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Static and dynamic Biogenic Carbon accounting in LCA: methodology and application to a wooden window

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LIST OF ABBREVIATIONS

C-PCR	Complementary Product Category Rules
CH_4	Methane
C	Carbon
CO	Carbon monoxide
CO_2	Carbon dioxide
DLCA	Dynamic Life Cycle Assessment
ECHA	European Chemical Agency
EoL	End of Life
EN	European Standard
EPD	Environmental Product Declaration
FSC	Forest Stewardship Council
GHG	Greenhouse Gas
GPI	General Programme Instructions
GWP	Global Warming Potential
GWP_dyn	Dynamic Global Warming Potential
HWPs	Harvested Wood Products
IPCC	Intergovernmental Panel on Climate Change
IRF	Impulse Response Function
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PCR	Product Category Rules
PEFCR	Product Environmental Footprint Category rules
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RSL	Reference Service Life
SVHC	Substances of Very High Concern
TH	Time Horizon
UNEP	United Nations Environmental Programme

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EXECUTIVE SUMMARY

This thesis analyzes how the treatment of **biogenic CO2 affects climate-change results in Life Cycle Assessment (LCA)**, with particular focus on the difference between **static and dynamic modelling approaches**. The topic is particularly relevant in the context of the **construction sector**, where bio-based materials such as wood are increasingly promoted as climate mitigation solutions due to their ability to temporarily store atmospheric carbon during biomass growth.
In conventional LCA study climate impacts are calculated using **time-independent characterization factors** (typically GWP100). Within this framework emissions are aggregated regardless of when they occur during the life cycle. This assumption can lead to an incomplete representation of biogenic carbon flow, since carbon uptake during biomass growth and carbon release at end-of-life of wood products occur at different points in time.
Dynamic Life Cycle Assessment (DLCA) overcomes this limitation by considering the **temporal distribution of emissions and removals**, modelling the atmospheric persistence of CO_2 through impulse response functions. Despite their potential advantages, dynamic approaches are still rarely applied in practical LCA studies, particularly in the building sector.

The objective of this thesis is therefore to **investigate how different accounting approaches for biogenic CO_2 influence climate-change results in LCA** and to assess the implications of explicitly incorporating time into the environmental evaluation of wood-based construction products.

The study is structured in two main phases. First, a **static cradle-to-grave LCA** was developed for **1 m^2 of a wooden window produced by the Italian company Navello**, using the OpenLCA software. The assessment follows the **EN 15804 framework** and the results are reported in the format of an **Environmental Product Declaration (EPD)**.

In the second phase, the study extends the analysis by implementing a **dynamic biogenic carbon assessment**, following the DLCA framework proposed by Levasseur et al.

(2013). The method starts from **inventory results biogenic**, which are then modelled over time through the atmospheric impulse response function of CO_2. The dynamic analysis was applied to **four end-of-life (EoL) scenarios** (mixed waste treatment, incineration, recycling and landfill) and repeated for **three different Reference Service Lives (RSL = 30, 40 and 50 years)** to evaluate the influence of emission timing.

The results highlight significant differences between the two approaches. Under the s**tatic accounting** method, the biogenic carbon balance remains **unchanged** across service-life assumptions, since the timing of emissions is not considered. In contrast, the **dynamic approach exhibits a strong sensitivity to the temporal distribution of carbon flows**. Scenarios involving delayed emissions show improved climate performance when the service life of the product increases. Among the analysed scenarios, the **incineration option is particularly sensitive to emission timing**, while landfill shows the most negative dynamic values due to long-term carbon storage.

By applying a dynamic modelling framework to a **real industrial case study** and explicitly analysing the influence of service life and EoL scenarios, this provides a transparent example of how dynamic LCA can be implemented in practice within the construction sector.

Overall, the results demonstrate that **explicitly incorporating time in biogenic carbon accounting can significantly affect both the magnitude and interpretation of climate indicators** compared with conventional static LCA. These findings highlight the importance of considering service life, end-of-life management and the temporal dynamics of carbon flows when evaluating the climate performance of wood-based construction products.

More broadly, this thesis contributes to the ongoing methodological discussion on **how biogenic carbon should be treated in LCA**, a topic that is currently the subject of active international research and methodological harmonisation efforts.

INTRODUCTION

Global warming is one of the most critical environmental challenges of the twenty-first century, primarily driven by the excessive emission of greenhouse gases (GHGs), particularly carbon dioxide (CO_2) (Breton et al., 2018). The concentration of atmospheric CO_2 has risen dramatically from approximately 280 μmol mol^{-1} in pre-industrial times to more than 415 μmol mol^{-1} in 2022, following a continuously increasing trend that parallels the rise in global average temperatures. Without significant mitigation measures capable of halting global GHG emissions, temperatures are expected to continue increasing throughout the twenty-first century, making the reduction of atmospheric CO_2 concentrations an urgent priority (Kirschbaum et al., 2024; Smith et al., 2019).

Life Cycle Assessment (LCA) has emerged as a widely recognized methodology for quantifying the environmental impacts of products and services across their entire life cycle, including their contribution to climate change and other impact categories (Andersen et al., 2022; Hoxha et al., 2020). LCA plays a central role in identifying mitigation strategies, particularly in sectors that contribute substantially to global emissions. Among these, the construction sector is especially relevant: the manufacture and transport of construction materials currently account for approximately 23% of anthropogenic GHG emissions (Abergel et al., 2017) and the built environment is responsible for nearly 39% of global process and energy related to CO_2 emissions, which are still increasing annually (Andersen et al., 2022). Achieving climate targets, such as limiting global warming to below 2°C by 2100 (Rockstrom et al., 2017) as established under the Paris Agreement, will require the building sector to transition toward carbon-neutral or even carbon-negative systems before 2030 (Breton et al., 2018).

Previous research and policy initiatives were concentrated on reducing the operational impacts of buildings, particularly through improving energy efficiency and increasing renewable sources (Lützkendorf et al., 2014; Passer et al., 2020, 2012). Currently recent studies highlights that now the focus must shift to other stages of the life cycle, including the embodied impacts associated with manufacturing, transport, construction, maintenance and end of life, in order to further reduce GHG emissions (Röck et al., 2020; Mirabella et al., 2018; Lützkendorf et al., 2014).

In the context of the construction sector, wood has emerged as a renewable and potentially low-carbon material. It stores biogenic carbon, which means that absorbs carbon through biological processes during tree growth. If Harvested Wood Products (HWPs) come from sustainably managed forests they can contribute to climate change mitigation by sequestering carbon delaying its return to the atmosphere through long-term storage in products. This positive aspect can be used for substituting the more emission materials such as steel, cement or aluminum (Breton et al., 2018; Liu et al., 2018; Lippke et al., 2009). Moreover, sustainable forestry practices, including afforestation and the prevention of deforestation, can provide both tangible carbon storage benefits and a range of additional environmental co-benefits (Kirschbaum et al., 2024; Smith et al., 2019).

Despite their potential advantages, the climate-change benefits of HWPs remain difficult to quantify. The contribution of forestry to the global carbon balance is heterogeneous, depending on how forests act as a net source of CO_2, because harvesting and deforestation can exceed regrowth (UNFCCC, 2022). Instead at the national level this balance can be a net carbon source or a sink depending on country-specific conditions (Leinonen et al., 2022).

The combined effects of biogenic carbon sequestration, storage in products and material substitution are highly sensitive to methodological choices in LCA (Breton et al., 2018). A central challenge concerns how biogenic carbon flows are modeled. Traditional LCA methods typically employ a static approach that does not capture the temporal dynamics of carbon uptake, emissions and storage. However, because the timing of carbon flows, particularly delayed emissions and temporary storage can significantly influence the climate impact of wood-based products, dynamic modelling approaches have been increasingly proposed to provide a more realistic representation of biogenic carbon behaviour (Breton et al., 2018; Liu et al., 2017).

European policy frameworks have further intensified the need for robust carbon accounting. For example the European Green Deal establishes the objective of achieving net-zero GHG emissions by 2050, emphasizing the role of research, innovation and energy-efficient construction practices in achieving this transformation (Hoxha et al., 2020). Recent EU directives also prioritize improving the energy performance of buildings, evidencing the importance of evaluating both operational and embodied emissions (Dodoo et al., 2025).

In this scenario, wooden windows are an example of objects, in the construction sector, for assessing environmental performance. This is due to two reasons: the impacts associated with their material life cycle and their influence on building energy performance during operation (Liu et al., 2017). Additionally, wood-based window components can store biogenic carbon for the duration of the product, making them suitable for exploring the methodological implications of static versus dynamic LCA.

Within this context, in order to contribute to the understanding of the behaviour of CO_2 in natural systems, this thesis investigates the role of biogenic CO_2. More specifically, the objective of the thesis is to understand how the accounting of biogenic CO_2 influences climate change results in LCA by comparing conventional static LCA with a Dynamic Life Cycle Assessment (DLCA) approach.
The study combines both theoretical analysis and a case-study-based approach. In particular, from a practical point of view, the research evaluates the environmental impacts of a wooden window produced by the Italian company Navello s.r.l., both from a static LCA, following the EN 15804 frameworks, and dynamic approach.
By applying the DLCA, the research illustrates how time can influence the interpretation of climate impacts associated with biogenic carbon. In fact, it allows a more accurate representation of the temporal distribution of carbon fluxes, including carbon uptake during tree growth and carbon release at the end-of-life (EoL) of wood-based products. Therefore, comparing static and dynamic results allows a better understanding of the role of biogenic carbon in wood-based products and helps evaluate how the inclusion of temporal dynamics influence the assessment of their climate performance.

The thesis is structured as follows. Chapter 1 introduces the carbon cycle in forest ecosystems and defines the concept of biogenic carbon. Chapter 2 reviews the LCA methodology and analyses the approaches for accounting the biogenic carbon, including both static and dynamic methods. Chapter 3 presents the case study of a wooden window produced by Navello s.r.l. and reports the results of the static LCA carried out according to the EN 15804 framework. Chapter 4 applies the dynamic accounting method, following the Levasseur approach, to the same case study, illustrating the modelling of temporal carbon flows and the resulting climate impact indicators. Chapter 5 compares the results obtained from these approaches and discusses their methodological and practical implications. Finally, Chapter 6 outlines the main limitations of the study and highlights future research on this argument.

1. FOREST CARBON CYCLE IN NATURE

1.1 Carbon in forest ecosystems

Forests play a central role in the global carbon cycle, functioning as major terrestrial carbon sinks capable of storing substantial quantities of carbon (C) in living biomass, dead organic matter and soils (Breton et al., 2018). Through photosynthesis growing forests remove CO_2 from the atmosphere and accumulate C in tree biomass, thereby contributing to climate change mitigation. However, the permanence of this sequestration is not guaranteed. Carbon stored in trees can be released back into the atmosphere through harvesting activities or natural disturbances such as fires, droughts, pest outbreaks and storms (Roshan Krishnan et al., 2023; Thom and Seidl, 2016; Kurz and Apps, 1999). Because sequestration in forests is reversible, its net climate benefit depends strongly on the duration of storage and on the long-term dynamics of forest ecosystems (Kirschbaum et al., 2024).

The capacity of forests to mitigate climate change is determined by their total carbon stocks rather than the instantaneous rate of carbon uptake. Young forests typically grow rapidly sequestering C at higher rates, whereas older forests accumulate larger overall C stocks due to their more complex structure and longer accumulation period (Kirschbaum et al., 2024; Cook-Patton et al., 2020; Waring et al., 2020). From an atmospheric perspective, maintaining high forest carbon stocks provides a mitigation benefit equivalent to avoiding fossil-fuel CO_2 emissions, provided that the stored carbon remains sequestered beyond the chosen assessment horizon (Kirschbaum et al., 2024). Conversely, when C sequestration is temporary, followed by harvesting or unplanned loss, the climate impact becomes more complex to evaluate because the release of stored carbon offsets the earlier atmospheric removals.

Figure 1a shows the C stocks in the biomass of a typical forest over time and *Figure 1b* shows the annual growth rate of C stocks. A young forest contains relatively low carbon stocks but are characterized by high growth rates, enabling rapid carbon accumulation. These curves describe the principal trends in forest growth. All forests follow this basic pattern, but there are differences in maximum C storage, growth rates, the timing and in the growth peak (Gundersen, 2021).

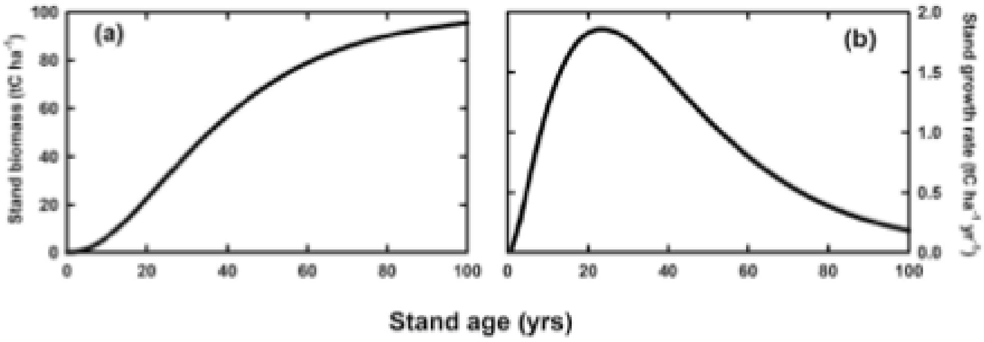

Figure 1: Typical pattern of C stocks showing forest biomass over time (a) and the derived rate of stand growth (b).

