not focus exclusively on the structure. Instead, a comprehensive approach addressing high-emission elements such as MEP systems, glazing systems, and interior partitions, through design efficiency, product selection, and supplier sourcing, can lead to more substantial reductions in a building's total embodied carbon footprint.For instance, we define just a sample scenario, called Optimized, in which we have enhanced the concrete recycled content, façade system, and MEP ducting and heating facilities. In one Click LCA there is a professional section for making a comparison between the different materials, based on the EPDs inside the database of the software. Here there are three examples for this research, for concrete we have considered the optimized material which has about 80 % recycled content.

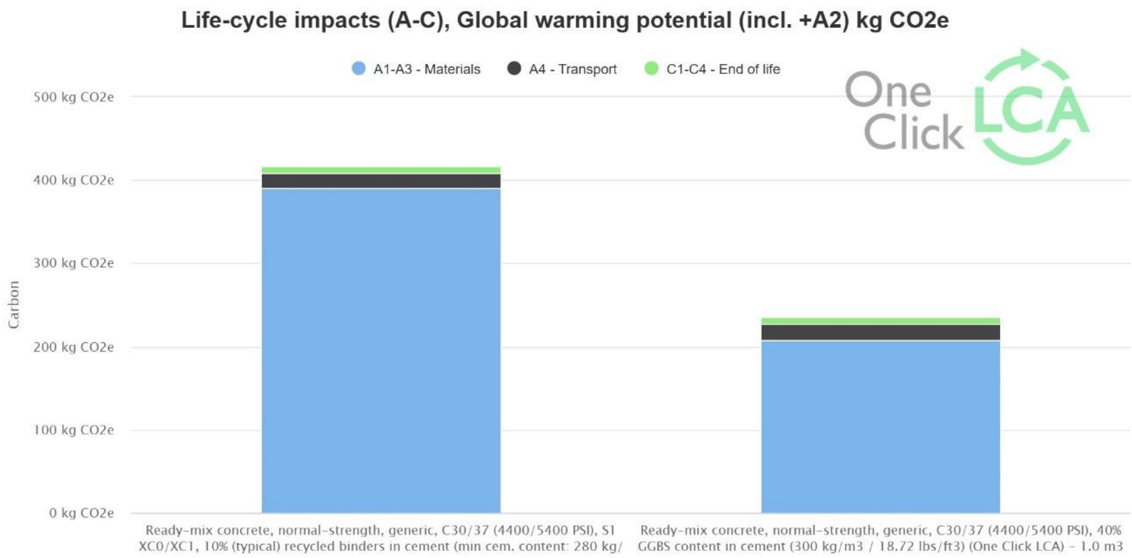


Figure 54. comparison between different concrete materials

As shown in graphs, the main stages that contribute to the product-centered emissions by software indicated A1-A3 Material production, A4 for transport and end of life carbon in C1-C4. Here can be seen how much overall embodied carbon could be affected by the choice of suitable material. But it is important to note that in this research the LCC is not considered, it is clear that the cost of the chosen material could be critical for the choice of materials. Whereas these upfront costs could be compensated for in the future upcoming costs. Another note should be mentioned is that in the comparison section we calculate the EPDs of +A2 too.

Here is the comparison of the alternative façade system with the baseline scenario glass system, it is important to consider that these are just in the conceptual design and tried to show that how different system can make differences.