Forest carbon dynamics are also influenced by forest management practices. In sustainable managed forests carbon released through the decomposition of residues and the processing of harvested logs is gradually balanced by subsequent forest regrowth, allowing the forest system to remain carbon neutral over time (Lippke et al., 2009). Despite this, nature-based carbon offset programs often fail to distinguish between the permanent sequestration associated to fossil fuel emissions avoided and the temporary sequestration. Carbon stored in forest biomass can persist for decades or centuries, but its vulnerability to disturbances and the way it is accounted in land-use reporting remains uncertain (Roshan Krishnan et al., 2023).

Carbon accumulation in trees varies significantly across climate zones, species, soil conditions and their management. These parameters strongly influence forest rotation lengths, the time span between planting and harvesting, which are essential for quantifying long-term carbon dynamics and harvested wood supply. Species and geographical origin are therefore critical variables and in the European context must be documented under the European Union Timber Regulation (EUTR) (Tellnes et al., 2017; EU, 2010). Understanding these dynamics is crucial for accurately assessing biogenic carbon flows in Life Cycle Assessments (LCA) of wood-based products and for evaluating the climate benefits associated with sustainable forest management.

1.2 Definition of biogenic carbon

Biogenic carbon comes from biological processes and it is part of carbon cycle. During biomass growth atmospheric CO_2 is removed through photosynthesis and sequestered in plant tissues, while emissions occur when biomass undergoes to degradation processes, such as combustion, digestion, composting or landfilling, leading to the release of CO_2, CO or CH_4 (Brandão et al., 2013). This type of carbon is sequestered in natural reservoirs, such as forests, soil and other biomass pools, and it is accounted within LCA. Bio-based construction materials, including wood, hemp and straw, contain approximately 50% carbon by dry mass (Pittau et al., 2018), enabling buildings that incorporate these materials to act as temporary carbon reservoirs (Churkina et al., 2020).

In sustainably managed forests the biogenic carbon flows, associated with wood products, generally follow a cyclical pattern, in contrast to the unidirectional release of fossil carbon from the geosphere to the atmosphere. The temporal dynamics of carbon emissions and removals are particularly relevant in wood-based systems, as the timing of sequestration, storage and release can significantly affect the overall climate profile of construction products. However, these temporal aspects remain underrepresented or insufficiently integrated in many LCAs of wood-based materials, despite their importance (Dodoo et al., 2026).

The use of biomaterials provides multiple advantages in climate-oriented assessments. These materials can reduce life cycle GHG associated with extraction and manufacturing processes, temporarily store biogenic carbon and limit emissions by replacing more carbon-intensive construction materials (Breton et al., 2018).

Nevertheless, the climatic implications of biogenic CO_2 emissions must be carefully considered. Biogenic CO_2 released through biomass combustion constitutes a one-time pulse emission that requires years of regrowth to be fully compensated (Cherubini and Strømman, 2011). Consequently, the global warming potential (GWP) of biogenic CO_2 should be explicitly considered in the climate change assessment of bioenergy and bio-based systems (Liu et al., 2017).

2. ACCOUNTING OF BIOGENIC CARBON IN LIFE CYCLE ASSESSMENT

2.1 Overview on Life Cycle Assessment methodology

The LCA methodology, codified by the UNI EN ISO 14040 series standards, is a standardized methodological framework for quantifying the environmental impacts associated to products, services or processes across all stages of their life cycle, from raw material extraction to EoL management, as shown is *Figure 2* (ISO 2006).

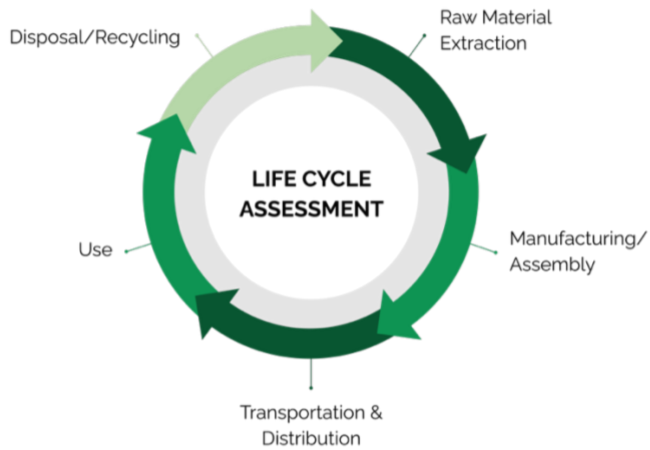

Figure 2: Life Cycle Assessment.

This methodology is based on objective criteria that allows the identification and evaluation of the potential environmental impacts and energy loads of a product/production process, through the identification of the incoming flows (materials, resources and energy) and outgoing flows (waste and polluting emissions into the environment) throughout the life cycle.

The LCA approach, of a quantitative nature and strictly engineering, was developed in the early 70s and has seen increasing diffusion since the 90s. It is an innovative methodology for addressing environmental issues related to a product or process, as it allows for a comprehensive assessment of impacts throughout the entire life cycle. It is a recommended process for measuring GHG emissions associated with constructing and operating buildings (Hoxha et al., 2020).

Through a “cradle to grave” analysis, the production system is considered in its entirety: for this reason, any hypotheses and/or attempts at specific improvement are evaluated with reference to the entire life cycle.

The assessment includes the phases of extraction and treatment of raw materials, production, transportation and distribution, up to use, reuse, recycling and final disposal. Initially LCA was adopted mainly in the industrial sector, now is widely applied in different fields, demonstrating its versatility and transversal relevance.

According to ISO 14040, the phases of a LCA are illustrated in *Figure 3*:

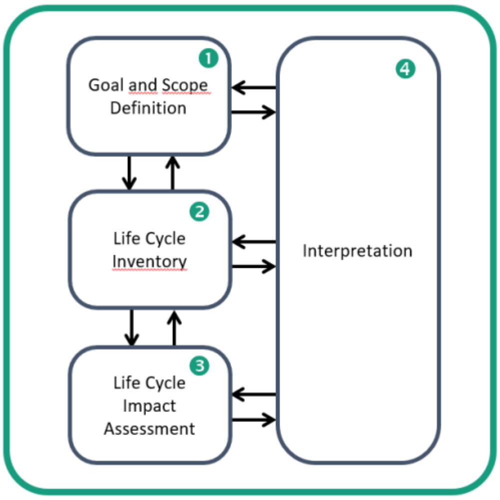

Figure 3: LCA scheme according to ISO 14040.

In the goal and scope definition phase (1), are defined the purposes and scope, the functional unit and the boundaries of the LCA. Therefore, this phase determines the entire setup of the study, describes the system and determines the categories of data to be collected, the assumptions and the limits.

The Life Cycle Inventory (LCI) analysis phase (2) includes the collection of data and calculation procedures that allow the quantification of the incoming and outgoing flows of a product system. It is certainly the most important phase in an LCA study: it creates a model of the real system examined and allows the determination of the physical inputs and outputs according to the objectives of the study. For this reason, this phase is usually supported by dedicated software and databases.

The Life Cycle Impact Assessment (LCIA) (3) is the processing phase of the acquired inventory results. The aim of this phase is evaluating the extent of the potential

environmental impacts and therefore highlighting the environmental modifications that are generated following the releases into the environment (emissions or wastewater) and the consumption of resources caused by the production activity.
Then the Life Cycle Interpretation and Improvement (4) is the final phase of LCA in which the results obtained in the inventory analysis and impact assessment are combined consistently with the pre-established objective and the purpose to be achieved. This phase aims to obtain conclusions and recommendations, necessary to reduce the environmental impact of the processes or activities considered, evaluating them iteratively.

In the construction sector LCA is strongly recommended for assessing GHG emissions associated with building materials and operations. It enables the evaluation of environmental impacts in an objective manner ensuring that all life-cycle stages are accounted ISO 14040 (Hoxha et al., 2020).

LCA results are often reported in Environmental Product Declarations (EPDs), which apply product-specific Product Category Rules (PCRs) to harmonize methodological choices and enhance comparability across products (Hoxha et al., 2020; Tellnes et al., 2014).
The LCA calculates a wide range of environmental impacts as air and water pollution, solid waste generation and ecosystem degradation. By quantifying these impacts, LCA helps identify opportunities for reducing emissions and improving the environmental performance of products and systems (Lippke et al., 2009).
When LCA is applied to mineral-based construction materials, the most critical life-cycle stages influencing global warming impacts are typically extraction and production (Lasvaux et al., 2014). However, for bio-based materials such as wood, focusing only on the production phase can yield incomplete results; in fact they are characterized by dynamic GHG flows, including sequestration during biomass growth and emissions at EoL, making it essential to consider both pre-harvest and post-use stages in the analysis. For these reasons is important to consider all stages of the LCA study (Hoxha et al., 2020; Fouquet et al., 2015; Levasseur et al., 2013). The timing of these flows can significantly influence the resulting global warming impact and, in some cases, lead to fundamentally different conclusions compared to time-independent (static) assessments (Breton et al.,

2018). Recent methodological advances allow for incorporating temporal aspects into LCA, such as dynamic characterization factors. These approaches remain uncommon in practice and are typically applied only in specialized case studies. Despite their importance, guidance remains limited on integrating time into building LCA, particularly for long-lived construction products (Breton et al., 2018).
Overall, LCA constitutes the leading methodological tool for comparing the environmental performance of products, including their global warming potential and provides the basis for robust and transparent environmental declarations in the building sector (Tellnes et al., 2014).

2.2 Biogenic carbon accounting methods

Currently there is no common approach within the LCA framework for consistently accounting for variations in biogenic carbon stocks in biomass, dead organic matter and soils. This methodological gap represents a critical challenge, particularly in the assessment of the climate sustainability of forestry and wood-based products. Under identical system conditions results may indicate either a carbon source or a carbon sink, depending on the accounting approach applied (Leinonen et al., 2022; Brandão et al., 2013). This lack of consensus is widely recognized as one of the most important methodological issues in current LCA development, reducing the credibility and comparability of climate impact evaluations (Leinonen et al., 2022).

The United Nations Environmental Programme (UNEP) research group started in 2024 to study and analyse the dynamic method. The goal of the project is to develop harmonized, scientifically and stakeholder-informed recommendations in a way to improve the biogenic carbon accounting in LCA. The study is expected to finish in 2027.

Within the LCA literature, two categories of biogenic carbon accounting methods are commonly distinguished: *static approaches* and *dynamic approaches*. Static approaches include both the simplified *0/0 approach*, also known as the carbon neutrality assumption, and the more detailed *–1/+1 approach*.

In the 0/0 approach, the uptake of CO_2 during biomass growth and the release of it at the EoL are assumed to be equal, so neither uptake and emission are included in the LCI or in the LCIA (Dodoo et al., 2025; Andersen et al., 2022; Hoxha et al., 2020; Fouquet et al., 2015). This assumption has been widely criticized for oversimplifying the climate impacts of bio-based systems, as it assigns a characterization factor of zero to all biogenic CO_2 emissions and neglects the effects of delayed regrowth and temporary storage (Breton et al., 2018).

As shown in *Figure 4*, biogenic CO_2 is not considered in any phase of the product life. Only the release of biogenic methane (CH_4) is considered during the EoL of the object, due to its higher impact on GW compared with biogenic CO_2 (Hoxha et al., 2020).

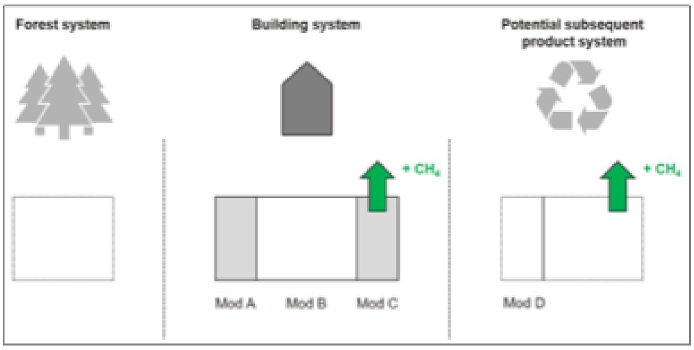

Figure 4: The 0/0 approach to model biogenic carbon uptake and release. Dotted lines indicate the product systems.

Instead, the –1/+1 approach represents a more comprehensive static accounting method, where all biogenic carbon flows are explicitly tracked across the life cycle. Carbon uptake during forest growth is recorded as a negative emission (–1), instead carbon release during degradation, combustion or disposal is recorded as a positive emission (+1) at EoL. This approach ensures mass balance consistency and provides greater transparency regarding biogenic carbon transfers between systems including recycling (ISO 2006) (Andersen et al., 2022; Hoxha et al., 2020). This approach considers the benefits of biogenic carbon uptake in the product and construction process stages and its release in the EoL stage of the building (Hoxha et al., 2020).

Figure 5 shows that the uptake of biogenic CO_2 during the forest growth is transferred to the building system and it is reported as a negative emission during the processing of the product. At the EoL of the building, biogenic CO_2 (or CO or CH_4) is released or the carbon content is further transferred to a subsequent product system (in the case of recycling). In both cases a positive emission is reported in module C. An important aspect in this approach is that the biogenic carbon balance should be zero for all product systems (Hoxha et al., 2020).

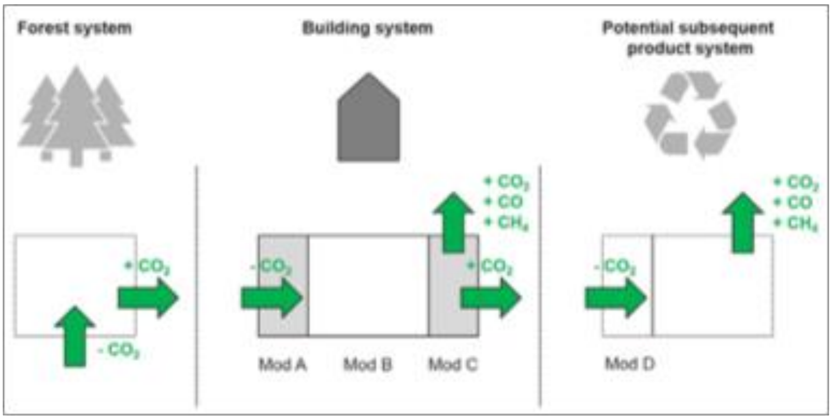

Figure 5: The −1/+1 approach to model biogenic carbon uptake and release. Dotted lines indicate the product systems.

A major limitation of static LCA approaches is their inability to account for the temporal dimension of carbon flows, including biomass regrowth rates and forest rotation periods (Breton et al., 2018). This limitation is especially relevant for wood-based products derived from slow-growing forests, where carbon payback times may span several decades. Studies have shown that not all bio-based materials can be considered carbon neutral within commonly applied assessment horizons. While fast-growing materials such as straw or hemp can provide rapid climate benefits, timber products derived from long-rotation forests may result in delayed carbon sequestration and temporary increases in atmospheric CO_2 concentrations (Pittau et al., 2018).

The role of time in GHG accounting emerges at two distinct levels: the LCI level and the LCIA level. At the LCI level time affects how present and future carbon uptake and emissions are represented, particularly with respect to the duration of carbon sequestration in biomass and harvested wood products. In this context, the permanence of carbon storage becomes a critical parameter. Carbon uptake associated with short-lived products is likely to be reversed rapidly through decomposition or combustion, whereas long-lived products, such as wooden furniture or building components, can store carbon for extended periods before it is released back into the atmosphere. However, no universally accepted threshold currently exists to distinguish between short-term and long-term storage and reaching consensus on this issue remains challenging (Brandão et al., 2013; Hoxha et al., 2020).

At the LCIA level time is reflected in the choice of the assessment horizon used to evaluate climate impacts following an emission. Most LCA studies rely on the 100-year Global Warming Potential (GWP100), which aggregates radiative forcing effects over a fixed time horizon. This choice implicitly determines how emissions occurring at different points in time are weighted in the impact assessment. A further methodological question concerns whether only present emissions should be considered or whether future emissions should also be included. In the latter case, it must be defined whether emissions are assessed over a finite time horizon or over an infinite one. The use of infinite time horizons may obscure potential future changes in emission profiles and overestimate cumulative warming effects, whereas short-term horizons may underestimate long-term temperature increases and cumulative climate impacts. Consequently, relying on a single time horizon may provide an incomplete representation of climate change impacts, suggesting that multiple temporal perspectives may be necessary for a comprehensive assessment (Breton et al., 2018; Levasseur et al., 2010).

To address these limitations, dynamic biogenic carbon accounting approaches have been developed. Dynamic LCA explicitly incorporates the timing of carbon uptake and release and links GHG emissions to their evolving effects on atmospheric concentrations over time. In these approaches, carbon neutrality over a life cycle does not necessarily imply climate neutrality, as the temporal distribution of emissions plays a decisive role in determining climate impacts (Breton et al., 2018). A time-dependent approach based on dynamic characterisation factors was introduced to account for the temporal profile of biogenic carbon emissions and removals (Levasseur et al., 2010). Specific characterisation factors for biogenic CO_2 were developed by incorporating biomass rotation periods into the assessment framework (Cherubini and Strømman et al., 2011). This methodological framework was later expanded to evaluate the climate impacts associated with carbon storage in wood-based products over time (Guest et al., 2013). Based on this research, it was found that carbon neutrality is achieved for a storage time of about half of the rotation period. Within the dynamic approach two scenarios can be considered related to the timing of biogenic carbon sequestration in the forest: (1)

assuming that trees grow before the use of the harvested wood product, following the natural carbon cycle; (2) accounting for the so-called ‘regrowth’ after harvesting, assuming an equal amount of the harvested trees would start growing right after the production process (Levasseur et al., 2010).

The first dynamic method is based on the concept of *temporary carbon storage*. In this approach, carbon sequestered in biomass or stored in wood products for a defined period leads to a temporary reduction in atmospheric CO_2 concentrations, which can be credited in the impact assessment. *Figure 6* illustrate how biogenic CO_2 is considered during all life cycle of a building.

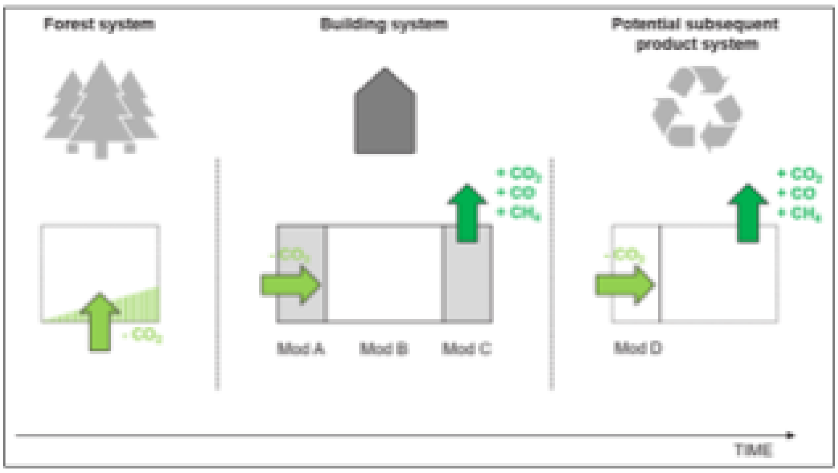

Figure 6: The dynamic approach, considering that trees grow before the use of the harvested wood product. Dotted lines indicate the product systems that fall outside the building system boundaries.

The second dynamic method relies on dynamic characterization factors, which explicitly model the temporal evolution of radiative forcing associated with biogenic CO_2 emissions and removals. This approach combines dynamic LCI with time-dependent characterization factors to quantify climate impacts as a function of the time emission. By integrating forest regrowth, product use, EoL emissions and substitution effects, DLCA can represent carbon flows across forest, product and substitution pools more accurately (Breton et al., 2018; Leinonen et al., 2022). *Figure 7* describes how biogenic CO_2 is considered in this approach.

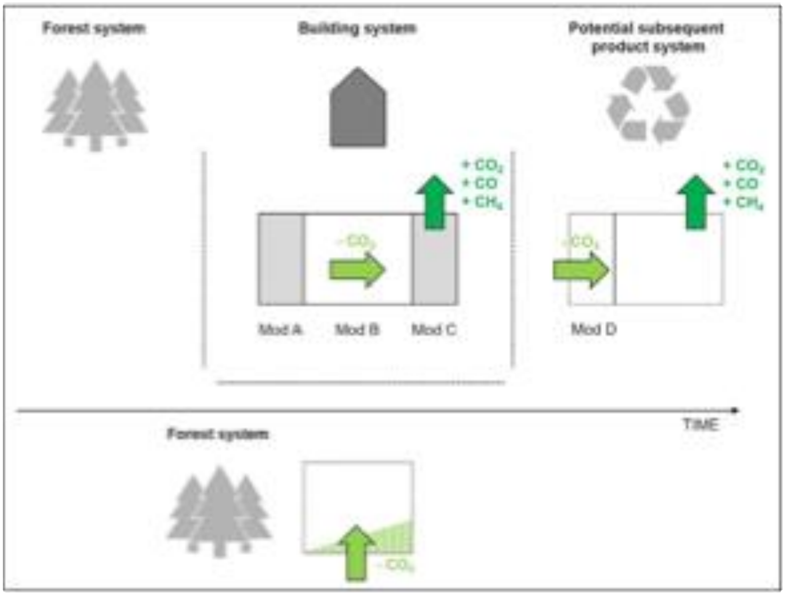

Figure 7: The dynamic approach, considering that trees regrow after harvesting. Dotted lines indicate the product systems that fall outside the building system boundaries.

Dynamic modelling is particularly relevant for wood-based products with long rotation periods, where delayed carbon uptake and long-term storage significantly influence climate outcomes (Liu et al., 2018; Pittau et al., 2017). Dynamic LCA enables a more accurate representation of biogenic carbon flows across forests, products and is particularly suited for assessing temporary carbon storage in long-lived wood products. Carbon storage is defined as the sequestration of carbon in products for a finite period, resulting in a temporary reduction of atmospheric CO_2 concentrations. Several standards distinguish between temporary storage (within a 100-year horizon) and permanent storage (beyond 100 years), and some methodologies such as PAS 2050 and the ILCD Handbook, allow credits to be assigned for temporary storage effects (Brandão et al., 2013; Hoxha et al., 2020).

A growing body of literature highlights the significant potential of wood-based buildings to mitigate climate change through reduced fossil fuel consumption and lower life cycle GHG emissions. However, most of these conclusions are derived from static modelling approaches that inadequately capture the dynamic behaviour of biogenic carbon flows throughout the life cycle of wood-based products (Leskinen et al., 2018; Food and Agricultural Organisation of the United Nations, 2016; Sathre and O'Connor et al., 2010). The complexity associated with 38odelling biogenic carbon uptake, storage and release has been emphasized in the literature, together with the need for methodological refinement and further research (Brandão et al., 2013; Dodoo et al., 2025).

Despite its conceptual advantages, time-dependent 38odelling has not been adopted in IPCC guidelines for national GHG inventories so its implementation in product-level LCAs remains limited (IPCC 2006) (Leinonenet al., 2022). Nevertheless, comparative studies indicate that the choice of biogenic carbon accounting method can significantly influence LCA outcomes. In fact the estimated climate change impact of a timber building may vary up to 16% depending on whether static or dynamic approaches are applied; with dynamic methods providing a more robust and transparent representation of biogenic carbon dynamics (Levasseur et al., 2013, 2010).

Finally, accurate quantification of biogenic carbon content in wood-based products is a prerequisite for all accounting approaches. This is commonly calculated using standardized methods which estimate biogenic carbon content based on wood density, moisture content, volume and an assumed carbon fraction of 0.5 on a dry mass basis (Dodoo et al., 2025). Together, these methodological considerations highlight the importance of moving beyond simplified assumptions toward more comprehensive and temporally explicit approaches for assessing the climate impacts of biogenic carbon in LCA.

2.3 Divergences in definitions across standards and guidelines

The assessment of biogenic carbon in LCA is characterized by substantial divergences across standards, guidelines and reporting frameworks, despite their shared objective of improving the consistency and transparency of climate change assessments. Most LCA-based standards are derived from ISO 14040 and ISO 14044, which provide the core framework for LCA studies, while other influential documents, such as the IPCC Guidelines and the GHG Protocol, are not LCA standards but strongly influence methodological choices and impact characterization practices (Soldal and Saur Modahl et al., 2022).

A schematic of the connectivity of all standards considered is presented in *Figure 8*.