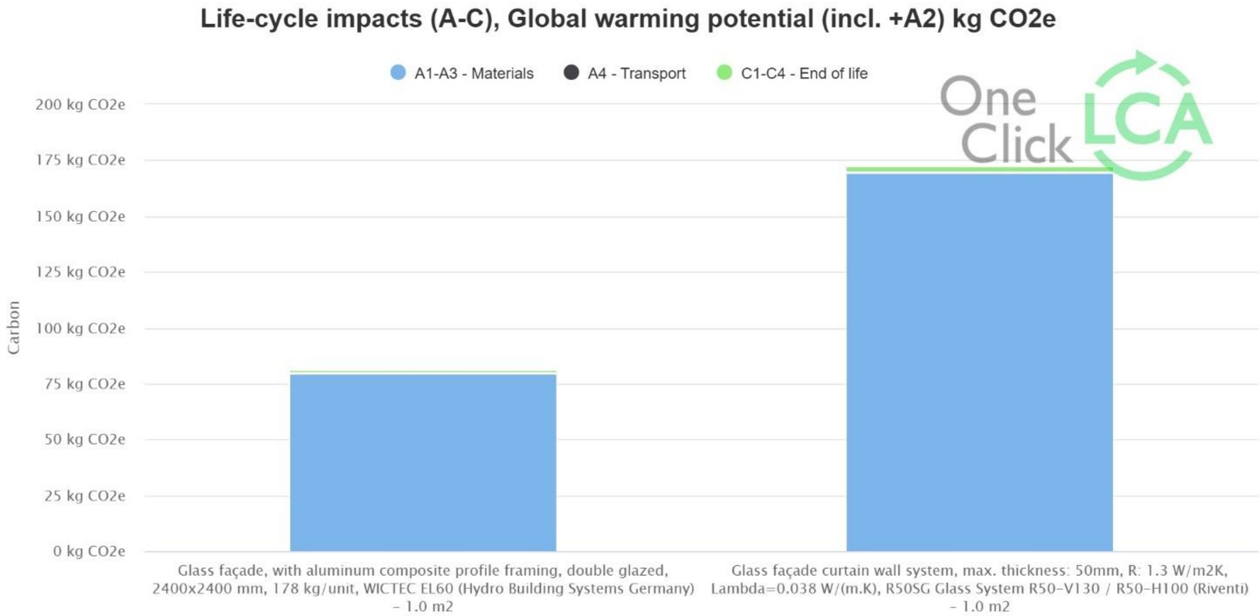


Figure 55. comparison between different façade systems materials

In this figure, it is obvious why the use of LCA could be critical before the detailed design phases. By deciding the proper material for the façade, here could be the type of glass or also the frame material, which is aluminum here, would be practically eco-friendly design decision for the envelope of the building.

Another hot spot that we can make impact is the MEP, mechanical, Electrical and piping related materials, by choosing the machinery with EPD and eco labels which declare not just their low emission performance but also their low embodied carbon could be absolutely more helpful to decrease our general carbon footprint. In these criteria the ducting material for ventilation system has been chosen as the change point. Below figure shows the comparison with the new alternative for the HVAC system ducts, which is made of galvanized sheets.