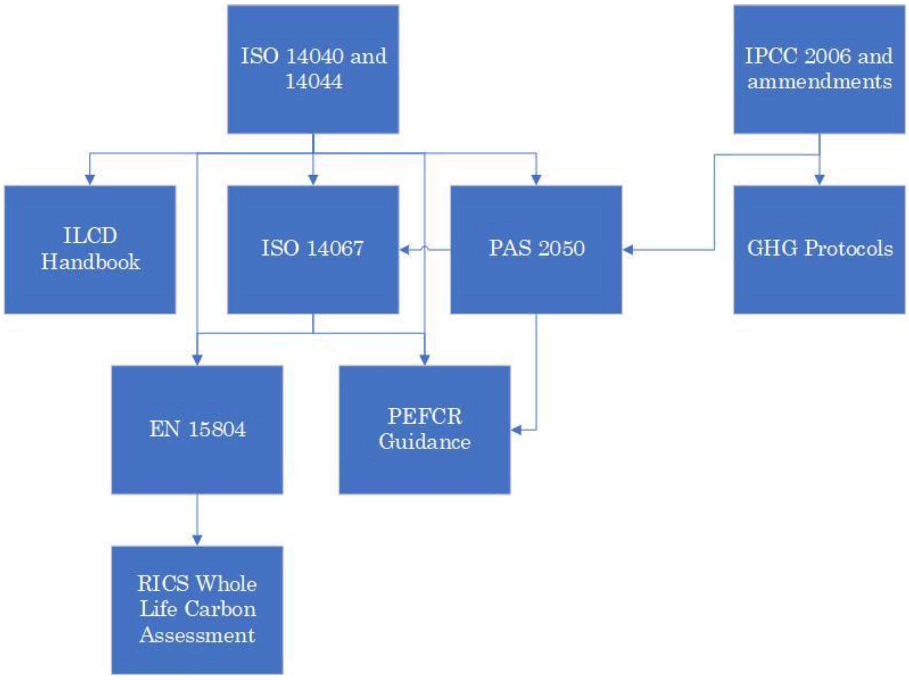

Figure 8: Relationship between the standards covered. All LCA standards covered are derived from ISO 14040 and 14044 in some form. IPCC and GHG Protocols are not LCA standards.

Across the reviewed LCA standards, several methodological similarities can be identified. All recommend the use of a 100-year time horizon for climate change assessment, consistent with the GWP100 characterization factors developed by the IPCC. Biogenic carbon is required to be reported separately from fossil carbon and EoL emissions are included whenever cradle-to-grave system boundaries are applied (Soldal and Saur Modahl et al., 2022; Hoxha et al., 2020).

Despite these common elements, significant divergences persist in the definition and treatment of biogenic carbon. While all standards define biogenic carbon as carbon derived from plant or animal biomass, specific inclusions and exclusions vary substantially. For example, soil carbon is included in the GHG Protocol under certain conditions, whereas it is classified under land use and land use change in the Product Environmental Footprint Category Rules (PEFCR). Similarly PAS 2050 uniquely includes CO_2 from air converted into non-biomass carbonates, such as carbonation processes in cement; this interpretation is not shared by other standards. These discrepancies of the definition inevitably lead to inconsistencies in reporting and limit the comparability of LCA results across studies and frameworks (Soldal and Saur Modahl et al., 2022).

Another major source of divergence concerns the treatment of carbon storage. While most standards adopt the −1/+1 accounting framework, they apply different rules regarding whether and how biogenic carbon stored within the assessment TH is credited. Some standards, such as PAS 2050 and PEFCR, consider carbon stored for more than 100 years as permanently stored and allow credits, whereas others, as EN 15804, do not permit any form of carbon storage credit and require all biogenic carbon to be released as emissions by the end of the assessment period. The ILCD Handbook adopts a distinct approach by explicitly crediting temporary carbon storage proportionally to the duration of storage within the 100-year time horizon, reflecting the absence of radiative forcing during that period (EC, 2017; Hoxha et al., 2020).

Further divergence arises in the treatment of biogenic carbon in cradle-to-gate assessments. EN 15804 does not include the biogenic carbon uptake in cradle-to-gate system boundaries, whereas other standards allow it but apply different balancing rules. Instead, PAS 2050 require the exclusion of EoL emissions from the system boundary, while PEFCR considers waste treatment in the life cycle stage where it occurs to preserve the −1/+1 balance. In contrast, several standards provide no explicit guidance, leaving methodological decisions to the discretion of the practitioner, thereby increasing variability in practice (Soldal and Saur Modahl et al., 2022).

Although the IPCC Guidelines for National Greenhouse Gas Inventories are not LCA standards, they play a foundational role in shaping climate impact assessment. It defines biogenic carbon as carbon derived from plant or animal biomass, explicitly excluding peat due to its long regeneration time, and applies a −1/+1 logic across carbon pools. However, the IPCC does not adopt time-dependent dynamic accounting within its inventory framework, which further contributes to discrepancies between national inventory approaches and product-level LCA studies (IPCC, 2019).

Overall, the lack of harmonization across standards in terms of definitions, storage treatment, time horizons and system boundary rules represents a major challenge for the consistent assessment of biogenic carbon in LCA. As none of the reviewed standards explicitly adopt a fully time-dependent dynamic approach, biogenic carbon uptake and release are generally represented as instantaneous pulses rather than as temporally distributed processes. This methodological fragmentation underscores the need for more coherent and temporally explicit accounting frameworks, which is particularly relevant for long-lived wood-based products and provides a strong rationale for the dynamic approaches discussed in the following section (Breton et al., 2018; Hoxha et al., 2020). *Table 1* describes the different handling of biogenic carbon in all the cited standards evidencing their differences.

Table 1: Summary of biogenic carbon accounting approaches in the covered standards.

	Caveats in definition	Approach	Storage	Region
ISO 14067	Does not include peat or geological carbon that was once biological.	-1/+1	No - All emissions and removals considered as released at beginning of assessment	Global
GHG Protocols – Product Life Cycle Accounting	Includes "a variety of" soil and water-based sources. If origin is ambiguous then count as non-biogenic.	-1/+1	Yes - If not released to atmosphere during waste treatment	Global
ILCD Handbook	No explicit inclusions or exclusions noted.	-1/+1	Yes - Credits for storage*	Global
PAS 2050	Includes CO_2 from air converted into non- biomass carbonates. Does not include soil carbon.	-1/+1 (-1/0**)	Yes - Considered for 100+ years only	UK with global adoption
PEFCR Guidance	Does not include soil carbon.	-1/+1 (-1/0**)	Yes - Considered permanent after 100 years	Global
EN 15804	Includes carbon transfers to/from: non-native forest, other product systems, emissions to air	-1/+1	No - neither temporary nor permanent storage is included	EU

	from combustion or degradation			
RICS Whole life carbon assessment for the built environment	Same definition as EN15804	-1/+1	Yes - Appendix N refers to the PAS 2050 approach	UK
IPCC Guidelines for National GHG Inventories	Plant or animal biomass. Excludes peat due to long restoration period	-1/+1	Yes – Not specific to biogenic carbon, any storage in a carbon pool is to be accounted for	Global

*Credits awarded for storage equal to "no. years stored"/100 in the short-term perspective
**If carbon remains in the biomass for 100+ years

2.4 Principles of the dynamic model

In recent years increasing attention has been focused on the insufficient consideration of temporal aspects of GHG emissions in conventional LCA and carbon-footprint methodologies. Two main drivers explain this concern: (1) the growing policy interest in recognizing the climate relevance of temporary carbon storage, (2) methodological inconsistencies arising from the use of fixed time horizons, such as GWP100, to evaluate emissions that occur at different moments in the life cycle (Levasseur et al., 2013).

Releasing a large quantity of pollutants instantaneously does not generally produce the same climate impact as releasing the same amount gradually over several years. DLCA explicitly accounts for the temporal distribution of emissions, meaning that LCI results are expressed as time-dependent emission functions rather than as single aggregated values. This temporal representation enables the calculation of climate impacts based on the evolution of atmospheric concentrations and radiative forcing over time rather than on static indicators (Levasseur et al., 2013).

However, some studies with climate models have shown that taking carbon out of the atmosphere and releasing it back several years later can lead to a higher atmospheric concentration of CO_2, thus a higher temperature at some point in time, than if the carbon

had not been stored (Korhonen et al., 2002). At the same time temporary carbon storage may provide time for mitigation while allowing technological development and emission-reduction strategies to process (Dornburg and Marland, 2008).
Conventional LCA approaches are generally unable to capture these dynamics, since biogenic carbon uptake during biomass growth is typically subtracted from EoL emissions, leading to a net-zero balance that neglects the timing of sequestration and release (Levasseur et al., 2013).

Dynamic LCA has therefore emerged as a more comprehensive method for assessing bio-based systems providing a physically consistent representation of the impacts associated with biogenic carbon flows. This approach is particularly relevant for wood-based construction products and buildings, whose long service lives and delayed EoL emissions strongly influence climate outcomes (Hawkins et al., 2021).
Recent studies indicate that static accounting underestimate the climate-mitigation benefits of forest management and harvested wood products, whereas dynamic modelling can reveal substantially larger benefits due to the timing of carbon sequestration and release (Song et al., 2024).

At the same time the methodological accounting of biogenic carbon in LCA remains debated, as different approaches may classify the same forestry product either as a carbon source or sink. This lack of consensus highlights the need for transparent and physically grounded dynamic modelling frameworks capable of consistently representing carbon-stock changes across biomass, products and EoL (Leinonen, 2022).

Overall, DLCA represents a key methodological progress for evaluating the climate performance of bio-based materials, enabling a more realistic interpretation of temporary storage, delayed emissions and long-term carbon dynamics compared with conventional static LCA (Cherubini et al., 2012).

2.5 Methodological foundation of static and dynamic LCA

LCA is based on time-independent characterization factors, meaning that GHGs emissions are aggregated regardless of when they occur during the product life cycle.

This assumption implicitly assigns equal importance to emissions occurring at different moments in time, which may not be appropriate when fixed TH are applied (Cherubini et al., 2012).
Within the EN 15804 framework and EPDs the GWP100 is used as the standard climate indicator. However, this metric does not differentiate between emissions occurring at year 0 and emissions occurring several years later. Conventional LCA therefore fails to account for the temporal dimension of biogenic carbon storage and delayed emissions, particularly in long-lived construction products (Hawkins et al., 2021).
DLCA was introduced to address these limitations by explicitly considering the timing of emissions and removals throughout the life cycle. In dynamic models, emissions are represented as time-dependent flows whose climate effects evolve over time. This approach is particularly relevant for bio-based systems, where carbon uptake during biomass growth and carbon release at EoL are temporally separated (Cherubini et al., 2012) .

2.6 Dynamic method

The dynamic assessment implemented in this study follows the framework proposed by (Levasseur et al., 2013) and is based on the calculation of time-dependent atmospheric CO_2 load and radiative forcing.

The calculation of the dynamic climate impact involves three main steps. First, the atmospheric persistence of CO_2 emissions is described using an impulse response function derived from carbon cycle models. Second, the time-dependent atmospheric load is calculated by combining the emission profile with the persistence function. Finally, the cumulative climate impact over the selected TH is obtained by integrating the atmospheric load and normalizing it relative to a reference pulse of fossil CO_2. The following subsections describe in detail the mathematical formulation and implementation of these steps.

2.6.1 Atmospheric persistence using the impulse response function

Atmospheric persistence was modelled using the Bern carbon cycle Impulse Response Function (IRF), adopted in IPCC climate assessments (IPCC, 2013).

$$IRF(\Delta t) = a_0 + a_1 \cdot e^{-\frac{\Delta t}{\tau_1}} + a_2 \cdot e^{-\frac{\Delta t}{\tau_2}} + a_3 \cdot e^{-\frac{\Delta t}{\tau_3}}$$

where a are fractional coefficients and τ are time constants:

a_0 = 0,217	
a_1 = 0,259	τ_1 = 172,9
a_2 = 0,338	τ_2 = 18,51
a_3 = 0,186	τ_2 = 1,186

This function represents the fraction of emitted CO_2 that remains in the atmosphere over time, thereby enabling the conversion of emission pulses into a time-dependent atmospheric carbon load.

In the file Excel the IRF CO_2 (Δt) is calculated for every time, from t = 0 to TH =100 years.

2.6.2 Calculation of the atmospheric CO_2 load

Since emissions occur at different times the total atmospheric perturbation at year t is the sum of the residual contributions of all previous annual emissions/removals. This is computed through a discrete convolution:

$$Load_{CO2}(t) = \sum_{k=0}^{t} g(k) \cdot IRF_{CO2}\,(t-k)$$

Where if:

- g(k) > 0: CO_2 is added → atmospheric load increases;
- g(k) < 0: CO_2 is removed (uptake/storage credit) → atmospheric load decreases.

This step links emission timing to climate response.

In the spreadsheet this calculation is implemented by computing the annual atmospheric load, Load_CO_2 (t), and then summed over the TH.

2.6.3 Dynamic climate indicator and normalization

Climate impact was obtained by integrating atmospheric load over 100 years.

$$\sum_{t=0}^{TH} Load_{CO2}(t)$$

Then the integrated impact of the biogenic emission history is normalized to 1 kg fossil CO_2 pulse over the same time, which express result in a CO_2 equivalent metric comparable to conventional GWP.

$$GWP_{dyn} = \frac{\sum_{t=0}^{TH} Load_{CO2}(t)}{\sum_{t=0}^{TH} IRF_{CO2}(t)}$$

This final formula yields to the GWP_{dyn} (Levasseur et al., 2013)

3. STATIC ACCOUNTING METHOD OF BIOGENIC CO_2: NAVELLO WOODEN WINDOW CASE STUDY

3.1 Definition of a case study

To evaluate the differences between static and dynamic approaches for biogenic carbon accounting, was selected a real case study. The analyzed product is a wooden window produced by the company Navello, which represents an example of a wood-based construction product characterized by the temporary storage of biogenic carbon during its service life.

The environmental performance of the product was first assessed through a LCA conducted in accordance with the Product Category Rules (PCR) for EPDs. These guidelines provide a standardized and widely recognized framework for performing LCAs of construction products, ensuring methodological consistency and comparability of results. Following the PCR requirements, the impact assessment was initially carried out using the conventional static approach, which is currently adopted in EPD studies.

For completeness, the results obtained for all the environmental indicators required by the PCR are presented in chapter 3.3.11. However, particular attention is given to the GWP indicator, as it is directly affected by the treatment of biogenic carbon flows. In this chapter the case study is therefore used as a basis for a more detailed analysis of climate change impacts, comparing the results obtained using the conventional static method with those derived from the dynamic accounting approach.

3.2 Description of the company and the product

Navello is an Italian manufacturer of wooden windows with a long-standing tradition since 1824. Founded in Dogliani, the company has combined artisanal expertise with advanced industrial production, becoming a leader in high-quality wooden windows and doors. Over seven generations, Navello has consistently invested in research and development, high-grade raw materials and innovative wood processing technologies, enabling the production of customized window systems for both residential buildings and large-scale architectural projects.

Sustainability represents a core element of Navello's philosophy. In fact, the company holds FSC® and PEFC™ certifications, which ensure that the wood used in its products comes from responsibly managed forests and complies with the requirements of the EUTR. These certifications reflect Navello's commitment to minimizing environmental impacts while safeguarding forest ecosystems.

Customer care, product customization and continuous quality improvement remain central to Navello's mission, reinforcing the company's position as one of the leading actors in the Italian wooden window industry.

3.3 LCA applied to the case study

In an LCA study it is essential to precisely define the objectives, in order to have a tool capable of capturing all the environmental implications associated with the system analyzed and of providing coherent answers to the issues considered relevant.
The main objective is to analyze, quantify and verify the average environmental impacts generated by the life cycle of 1 m^2 of a window, through the LCA methodology and in compliance with the provisions of the Product Category Rules (PCR) 2019:14 – Construction products, Version 2.0.1 and the General Programme Instructions (GPI) for the International EPD® System, Version 5.0.0. There is also the specific C-PCR (Complementary PCR), (C-PCR 007), Version 1.0.0 related to windows and doors. Moreover, reference was made to the general requirements established in the PCR and in the relevant international standards: (EN 15804:2012+2019:A2/AC:2021), ISO 14040:2006, ISO 14044:2018, ISO 14025:2010 and ISO 21930:2017.
In particular, the study focuses on a single window model manufactured by Navello named Seta 2.0. This model was selected because it accounts for 68% of the company's total sales in 2024 and is made of finger-joint laminated pine, which was used in 46% of the orders placed during the same year.
The broader environmental objective is to estimate the average environmental impacts associated with the complete life cycle of a window finishing up to a likely EoL scenario, then focusing on the impact regarding the biogenic CO_2. A further objective of the study is to identify the processes most responsible, on average, for the potential impact on climate change, thus providing useful information for environmental improvement interventions.

3.3.1 Product description and content declaration

The product analysed in the LCA study is a wood window with dimension of 1230 mm x 1480 mm, equipped with a 115 mm central mullion (instead of the traditional 128 mm), single-glazed unit, smooth single sash, and fixed frame with a 68 x 68 mm section made of finger-jointed laminated pine. The profiles are manufactured with counter-moulding and joined at 90° using double tenon joints and adhesive tested according to EN 14257 standard. In accordance with the United Nations classification, the products fall under the UN CPC code 31621 "Windows, French-windows and their frames made out of wood", under category 3162 "Builder's joinery and carpentry of wood (including cellular wood panels, assembled parquet panels, shingles and shakes)" and are characterized by high durability and stable technical performance over time. In this regard, the Reference Service Life (RSL) of the products, taking into account their nature and intended applications, was assumed to be equal to 40 years (Asif et al., 2005).

From a chemical safety perspective, none of the products studied contain substances included in the SVHC (Substances of Very High Concern) list drawn up by the European Chemicals Agency (ECHA) in concentrations above 0.1% by weight, thus ensuring compliance with REACH requirements for human health and the environment.

For the evaluation of the impacts related to the downstream and beneficial modules, an average wood bulk density of 500 kg/m^3 is considered, so 1 m^2 of wood corresponds to 35.30 kg.

The *Table 2* and *Table 3* present the content of biogenic material and other details regarding the analyzed product and packaging. The wood is assumed to have 12% moisture content and half of the dry wood is carbon, C. Each kg of stored biogenic carbon is equal to 44/12 kg of CO_2.

Table 2: Product Content Declaration.

Component	Average weight [kg]	Weight [% of declared unit weight]	Post-consumer recycled material, weight-% of product	Biogenic material, weight-% and kg C / Kg
Wood	11.21	31.77%	0%	100% and 0.44 Kg C / Kg
Glass	22.63	64.12%	0%	-
Aluminium	0.03	0.07%	0%	-
Steel	1.08	3.07%	0%	-
Brass	0.08	0.22%	0%	-
Seals	0.25	0.70%	0%	-
Silicone	0.02	0.04%	0%	-

Table 3: Declaration of packaging content.

Packaging material	Weight [kg/m2]	Weight [% of declared unit weight]	Biogenic material, weight-% and kg C / Kg
Corrugated board	0.49	0.61%	100% and 0.44 Kg C / Kg
Polyethylene	0.32	0.39%	-

3.3.2 System boundaries

The definition of system boundaries represents one of the most crucial and delicate aspects of an LCA study, since the choices made in this phase significantly impact the final results and their interpretation.

It is therefore essential to establish precisely which phases of the product life cycle and which segments of the production chain are included in the analysis. This step allows to ensure methodological coherence and completeness in the assessment of environmental impacts.

In the case of a window production, environmental impacts are not limited to the processes carried out within the plants directly. In fact, indirect environmental

consequences, i.e. those that occur outside the physical boundaries of the plants but that are attributable to the product analysed, can be even greater than the direct ones.
The boundaries of the system under study are therefore not limited to the physical boundaries of the window and the plant, but extend upstream and downstream to include the entire supply chain, including the following subsystems:

- the production and supply of raw materials and auxiliary materials (wood, sandpaper, paint, glass, ...);
- the production and use of energy consumed in various processes (51% generated from photovoltaic panels installed in the company and the remaining 49% supplied by grid electricity);
- the use of road and naval transport systems;
- the internal processing activities in the plant: cutting, sanding, gluing, puttying, painting, hardware assembly, packaging, transport, and window installation;
- waste treatment and management;
- end-of-life phases, including demolition, treatment and disposal.

The geographical boundaries are identifiable in the Italian national area with regards to the processing carried out in the company and in the European landscape for the extraction and transportation of raw materials, product EoL scenarios and for module D benefits.

The time boundaries refer to the years 2024 and 2025 for the energy consumption, and just to the year 2025 for the production and transport data.

Additionally, the following exclusions from the system boundaries have been made in line with the guidance of the reference PCR:

- the construction of company buildings and related infrastructure (i.e. capital goods);
- the production and maintenance of machinery and equipment (i.e. capital goods);
- staff-related activities (i.e. personnel processes);
- the maintenance and production of spare parts;

- the maintenance operations of vehicles;
- all company operations not related to the processing of the material considered in the study.

3.3.3 Cut-off criteria and proxy data

The criterion adopted for the inclusion of inputs and outputs is based on a cut-off level of 1% by mass and energy for each individual process. However, all processes for which data were available were included in the analysis, even if their contribution was below this threshold. Consequently, the cut-off was applied solely to avoid collecting unavailable data, and not to exclude information already acquired. Specifically, the wood waste generated by sanding with abrasive paper during the surface finishing phase was not considered.

3.3.4 Declared modules and content of life cycle phases

This study complies with (EN 15804:2012+2019:A2/AC:2021) and adopts a "cradle-to-gate with modules C1-C4 and module D" approach, specifically including modules C1-C4 and module D, related to EoL and potential benefits.
Below, the *Table 4* provides an overview of the life cycle information modules declared in the study, specifying for each of them the geographical scope of reference, the source of the data and the expected coverage according to the standard. To ensure a coherent, transparent and comparable environmental assessment, the study uses a model divided into three main phases: upstream, core and downstream, with the inclusion of module D. *Table 5* describes the specific contents included in each phase of the life cycle, in accordance with the structure defined by the reference standard.

Table 4: Declared modules, geographical coverage and data origin.

	Product stage			Construction process stage		Use stage							End of life stage				Resource recovery stage
	Raw material supply	Transport of raw materials	Manufacturing	Transport to customer	Installation	Use	Maintenance	Repair	Replacement	Refurbishing	Operational energy use	Operational water use	Deconstruction/Demolition	Transport to waste processing	Waste processing	Disposal	Reuse – Recovery - Recycling potential
Module	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Declared module	X	X	X	X	X	ND	ND	ND	ND	ND	ND	ND	X	X	X	X	X
Geography	EU	EU	IT	EU	EU	-	-	-	-	-	-	-	EU	EU	EU	EU	EU
Specific data	> 90%					-	-	-	-	-	-	-	-	-	-	-	-
Variation - Products	Not applicable					-	-	-	-	-	-	-	-	-	-	-	-
Variation - Sites	Not applicable					-	-	-	-	-	-	-	-	-	-	-	-

Table 5: Structure and contents by life cycle phase according to EN 15804.

Phase	Module	Main contents
UPSTREAM	A1	Production of auxiliary materials
	A2	Transport of auxiliary materials to the production plant
CORE	A3	Internal wood processing processes Treatment and management of waste produced in the plant Packaging for shipping the finished product
TRANSPORT	A4	Transportation of the final product to the client
ASSEMBLAY	A5	Assembly of the final product
DOWNLOADSTREAM	C1	Removal and demolition of the window at the end of its useful life
	C2	Transport of materials to the treatment or disposal facility
	C3	Waste processing
	C4	Landfill disposal
BENEFITS	D	Recovery, reuse or recycling activities of the window's material that has reached the end of its life

3.3.5 Declared unit

For the comparison and evaluation of the average environmental impacts of a window, the declared unit adopted is equal to 1 m^2 a window finish, ready to be delivered to the consumer, in compliance with the reference PCR.

However, for the purposes of calculating the environmental impacts along the various phases of the product life cycle, specific declared units have been defined for each module, in relation to the nature of the processes involved, as reported in *Table 6*.

Table 6: Declared units adopted for life cycle module.

Modules	Declared unit
A1-A3	1 m^2 of manufactured window
A4	1 m^2 packed for delivery
A5	1 m^2 for the assembly
C + D	1 m^2 of disposed window

Specifically, in cases where the declared unit is not expressed in mass, a conversion factor based on the bulk density of the material is applied in line with the provisions of the reference legislation.

3.3.6 Data quality assessment and LCA IT tools

The company participating in the project provided specific data relating to its production in the processing plants. All primary data used in the model were collected through questionnaires filled out by company representatives between April and June 2025 and referred to the years 2024 and 2025. Most of the data employed in the model for the module A3 were directly measured, and therefore the reference year is 2025.

Table 7 declares the source, reference year, data category, and the share of primary data of GWP-GHG results for all processes contributing more than 10% to the GWP-GHG results of modules A1-A5, plus other relevant processes, which all together contribute to more than 90% of the declared results.

The share of primary data is calculated based on GWP-GHG results. It is a simplified indicator for data quality that do not capture all relevant aspects of data quality. The indicator is not comparable across product categories.

Table 7: Declaration of sources, reference years, categories and share of primary data.

Process	Source type	Source	Reference year	Data category	Share of primary data, of GWP-GHG results for A1-A5
Glazing production	Database	Ecoinvent 3.10 and participating companies	2025	Primary data	46.46%
Energy	Data collection	Participating companies	2024-25	Primary data	22.54%
Transportation	Data collection	Participating companies	2025	Primary data	13.95%
Raw material (except glass and wood)	Data collection	Participating companies	2025	Primary data and secondary data	11.99%
Total share of primary data in GWP-GHG results for modules A1-A5					> 90%

Due to the partial unavailability of data from the reference company, it was necessary to integrate the information, where missing, with data relating to a technically similar material considered representative.

For the production of auxiliary materials used in the window supply chain (e.g. sandpaper and handle), were used data from previous studies (3M, 2016; ARGE, 2024) . Therefore, these data were classified as representative secondary data, compatible with the quality criteria required by EN 15941.

The IT tools supporting the development and analysis of the LCA model are the following:

- LCA Software: OpenLCA 2.5.0;
- LCA database: The Ecoinvent 3.10 database developed by the Swiss Centre for Life Cycle Assessment was used as a source of selected generic data.

3.3.7 Inventory Analysis (LCI)

Here are described all the "subsystems", the subset of activities, or a specific sequence of process units (ISO14040) within the life cycle that constitute the LCA models, of the production of the window Seta 2.0.

The processes and activities within the sequence that constitutes the life cycle of the window are described as they were entered into the OpenLCA software application.

Each single process unit is conceived as an input/output system, where the incoming and outgoing flows of materials, emissions and energy are quantified.