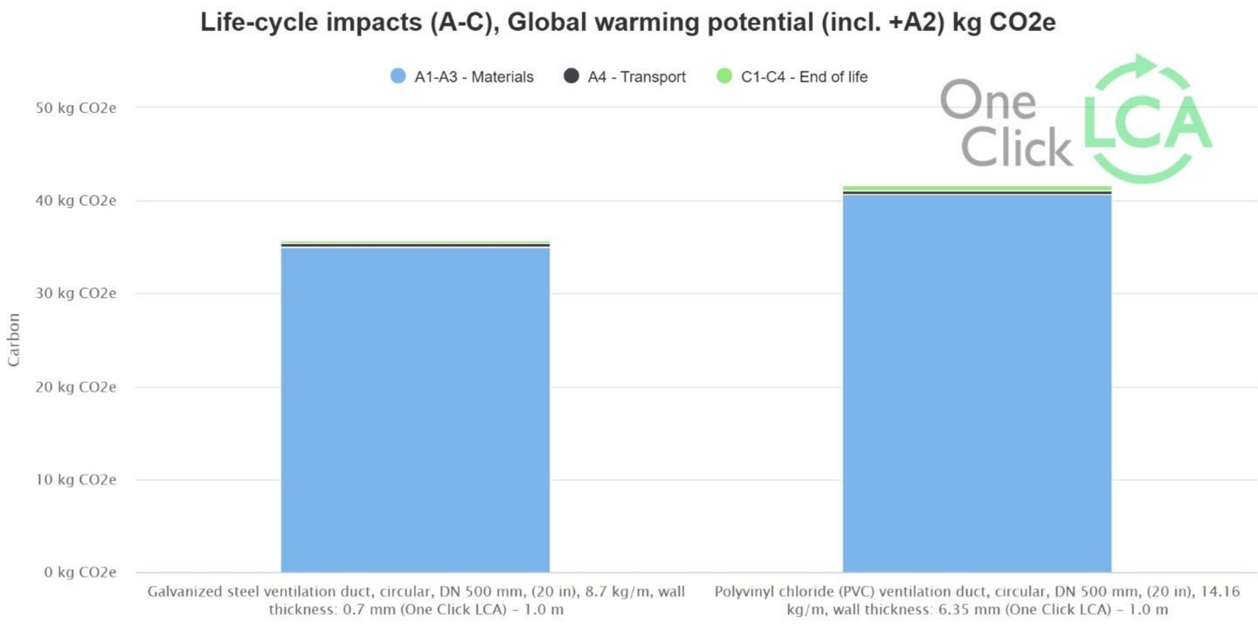


Figure 56. comparison between different duct materials

At first glance, maybe this decrease in carbon emission is not totable but, all the optimizations like this with small effects, around 15%, in hot spots together can make a noticeable difference overall.

Here are the results of the *optimized scenario* to show whole life carbon, embodied carbon and upfront carbon.

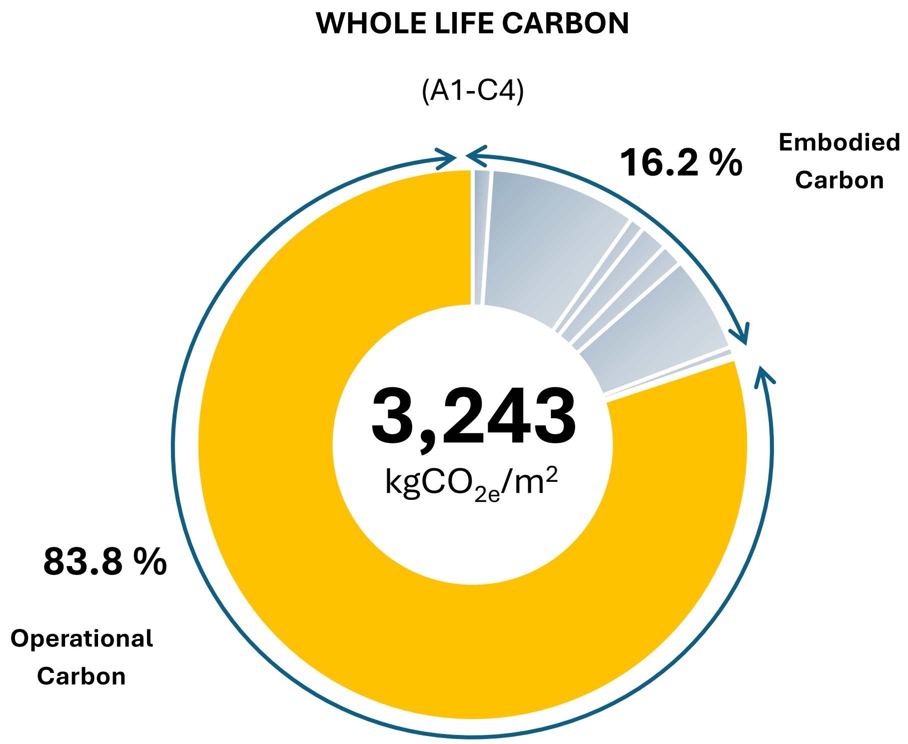
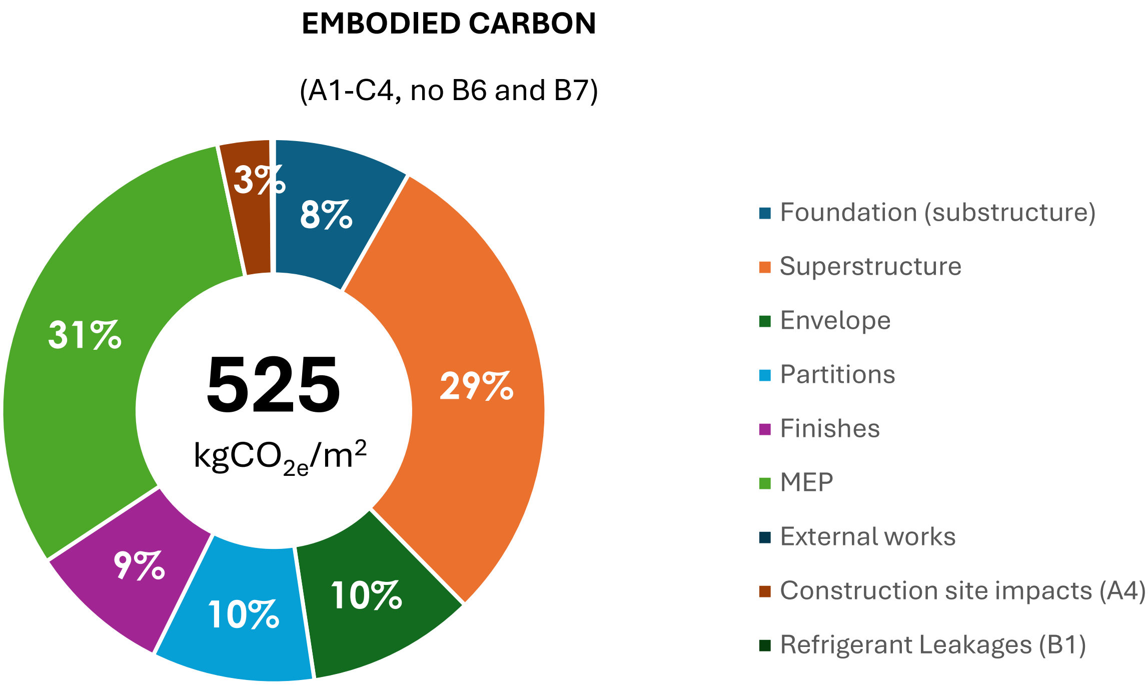