The life cycle considered in the study is illustrated in *Figure 9*, which represents the process diagram used to define the system boundaries of the LCA analysis related to the production of the window. The diagram highlights the main phases of the production cycle, the related information modules and the processes included in each phase. For each step, the environmental inputs and outputs are indicated, i.e. the flows of materials and energy and the waste produced.

The big pink rectangle delimits the system boundaries used to calculate environmental impacts throughout the entire life cycle of the product, up to the EoL phases.

The cycle begins with the made of raw material needed for the production of the window (wood, sandpaper, glue, putty, paint, hardware, glass, seals, silicone, packaging film, bubble wrap and the handle) (A1). Subsequently, the raw materials are transported to the plant (A2). Then starts all the processes involved in production of the window (A3), some steps are performed manually others by using the proper machines. Once the product is finished it is transported to the final users (A4) and assembled (A5).

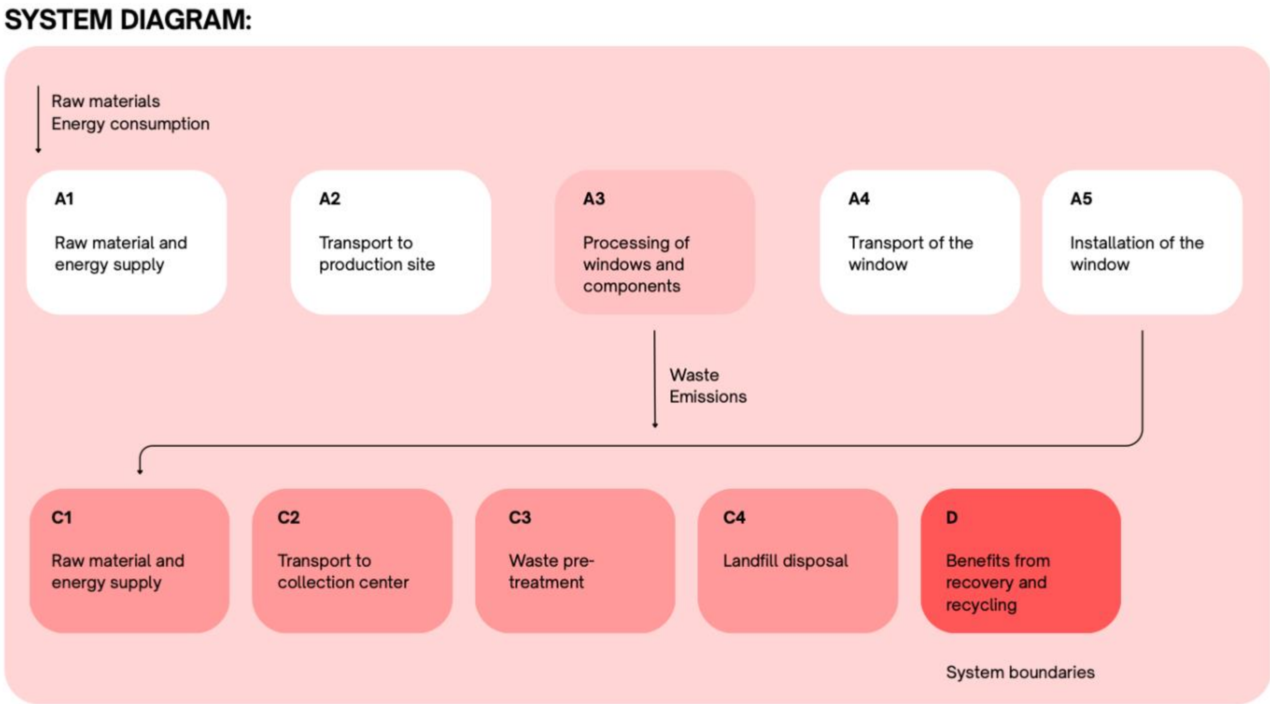

Figure 9: LCA system boundaries: the big pink rectangle delimits the system boundaries for calculating the impacts of the window during their life cycle.

Figure 10 illustrates all the process steps carried out in the Navello company to obtain the final product. All these processes are included in module A3.

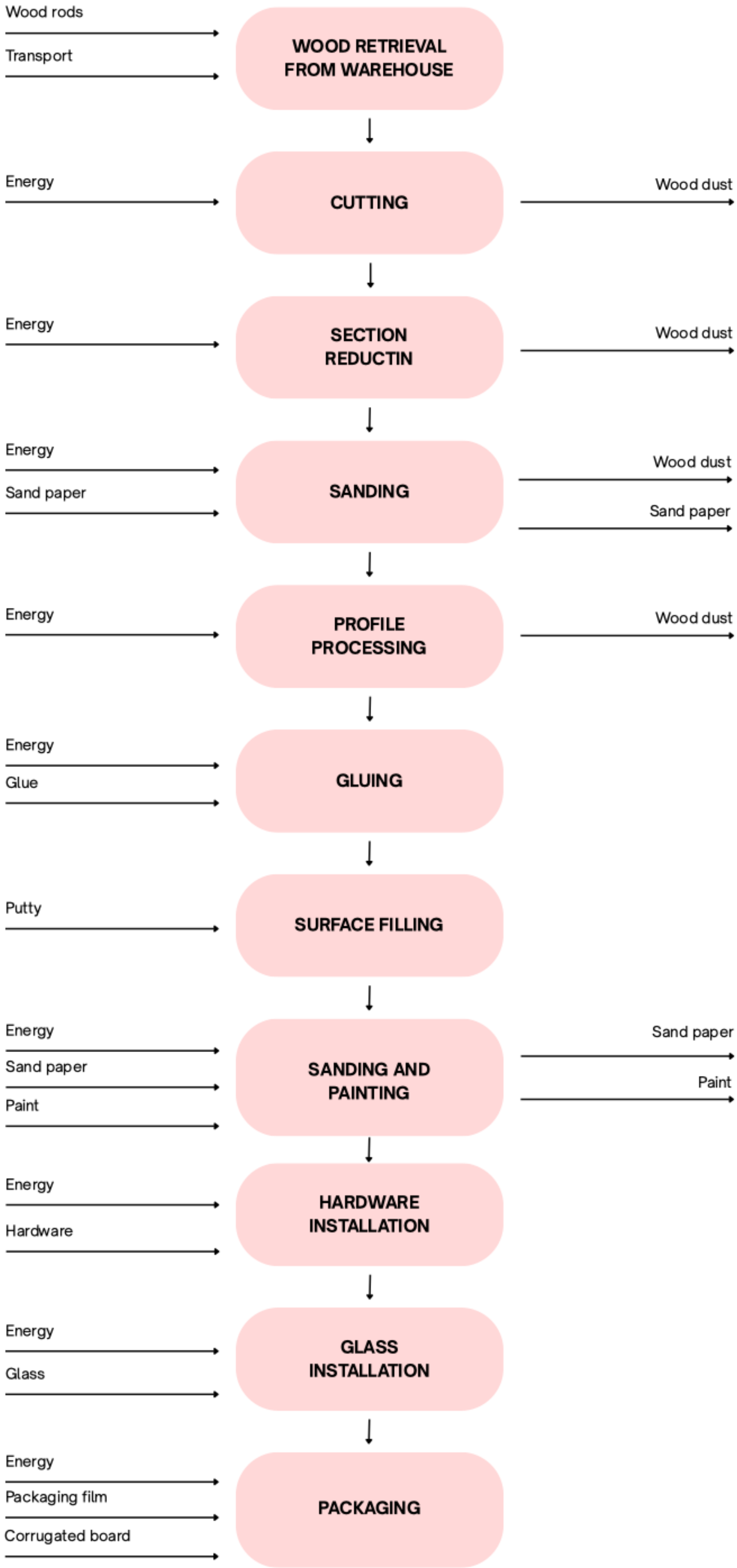

Figure 10: Detailed process steps of the module A3.

Once the processing is completed, the product is packaged (A3) for shipping, using materials such as corrugated board and packaging film. Each phase is accompanied by energy and material inputs, as well as waste generation.
The life cycle ends with the EoL phases, which include the demolition of the product (C1), the subsequent waste transportation (C2) and their final processing. In this case for each material we assume the following scenario:

- Glass: 30% recycled (C3) and 70% goes to landfill (C4);
- Steel: 95% recycled (C3) and 5% goes to landfill (C4);
- Aluminum: 95% recycled (C3) and 5% goes to landfill (C4);
- Rubber: 100% goes to landfill (C4);
- Brass: 95% recycled (C3) and 5% goes to landfill (C4);
- Wood: 95% recycled (C3) and 5% goes to landfill (C4).

The electricity used in this study for the module A was modelled considering 51% coming from photovoltaic panels, using the dataset "Electricity, medium voltage, renewable energy products | Cutoff, S – CH". The remaining 49% is based on the Italian residual mix from the Ecoinvent 3.10 dataset "Electricity, medium voltage, residual mix | electricity, medium voltage | Cutoff, S – IT". This dataset reflects the 2022 Italian residual mix as reported in the 2023 AIB report (*Table 8*). Instead for the modules C and D was considered just the dataset "Electricity, medium voltage, residual mix | electricity, medium voltage | Cutoff, S – IT".

Table 8:Italian energy mix for the year 2022 (AIB, 2023).

	RE total	RE unspecified	RE biomass	RE solar	RE geothermal	RE wind	RE hydro	Nuclear	FO total	FO unspecified	FO hard coal	FO lignite	FO oil	FO gas
IT	9.4%	0.0%	1.68%	5.97%	0.0%	0.84%	0.54%	2.62%	88.34%	2.73%	12.2%	0.02%	4.47%	68.92%

The climate impact (in kg CO_2 eq./kWh using the GWP-GHG indicator) of electricity purchased in the manufacturing process in A3 considering the datasets presented above is 14.14 kg CO2 eq./kWh.

The raw materials and the means of transport used to deliver each of them to the Navello company, needed for the production of 1 m^2 of a window Seta 2.0 are listed in the *Table 9*.

Table 9: Raw materials and means of transport.

Flows	Amount [Kg]	Ecoinvent Dataset	Mean of transport	Distance [Km]
Wood	17.64	Glued laminated timber, PUR-glue	Transport, freight, lorry >32 metric ton, EURO4	2392
Sandpaper	0.90	0.40 Aluminium hydroxide 0.40 Kraft paper 0.20 Phenolic resin	Transport, freight, light commercial vehicle	473
Glue	0.015	Melamine urea formaldehyde adhesive	Transport, freight, light commercial vehicle	214
Putty	0.001	Acrylic filler	Transport, freight, light commercial vehicle	22
Paint	1.322	Acrylic dispersion, with water, in 58% solution state	Transport, freight, light commercial vehicle	26
Hardware	1.119	Steel, low-alloyed	Transport, freight, light commercial vehicle	516

Glass	22.627	Glazing, double, U<1.1 W/m2K	-Transport, freight, lorry 3.5-7.5 metric ton, EURO6 -Transport, freight, lorry 3.5-7.5 metric ton, EURO4	6.7 32.2
Seals	0,247	polyvinylchloride, bulk polymerised	Transport, freight, light commercial vehicle	410
Silicone	0,015	Silicone product	Transport, freight, light commercial vehicle	446
Packaging film	0.315	Packaging film, low density polyethylene	Transport, freight, light commercial vehicle	352
Corrugated board	0.494	Corrugated board box	Transport, freight, light commercial vehicle	5
Handle	0.103	121.3 electricity, medium voltage alloy 0.75 brass 0.25 steel, low-alloyed	Transport, freight, light commercial vehicle	119
Screws	0.021	Metal working, average for steel product manufacturing	Transport, freight, light	446

			commercial vehicle	
Spessorini	0.010	polypropylene, granulate	Transport, freight, light commercial vehicle	20

The dataset for sandpaper is modelled using the technical data sheet provided by 3M, instead the dataset for the handle is based on the EPD published by Hoppe which is the supplier of handles for Navello.

The company is equipped with photovoltaic panels that supply approximately 51% of its total electricity demand. For this portion, the dataset "Electricity, medium voltage, from renewable energy sources" was used. The remaining 49% of the electricity consumption is covered by the national grid and is modelled using the dataset "Electricity, medium voltage, residual mix | electricity, medium voltage | Cutoff, S – IT."

In addition during working hours the company operates air extraction, indicated with a dataset named "Impianto di aspirazione", and air compression systems, indicated with a dataset named "Compressore". These machines are powered by electricity and contribute to the overall energy consumption of the production site.

3.3.8 Production processes for 1 m^2 of the window

The following section describes all the activities carried out within the Navello company to manufacture the Seta 2.0 window. For each processing stage, the main material inputs and outputs are identified and quantified. All the quantities indicated in t have been elaborated starting from information provided by the Navello company.

The process starts with the wood retrieval from the warehouse, which consists in transporting the wood from the storage warehouse to the company's production area. *Table 10* shows the inventory data for the first phase.

Table 10: Inventory relating to wood retrieval from warehouse.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Wood [Kg]	17.64		Allocation: 100%
Input			
Wood [Kg]	17.64	Glued laminated timber, PUR-glue	
Operating machine [min]	2	Machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators	

Table 11 reports the inventory data for the cutting operations, during which the wooden bars are sized appropriately for the manufacturing of the window.

Table 11: Inventory relating to the cutting of the wooden bars.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Cutted bars	17.33		Allocation: 100%
Waste wood	0.303	Waste wood, untreated	
Input			
Wood [Kg]	17.64	Glued laminated timber, PUR-glue	
Electricity [kWh]	0.956	Elettricità	
Industrial air compressors [kWh]	18.66	Compressore	

Table 12 illustrate the inventory data for the reduction of the section of the wooden bars. It is made by a machine named “Quadrotto”.

Table 12: Inventory relating to the section reduction.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Wood bar, sectioned [Kg]	16.457		Allocation: 100%
Waste wood [Kg]	0.002	Waste wood, untreated	
Input			
Cutted bars [Kg]	17.333		
Electricity [kWh]	3.173	Elettricità	
Air extraction [kWh]	11.670	Impianto di aspirazione	

Table 13 provides the inventory data for the sanding phase of the wooden bars.

Table 13: Inventory relating to the sanding of wooden bars.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Sanded wood bar [Kg]	16.313		Allocation: 100%
Waste wood [Kg]	0.144	Waste wood, untreated	
Sandpaper [Kg]	0.714	Inert waste, for final disposal	
Input			
Wood bar sectioned [Kg]	16.457		
Electricity [kWh]	1.590	Elettricità	
Sandpaper [kg]	0.714	Carta vetro	

Table 14 reports the inventory data for the profile processing of the wooden bars, which is performed by using a machine named “Biesse”. The output of the process is a wooden bar shaped with the final window profile.

Table 14: Inventory relating to the profile processing.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Profiled wood bars [Kg]	9.871		Allocation: 100%
Waste wood [Kg]	6.438	Waste wood, untreated	
Input			
Sanded wood bar [Kg]	16.313		
Electricity [kWh]	4.292	Elettricità	

Table 15 presents the inventory data related to the gluing phase, during which the profiled wooden bars are assembled and bonded together to form the structural frame of the window.

Table 15: Inventory relating to the gluing of wooden bars.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Glued bars [Kg]	9.886		Allocation: 100%
Input			
Profiled wood bars [Kg]	9.871		
Glue [Kg]	0.015	Melamine urea formaldehyde adhesive	

Table 16 outlines the inventory data related to the surface filling phase, in which the imperfections of the wood are repaired by using the putty.

Table 16: Inventory relating to the surface filling.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Filled window [Kg]	9.888		Allocation: 100%
Input			
Glued bars [Kg]	9.886		
Putty [Kg]	0.001	Acrylic filler	

Table 17 reports the inventory data for the phases of sanding and painting. The paint is applied using a spray machine: specifically are applied two coats of primer and one coat of finishing paint.

Table 17: Inventory relating to the sanding and paining.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Painted window [Kg]	11.21		Allocation: 100%
Waste paint [Kg]	1.477	Waste paint	
Sandpaper [Kg]	0.188	Inert waste, for final disposal	
Input			
Filled window [Kg]	9.888		
Electricity [kWh]	4.157	Elettricità	
Sandpaper [kg]	0.188	Carta vetro	
Paint [Kg]	1.322	Alkyd paint, white, without solvent, in 60% solution state	

Table 18 illustrates the inventory data related to the installation of the hardware along the windows profiles.

Table 18: Inventory relating to the hardware installation.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Window with hardware [Kg]	12.292		Allocation: 100%
Scrap of hardware	0.058	scrap steel	
Input			
Painted window [Kg]	11.21		
Hardware [Kg]	1.119	Steel, low-alloyed	
Steel nails [Kg]	0.021	Metal working, average for steel product manufacturing	

Table 19 shows the inventory data related to the installation of the glass on the window.

Table 19: Inventory relating to the glass installation.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Window with glass [Kg]	35.193		Allocation: 100%
Input			
Window with hardware [Kg]	12.292		
Glass [Kg]	22.627	Steel, low-alloyed	
Seals [Kg]	0.247	Polyvinylchloride, bulk polymerised	
Silicone [Kg]	0.0154	Silicone product	
Steel nails [Kg]	0.0005	Metal working, average for steel product manufacturing	

Spessorini	0.010	polypropylene, granulate	

Table 20 reports the inventory data for the packaging phase of the final product. The window is covered by using both the packaging film and the corrugated board.

Table 20: Inventory relating to the packaging.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Packed window [Kg]	36.00		Allocation: 100%
Input			
Window with glass [Kg]	35.193		
Electricity [kWh]	0.0073	Elettricità	
Packaging film	0.315	Packaging film, low density polyethylene	
Corrugated board	0.494	Corrugated board box	

Table 21 presents the inventory data related to the transportation of the final product. The distance of 158.55 km was determined by analysing all the orders of 2024.

Table 21: Inventory relating to the transportation.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Transported window [Kg]	36.00		Allocation: 100%
Input			
Packed window [Kg]	36.00		

Transportation [km]	158.55	Transport, freight, lorry 3.5-7.5 metric ton, EURO6	

Table 22 provides the inventory data related to the installation of the window. In this phase also the handle in mounted, but since it is mainly a manual activity, the energy consumption is assumed to be negligible.

Table 22: Inventory relating to the installation.

Flows	Amount	Ecoinvent Dataset	Notes
Output			
Installed window [Kg]	35.30		Allocation: 100%
Input			
Transported window [Kg]	36.00		
Handle [kg]	0.103	Maniglia	

3.3.9 End-of-Life phases

This scenario, although hypothetical, is required to allow a complete environmental comparison. In reality it is difficult to make generalizations as practices may differ depending, for example, on regulations for waste produced by construction and demolition activities.

The construction sector, due to the intense use of natural resources, is one of the main responsible for environmental impacts on the territory, contributing significantly to the impoverishment of non-renewable raw materials. According to the European Environment Agency, the construction sector is responsible for over 30% of the total waste generated in Europe and consumes approximately 50% of all extracted resources.

In this context, the European Union has set ambitious targets to improve waste management. With the update of Directive 2018/851/EU, which amends the previous Waste Framework Directive (2008/98/EC) part of the Circular Economy Package, new targets for municipal waste recycling have been introduced: at least 55% by weight by 2025. This target will aim at 60% by 2030 and 65% by 2035.

The product life cycle ends with the EoL phases, modelled according to the modules provided by the EN 15804 standard. Following the reference PCR 2019:14 and considering a RSL of 40 years, as anticipated in paragraph 2.2.1, the EoL scenario that has been considered for the window is the following one:

- Glass: 30% recycled (C3) and 70% goes to landfill (C4);
- Steel: 95% recycled (C3) and 5% goes to landfill (C4);
- Aluminum: 95% recycled (C3) and 5% goes to landfill (C4);
- Rubber: 100% goes to landfill (C4);
- Brass: 95% recycled (C3) and 5% goes to landfill (C4);
- Wood: 95% recycled (C3) and 5% goes to landfill (C4).

These data are aligned with the EPD of VELFAC 200 ENERGY (registration number S-P-07591) which applies this EoL scenario for glass, steel, aluminum and wood. For brass has been adopted the same recycling and landfill percentages as steel and aluminum since all are metallic materials. Instead for the rubber seals has been assumed that 100% of the material is sent to landfill.

The end of life includes modules C1-C2-C3-C4 and D.

In *Table 23* are shown the corresponding amount of waste sent to treatment and to landfill; instead *Table 24* illustrates the quantity of all materials sent for specific process of end of life.

Table 23: Quantity of waste sent for recycling and to landfill.

Material	Quantity sent to recycling [kg]	Quantity sent to landfill [kg]
Glass	6.79	15.83
Steel	1.03	0.05
Aluminum	0.02	0.00
Wood	10.65	0.56
Brass	0.07	0.00
Rubber	0	0.25
TOTAL	18.56	16.71

Table 24: End of life.

Process	Units (per declared unit and per material type)	Values (kg/m2)
Collection process	kg collected separately	35.30
	kg collected together with construction waste	0
Recovery system	kg for reuse	0
	kg for recycling	18.56
	kg for energy recovery	0
Disposal	kg of material for final disposal	16.71

The modeling of the EoL scenario was carried out in compliance with the general rules indicated in the EN 15804 standard, as reported in the reference PCR. These rules establish that the EoL scenario must be realistic and representative of the most likely alternatives, considering the geographical context in which the product is used. They must also exclude processes not currently in use or not proven to be practicable. In accordance with what is expected, the scenario declared in this study, even if not always corresponding to local practice, ensure comparability between environmental declarations of similar products.

In particular, in the absence of specific primary data (e.g. data on demolition methods, average transport distances, recovery rates or final destinations of materials), it was decided to adopt the default data indicated in the PCR following regulatory requirements. This choice ensures methodological coherence, allows filling data gaps and guarantees alignment with international standards, preserving the reliability of the model.

Table 25 summarizes the assumptions for module C, which were developed based on default data and standardized assumptions provided by PCR 2019:14 and EN 15804, in the absence of specific primary data for the market context. The materials are subjected to valorisation treatments as recycling, so they are delivered directly to authorized plants, in compliance with current legislation.

Table 25: Parameters assumed for modelling end-of-life modules.

Module	Process	Energy vector	Quantity [kWh/kg]	Distance	Means of transport
C1	Demolition/removal of the window	Diesel	0.0011	-	-
C2	Transport (for products/materials not intended for incineration)	-	-	80 km	Truck 16–32 t (EURO 5), load factor 50%
C3	30% of glass sent for recycling	Diesel	0.0008	-	-
C3	95% of steel sent for recycling	Diesel	0.0074	-	-
C3	95% aluminum sent for recycling	Diesel	0.0074	-	-
C3	**95% of wood sent for recycling**	Diesel	0.006	-	-
C3	95% of brass sent for recycling	Diesel	0.0074	-	-
C4	70% of glass + 5% of steel + 5% of aluminum + **5% of wood** + 5% of brass + 100% of rubber are sent to landfill	-	(from dataset)	-	-

<u>Removal and demolition (C1)</u>

The removal of the window occurs when it arrives at the end of its life. In line with the PCR, this phase was modeled assuming an energy consumption associated with this process of 0.0011 kWh/Kg of treated material.

<u>Transport to treatment centers (C2)</u>

In this module, the transportation of waste resulting from the demolition phase to treatment or disposal centers has been modeled. After removal on the construction site, the materials that were composing the window are loaded onto heavy vehicles to be transferred to EoL destinations.

The transportation of demolition waste to treatment or disposal centers was modeled assuming an average distance of 80 km, traveled by EURO 5 diesel trucks with mass between 16 and 32 metric ton and load factor of 50%.

Waste processing (C3)

The material is not reused so it is delivered directly to authorized plants, in compliance with current legislation for the proper treatment of the different type of materials. This approach was applied to all waste types. The modelling of module C3 for each material is described below:

- *Glass*: recycling was modelled with an energy consumption of 0.0008 kWh/kg which yields "glass cullet, sorted, Recycled Content cut-off | glass cullet, sorted | Cutoff, S - GLO", from Ecoinvent 3.10.
- *Steel*: recycling was modelled with an energy consumption of 0.0074 kWh/kg with the resulting output being "steel production, converter, low-alloyed | steel, low-alloyed | Cutoff, S - RoW", from Ecoinvent 3.10.
- *Aluminum*: recycling was modelled with an energy consumption of 0.0074 kWh/kg and the recovered product is "treatment of aluminum scrap, post-consumer, prepared for recycling, at remelter | aluminum, wrought | Cutoff, S - RER", from Ecoinvent 3.10.
- *Wood*: recycling was modelled with an energy consumption of 0.006 kWh/kg which provides "playwood production | wood chips, dry, measured as dry mass | Cutoff, S - RER", from Ecoinvent 3.10.
- *Brass*: recycling was modelled with an energy consumption of 0.0074 kWh/kg which yields "casting, brass | casting, brass | Cutoff, S - CH", from Ecoinvent 3.10.

Landfill disposal (C4)

Once the window has reached the end of its life, it is dismantled and different percentage of the materials are sent to landfill as inert waste, as shown in the *Table 23*. The materials are delivered directly to authorized plants, in compliance with current legislation.

The processes were modelled for all the materials using the dataset “Process-specific burdens, inert material landfill | process-specific burdens, inert material landfill | Cuttoff, S - CH”, from Ecoinvent 3.10. This dataset includes the energy use linked to landfilling operations, which correspond to 0.34 kWh/kg.

Benefits (D)

Finally, module D allows to quantify the potential environmental benefits or loads deriving from the recovery, reuse or recycling of the product at the end of its life and from net flows leaving the product system that have passed the end-of-waste state. In terms of LCA, these benefits are accounted for "beyond the system boundaries" and contribute to improving the overall environmental balance of the product, promoting greater resource efficiency and reducing the impact of the construction sector on the environment.