Figure 57. Operational vs Embodied Carbon for Optimized scenario



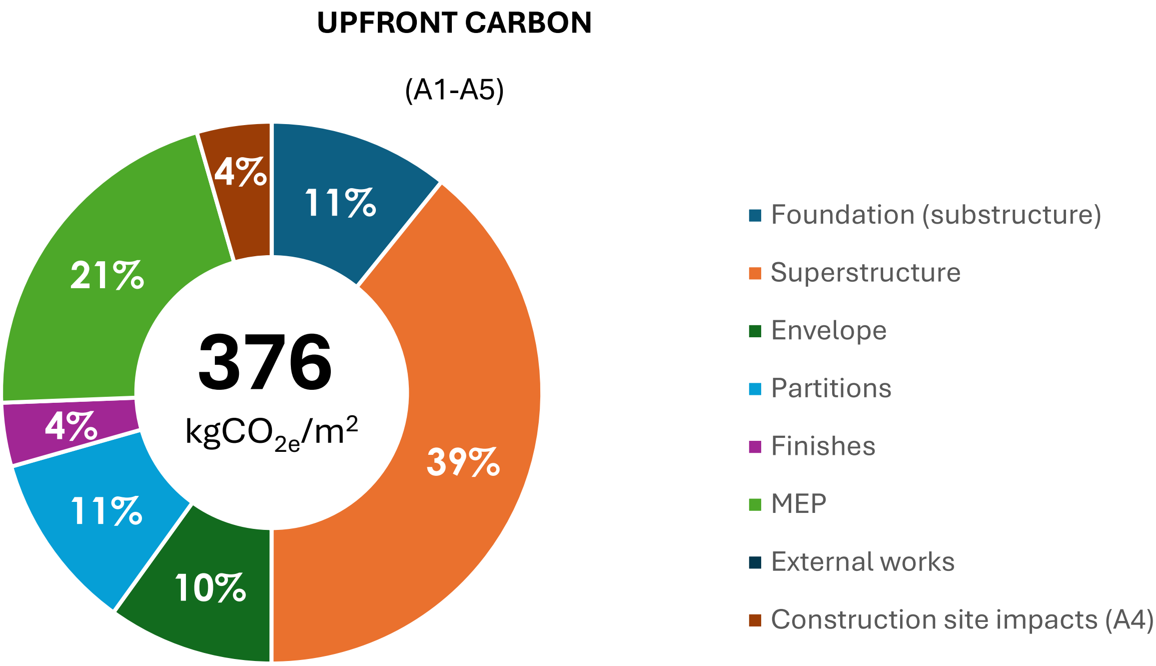


Figure 58. Upfront and Embodied Carbon for optimized scenario

The Optimized scenario builds upon the CLT-based structural design, implementing further refinements in material efficiency and system choices to reduce the building's total embodied carbon. When compared to the Baseline (BAS) scenario, which totals 676 $kgCO_2e/m^2$, the Optimized case achieves a 22% reduction, lowering emissions to 525 $kgCO_2e/m^2$. This improvement results from integrated design decisions applied beyond the structural frame, targeting high-impact elements such as MEP systems, superstructure, and envelope materials.

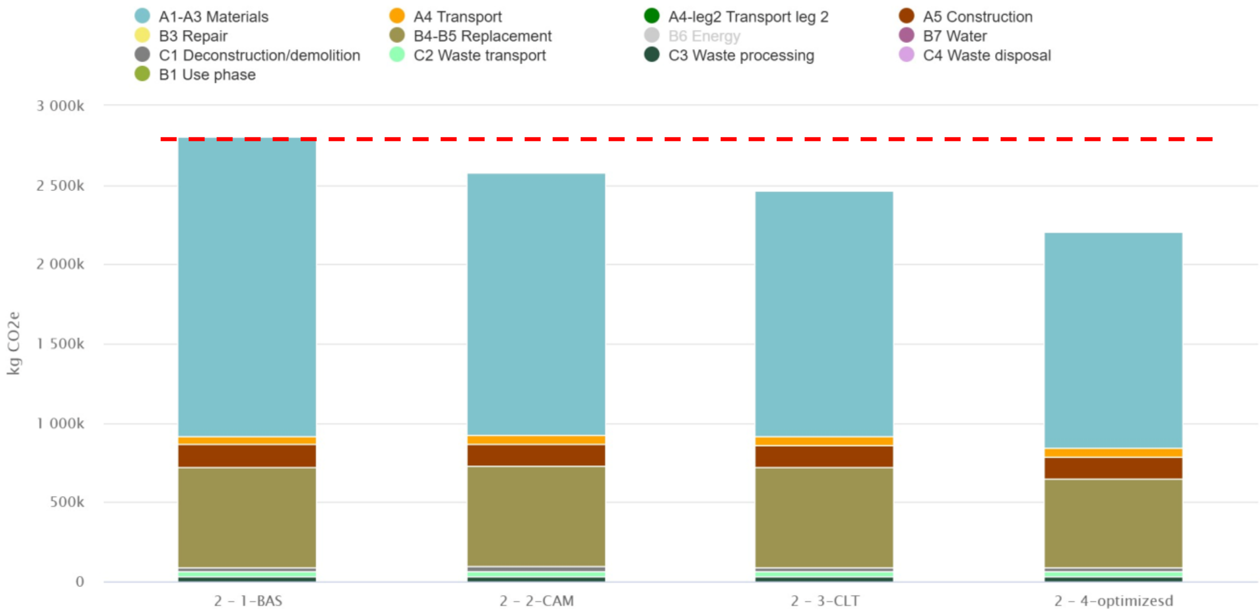


Figure 59. Kg CO2e by stages in different scenarios

The superstructure, already improved in the CLT scenario, is further optimized, with emissions reduced to 154 $kgCO_2e/m^2$, representing a 47% decrease from the BAS figure of 293 $kgCO_2e/m^2$. Similarly, the MEP systems, a consistent emissions hotspot across all scenarios, are lowered from 193 $kgCO_2e/m^2$ (BAS) to 163 $kgCO_2e/m^2$, a 16% reduction. Notably, the envelope emissions increase to 52 $kgCO_2e/m^2$ from 29 in BAS; however, this may reflect a more comprehensive facade system or greater thermal performance rather than a regression in environmental performance.

Upfront carbon (A1–A5) sees the most significant drop, from 501 $kgCO_2e/m^2$ in BAS to 376 $kgCO_2e/m^2$ in the Optimized scenario, a 25% reduction, confirming the importance of early-stage material and process choices. End-of-life impacts are also improved, dropping from 21 to 14 $kgCO_2e/m^2$.

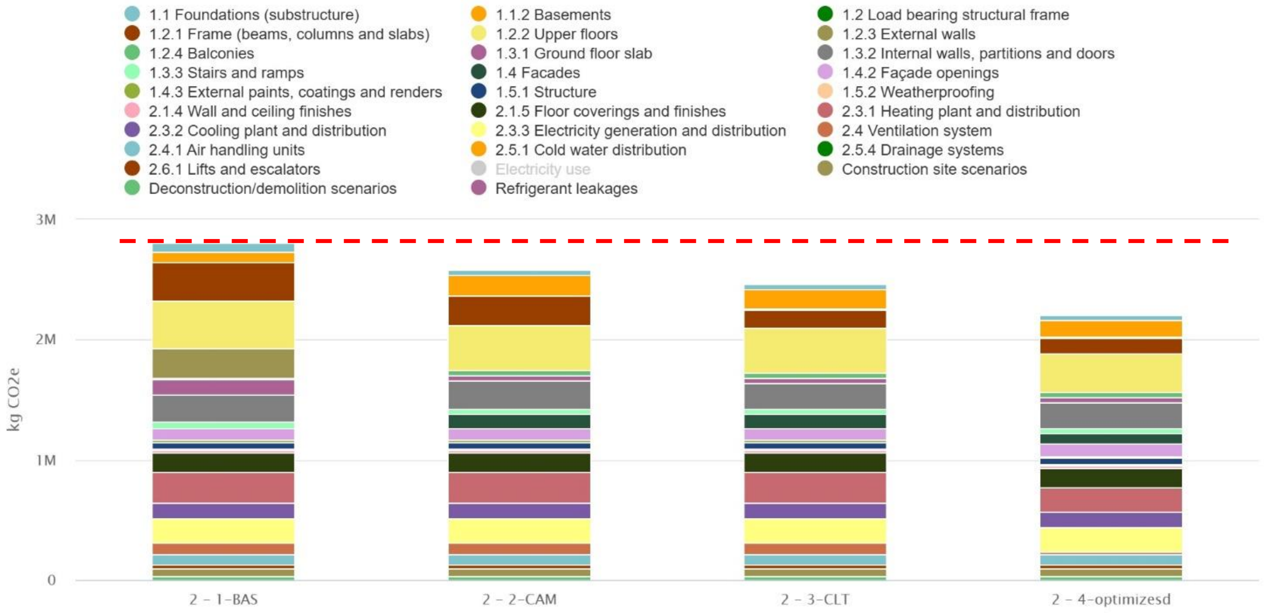


Figure 60. Kg CO2e by building parts in different scenarios

Overall, this progression, from the CLT to the Optimized scenario, demonstrates that maximizing embodied carbon savings requires not only low-carbon structural materials but also targeted improvements in services, finishes, and envelope systems. When these optimizations are holistically applied, they yield a substantially lower carbon footprint compared to conventional construction methods.

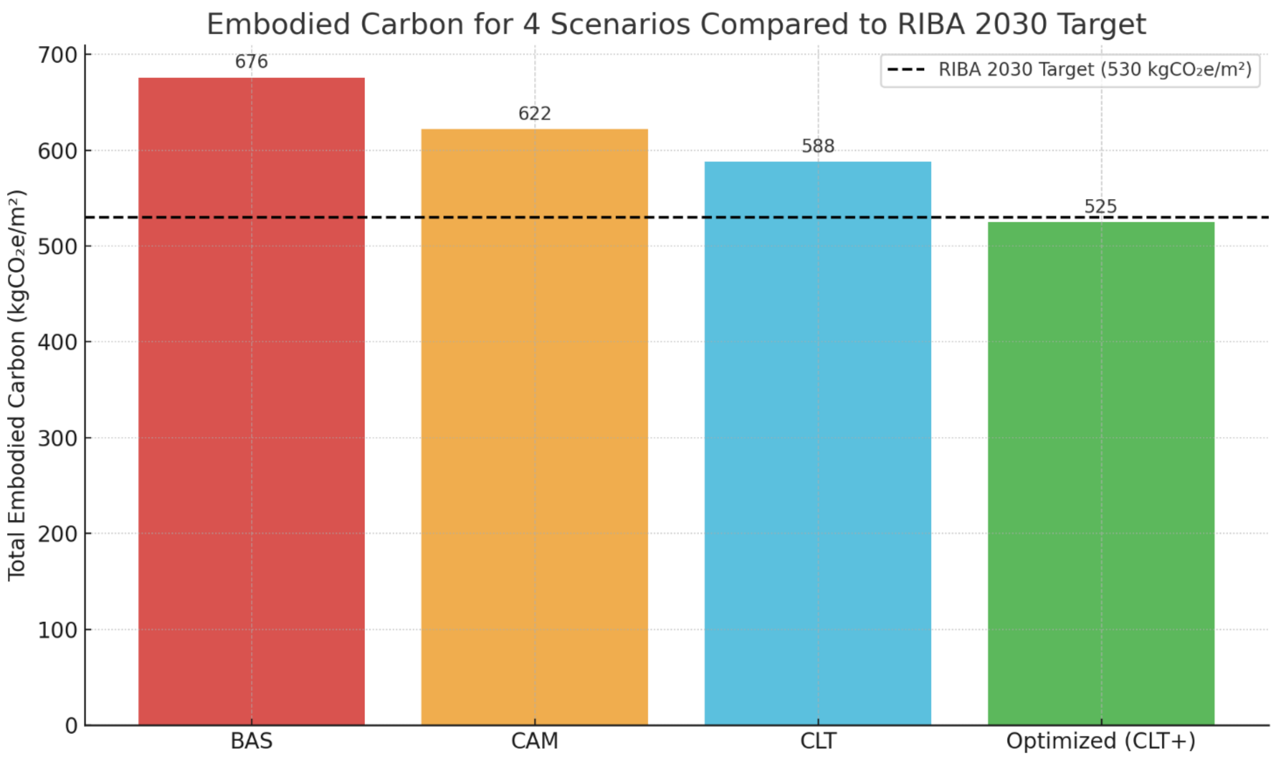


Figure 61. comparison between different scenarios and RIBA 2030 target

The bar chart presents a comparative analysis of the total embodied carbon emissions ($kgCO_2e/m^2$) for four design scenarios of the office building, benchmarked against the RIBA 2030 Design Target for non-residential buildings, which sets a limit of **530 $kgCO_2e/m^2$**. The data clearly illustrate that the Baseline (BAS), CAM, and CLT scenarios exceed this threshold, while only the Optimized (CLT+) scenario successfully meets the target with an embodied carbon of 525 $kgCO_2e/m^2$.

This outcome emphasizes the critical role of targeted material and system-level interventions in reducing carbon impacts. Incorporating optimization strategies—such as the use of CLT structures, increased recycled content, and reduced emissions from building services—proves essential for achieving carbon compliance. As a conclusion, this comparison underlines how early-stage life cycle assessment (LCA) and benchmarking against recognized industry targets like RIBA 2030 can guide more sustainable design decisions, helping architects and engineers prioritize carbon performance throughout the design process.

4 - Strategies for Reducing Environmental Impacts

4.1. Rethinking Carbon in Construction: Strategies for a Low-Impact Future

Based on the analyses conducted by Ferrari (2023/2024), as the climate crisis accelerates, the construction industry finds itself at a crossroads. While the sector has made notable strides in reducing operational carbon, the emissions generated from energy used during a building's life, embodied carbon has quietly grown into a larger concern. Embodied carbon refers to the emissions associated with materials, construction, and renovation. And although it often remains overlooked, experts now agree it demands just as much attention.

With construction and buildings responsible for nearly 39% of global carbon emissions, the path to net-zero must go beyond energy performance and examine how buildings are *designed*, *built*, and *maintained*. The shift calls for an integrated strategy, one that combines efficiency with innovation, and long-term adaptability with low-impact materials.

4.1.1. Building from the Ground Up: Foundations and Substructures

Foundations are the least flexible part of any building, but that doesn't mean they're beyond improvement. Designers can reduce their carbon impact through smart choices, like modular designs that allow for prefabrication, or alternative materials such as timber piles, screw piles, or low-carbon cement blends.

Flexibility is key. Buildings should be designed for disassembly, enabling materials to be repurposed instead of demolished. A foundation today might serve another building tomorrow. And reusing existing structures is one of the simplest, yet most effective, ways to reduce embodied emissions.

Key strategies:

- Reuse of existing structures
- Modular design for efficiency
- Flexible, adaptable planning
- Use of natural and low-carbon materials

4.1.2. Reimagining the Frame: Vertical Structures

Vertical structural elements carry most of a building's weight—and most of its emissions. Traditionally made with high-impact materials like concrete and steel, these components offer substantial room for carbon reduction. A growing number of architects are now turning to cross-laminated timber (CLT) and rammed earth, which offer strength and sustainability in one package.

Efficient structural design can reduce the quantity of material required in the first place. Innovations like pre-stressed concrete, recycled steel, and hybrid systems that combine structural and shading functions show that creativity and sustainability can go hand in hand. Crucially, designers are advised to avoid composite materials and embrace dry assembly systems, allowing for easier deconstruction and reuse in the future.

Key strategies:

- Minimize material use
- Choose sustainable, low-impact materials
- Incorporate recycled content
- Design for flexibility and adaptability

4.1.3. Interiors That Don't Cost the Earth

Interior finishes and partitions, while lightweight, are replaced and modified more frequently than structural elements, making their impact over time significant. The solution? Prioritize natural, recyclable, and durable materials. Think linoleum instead of vinyl, lime-based paints instead of acrylics, and bamboo or cork flooring instead of synthetic options.

Avoiding adhesives and wet-applied products also makes a difference—not only in reducing carbon emissions but in improving indoor air quality. Products with verified sustainability credentials, such as Environmental Product Declarations (EPDs), are increasingly essential tools in green building design.

Key strategies:

- Expose structural/MEP systems
- Use dry-assembled, recyclable materials
- Favor durable, flexible, and non-toxic solutions
- Choose products with verified sustainability credentials

4.1.4. Rethinking the Systems: Mechanical, Electrical, and Plumbing (MEP)

In modern buildings, MEP systems, from heating and cooling to lighting and ventilation, are often the stealth culprits of embodied carbon. They may account for less mass, but they can represent around 30% of total emissions in certain projects, as was the case in the Project building in Milan.

One of the most effective strategies is simplification: install only what is necessary, size it precisely through energy modeling, and avoid over-engineering. Passive design principles can sometimes eliminate the need for active systems altogether. Where mechanical systems are required, modular and renewable-ready designs are preferred.

Ventilation systems that combine mechanical components with natural airflow offer a balanced, low-carbon solution. For lighting, using modular fixtures that can be easily replaced or upgraded also contributes to a more circular, less wasteful design.

Key strategies:

- Avoid oversizing—model energy needs precisely
- Favor simpler systems with fewer components
- Enable future flexibility (e.g., zones, renewable-ready)
- Use low-GWP refrigerants and insulate distribution lines
- Minimize and modularize lighting/ductwork
- Evaluate material safety and recyclability holistically

4.1.5. Making the Case: Life Cycle Assessment in Action

The Life Cycle Assessment (LCA) tool is emerging as a cornerstone of sustainable architecture. By analyzing the entire lifespan of a building, from raw material extraction to end-of-life disassembly, LCA allows designers to make informed decisions that reduce emissions before ground is even broken.

The case study demonstrates how reuse of existing structures, smart material selection, and strategic design choices can outperform traditional or even regulation-compliant models. While following Italy's *Minimum Environmental Criteria* (CAM) offers a baseline for sustainable construction, this project went further proving that deeper emission cuts are possible when the entire lifecycle is considered.

For instance, reused structural elements, low-carbon steel reinforcements, and the use of timber in key load-bearing components all contributed to the building's lower carbon profile. The success of such strategies shows that going beyond CAM isn't just feasible, it's necessary.

4.1.6. The Road Ahead: A Holistic Model for Sustainable Construction

The transition to low-carbon building design hinges on more than just swapping materials or checking boxes. It requires a system-wide rethink of how buildings are conceived and constructed.

Four strategies stand out:

1. Material Minimization: Use less, but smarter. Structural efficiency, prefabrication, and material substitution are foundational tactics.
2. Natural Alternatives: Embrace materials like timber, straw bale, or geopolymer concrete for their lower carbon footprints and renewability.
3. Design for Change: Adaptability prolongs a building's usefulness and keeps materials in circulation. Flexibility is sustainability.
4. Dry and Deconstructable Systems: Build to unbuild. Dry construction not only reduces initial emissions but also enables future reuse, aligning with circular economy principles.

The imperative for future-proofing construction, emphasizing the integration of carbon-conscious design and lifecycle thinking, has been robustly demonstrated through various analyses. Notably, Ferrari (2023-2024) provides a detailed examination of these principles, reinforcing the consensus found in broader literature (Brandt et al., 2021; Chia et al., 2020; Akin & Samet, 2018; Althoey et al., 2023). This collective understanding points towards a future for construction that is not just green, but also adaptable, efficient, and regenerative. It fundamentally redefines how we perceive building materials, viewing every beam, pipe, and panel as part of an extended lifecycle that continues through reuse, renewal, and resilience, rather than ending at demolition.

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