In particular, the benefits coming from glass, steel, aluminum, brass and wood recycled in module D. Given the EoL assumptions previously described, module D contribution has been calculated with the following equations (1) and (2) adapted from EN 15804:2012+2019:A2/AC:2021 Annex D.

$$e_{moduleD} = e_{moduleD1} \tag{1}$$

Where module D1 is the loads and benefits related to the export of secondary materials and is calculated with equation (2) adapted from EN 15804:2012+2019:A2/AC:2021 Annex D for each material studied in this sector EPD. The final result will be the weighted average.

$$e_{moduleD1} = M_{MRout} * \left(E_{MRafterEoWout} - E_{VMSubout} * \frac{Q_{Rout}}{Q_{sub}}\right) \tag{2}$$

Where:

- M_{MRout} is the mass of each type of waste sent to recycling;
- $E_{MRafterEoWout}$ specific emissions and resources consumed per unit of analysis arising from material recycling processes;
- $E_{VMSubout}$ specific emissions and resources consumed per unit of analysis arising from acquisition and pre-processing of the primary material;

- $\frac{Q_{Rout}}{Qsub}$ is the quality of the secondary material.

Table 26 shows how module D was modelled:

Table 26: Datasets and quality used for module D.

Material	Dataset $E_{MRafterEoWout}$	Dataset $E_{VMSubout}$	Q_{Rout}/Q_{Sub}
Glass	C3_Recycling_glass	Flat glass production, uncoated I flat glass, uncoated | Cutoff, S - RER	1
Steel	C3_ Recycling_steel	Steel production, converter, low-alloyed | steel, low-alloyed | Cutoff, S - RER	1
Aluminum	C3_ Recycling_aluminium	Aluminium production, primary, ingot | aluminium, primary, ingot | Cutoff, S - |A| Area, EU27 & EFTA	1
Wood	C3_ Recycling_wood	Glued laminated timber production, PUR-glue | glued laminated timber, PUR-glue | Cutoff, S - CH	0.79
Brass	C3_ Recycling_brass	Brass production | brass | Cutoff, S - CH	1

In the software all the datasets related to $E_{VMSubout}$ are marked as "Avoid Product". The quality values of the recycled products were determined as follows:

- *Glass*: Glass is a unique material that can be recycled indefinitely without losing its quality or purity (Elstner et al., 2024), so it was assumed a quality value equal to 1.
- *Aluminum*: Aluminum properties do not change during use, therefore it can be recycled multiple times without losing its original properties (Georgitzikis K et al., 2021). For this reason, a quality value equal to 1 was assumed.
- *Brass and steel*: A quality value of 1 was also assumed, based on the fact that they are metals as aluminum.

- *Wood*: The quality value was calculated based on the data published by (Iždinský et al., 2020), that investigated the variation of the main properties of virgin wood compared to recycled wood.

3.3.10 Impact assessment method

To make the results of the LCA analysis fully understandable, enhance their environmental significance and communicate them effectively to both professionals and the public, it is essential to identify specific areas of environmental interest, known as impact categories. Category indicators, i.e. indicators referring to individual environmental impacts, have the task of summarizing the potential environmental effects associated with the flows of matter and energy entering and leaving the system analyzed. For each impact category, characterization coefficients are used to homogenize the contribution of individual emissions into the environment (into the air, soil or water). Measuring overall impact requires an interpretation of the data and a hierarchical ordering of the impacts themselves.

The categories used for the assessment of the impacts of the products under study and the characterization factors used, in accordance with the EN 15804:2012+2019:A2/AC:2021 standard (Annex C), are reported in *Table 27*. In this study, in the impact analysis phase, the EN15804 + A2 method was applied through the OpenLCA software. This uses the characterization factors required by the regulation and reported in *Table 27*. For the climate change indicator, impacts are analysed in detail along the production chain, to identify which sub-processes contribute, and to what extent, to the total impact and the individual phases required by the current EN 15804:2012+2019:A2/AC:2021 standard. A broader overview is also provided by considering additional indicators provided by the method.

Table 27: Main and additional environmental indicators (in grey) with units of measurement, warnings and characterization models.

Impact category	Indicator	Unit of measurement	Disclaimer	Model
Acidification	AP	mol H+ eq	-	Accumulated Exceedance, Seppälä et al. 2006, Posch et al., 2008
Climate change	GWP total	kg CO2eq	-	

Climate change - Biogenic	GWP-fossil	kg CO2eq	-	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change - Fossil	GWP-biogenic	kg CO2eq	-	
Climate change - Land use and LU change	GWP-luluc	kg CO2eq	-	
Eutrophication, marine	EP-marine	kg N eq	-	EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe
Eutrophication, freshwater	EP-freshwater	kg P eq	-	EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe
Eutrophication, terrestrial	EP-terrestrial	mol N eq	-	Accumulated Exceedance, Seppälä et al. 2006, Posch et al.
Ozone depletion	ODP	kg CFC11 eq	-	Steady-state ODPs, WMO 2014
Photochemical ozone formation	POCP	kg NMVOC eq	-	LOTOS-EUROS, Van Zelm et al., 2008, as applied in ReCiPe
Resource use, fossils	ADP-fossil	MJ	2	CML 2002, Guinée et al., 2002, and van Oers et al. 2002.
Resource use, minerals and metals	ADP-minerals&metals	kg Sb eq	2	
Water use	WDP	m3 world eq. depriv.	2	Available WAter REmaining (AWARE) Boulay et al., 2016
Particular matter	PM	disease inc.	-	SETAC-UNEP, Fantke et al.2016
Ecotoxicity, freshwater	ETP-fw	CTUe	2	Usetox version 2 until

<table>
<tr><td>Human toxicity, cancer</td><td>HTP-c</td><td>CTUh</td><td>2</td><td rowspan="2">modified USEtox model is available from EC-JRC</td></tr>
<tr><td>Human toxicity, non-cancer</td><td>http-nc</td><td>CTUh</td><td>2</td></tr>
<tr><td>Ionizing radiation</td><td>IRP</td><td>kBq U-235 eq</td><td>1</td><td>Human health effect model as developed by Dreicer et al. 1995 update by Frischknecht et al., 2000</td></tr>
<tr><td>Land use</td><td>SQP</td><td>Dimensionless</td><td>2</td><td>Soil quality index based on LANCA</td></tr>
<tr><td colspan="5">Disclaimer 1 – This impact category mainly concerns the potential effect of low doses of ionizing radiation on human health related to the nuclear fuel cycle. It does not consider the effects due to possible accidents.</td></tr>
<tr><td colspan="5">Disclaimer 2 – The results of this environmental impact indicator should be used with caution, as they present a high degree of uncertainty or because there is limited experience in the use of this indicator.</td></tr>
</table>

Additionally, three additional sets of inventory-based indicators are presented to describe resource consumption, waste categories, and output flows for each module (expressed per declared unit):

Resource consumption:

PERT = Total use of renewable primary energy resources (MJ),

PERM = Use of renewable primary energy resources used as raw materials (MJ),

PEARS = Use of renewable primary energy excluding renewable primary energy resources used as raw materials (MJ),

PENRT = Total use of non-renewable primary energy resources (MJ),

PENRM = Use of non-renewable primary energy resources used as raw materials (MJ),

PENRE = Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials (MJ),

SM = Use of secondary material (kg),

RSF = Use of renewable secondary fuels (MJ),
NRSF = Use of non-renewable secondary fuels (MJ),
FWT = Total use of net fresh water (m^3).
Waste categories:
HWD = Hazardous waste disposed (kg),
NHWD = Non-hazardous waste disposed (kg),
RWD = Radioactive waste disposed (kg).
Outgoing flows:
CRU = Components for reuse (kg),
MFR = Materials for recycling (kg),
MER = Materials for energy recovery (kg),
EE = Exported energy (MJ).

3.3.11 Declared results

Table 28 presents the aggregated values of the phases A1-A3, A4, A5, the impacts of the EoL phase C1, C2, C3, C4 modules and the environmental benefits D relating to the sector average. All results are relative to the declared unit of 1 m^2 of a window.

Table 28: Impacts of modules: A1-A3, A4, A5, C1, C2, C3, C4 and D.

	EN15804+A2								
Impact Category	Reference unit	A1-A3	A4	A5	C1	C2	C3	C4	D
GWP Total	kg CO_2eq	4.11E+01	3.44E+00	2.78E+00	7.14E-04	5.47E-01	-1.48E+01	4.66E-02	-1.39+01
GWP Fossil	kg CO_2eq	6.56E+01	3.44E+00	2.75E+00	7.05E-04	5.46E-01	3.98E+00	4.65E-02	-6.99E+00
GWP Biogenic	**kg CO_2eq**	**-2.47E+01**	**2.26E-03**	**3.14E-02**	**9.17E-06**	**3.74E-04**	**-1.88E+01**	**1.23E-04**	**-6.90E+00**
GWP Luluc	kg CO_2eq	1.15E-01	1.32E-03	1.04E-03	5.73E-08	1.79E-04	8.54E-03	4.84E-06	-3.23E-02
ODP	kg CFC-11 eq.	1.66E-06	6.79E-08	5.25E-08	1.51E-11	1.09E-08	5.74E-08	7.17E-10	-1.34E-07
AP	Moles H+ eq.	4.41E-01	6.95E-03	3.73E-02	1.86E-06	1.71E-03	2.42E-02	4.12E-04	-9.37E-02
EP Freshwater	kg P eq	1.49E-02	2.74E-04	2.80E-03	9.16E-08	3.65E-05	1.72E-03	1.37E-06	-3.27E-03
EP Marine	kg N eq	8.55E-02	1.53E-03	2.88E-03	3.66E-07	5.76E-04	7.32E-03	1.90E-04	-1.16E-02
EP Terrestrial	Mole N eq.	9.24E-01	1.65E-02	3.56E-02	3.88E-06	6.27E-03	8.01E-02	2.08E-03	-1.44E-01

POCP	kg NMVOC	3.27E-01	1.10E-02	1.22E-02	1.77E-06	2.68E-03	2.52E-02	6.24E-04	-4.91E-02
ADP (minerals & metals)	kg Sb eq	4.78E-04	1.53E-05	4.34E-04	7.65E-10	1.79E-06	3.06E-05	1.95E-08	-4.63E-04
ADP (fossil)	MJ	8.98E+02	4.78E+01	3.93E+01	1.04E-02	7.67E+00	5.73E+01	6.08E-01	-7.12E+01
WDP	m^3	3.30E+01	2.70E-01	5.76E-01	5.33E-05	3.71E-02	3.63E+00	1.68E-03	-5.09E-01
	Resource consumption								
Impact Category	Reference unit	A1-A3	A4	A5	C1	C2	C3	C4	D
PERT	MJ	8.29E+02	1.15E+00	2.09E+00	1.77E-04	1.30E-01	1.07E+02	1.81E-02	-2.26E+02
PERM	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PEARS	MJ	8.29E+02	1.15E+00	2.09E+00	1.77E-04	1.30E-01	1.07E+02	1.81E-02	-2.26E+02
PENRT	MJ	8.98E+02	4.78E+01	3.93E+01	1.04E-02	7.67E+00	5.73E+01	6.08E-01	-7.13E+01
PENRM	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PENRE	MJ	8.98E+02	4.87E+01	3.93E+01	1.04E-02	7.67E+00	5.73E+01	6.08E-01	-7.13E+01
SM	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RSF	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NRSF	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FWT	m^3	8.49E-01	7.49E-03	2.99E-02	5.22E-06	1.02E-03	8.56E-02	4.38E-05	-1.40E-02
	Waste								
Impact Category	Reference unit	A1-A3	A4	A5	C1	C2	C3	C4	D
HWD	kg	4.47E+00	5.03E-02	1.71E-01	5.96E-06	7.52E-03	8.95E-01	5.22E-04	-2.30E-01
NHWD	kg	1.06E+02	6.80E-01	7.25E-01	5.92E-05	8.32E-02	2.60E+00	4.02E-03	-3.61E+00
RWD	kg	1.09E-03	2.25E-05	3.56E-05	6.66E-09	2.45E-06	1.31E-04	8.11E-08	-3.69E-05
CRU	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
MFR	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
MER	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EE	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Additional indicators								
Impact Category	Reference unit	A1-A3	A4	A5	C1	C2	C3	C4	D
GWP-GHG	kg CO_2eq	6.64E+01	3.44E+00	2.75E+00	7.05E-04	5.47E-01	4.00E+00	4.65E-02	-7.08E+00
Particular matter	disease inc.	6.17E-06	1.81E-07	1.06E-07	8.49E-12	4.29E-08	5.44E-07	1.19E-08	-1.24E-06
Ionizing radiation	kBq U-235 eq	4.33E+00	8.98E-02	1.42E-01	2.72E-05	9.84E-03	5.14E-01	3.35E-04	-1.68E-01
Land use	Pt	1.81E+03	2.00E+01	1.28E+01	7.07E-04	4.56E+00	4.99E+02	7.49E-01	-2.30E+02
Ecotoxicity, freshwater	CTUe	4.44E+02	1.58E+01	5.19E+01	1.08E-03	2.06E+00	7.58E+01	8.57E-02	-1.85E+02

Human toxicity, cancer	CTUh	2.56E-07	2.63E-08	2.21E-08	1.10E-12	3.82E-09	2.19E-07	1.79E-10	-3.28E-07
Human toxicity, non-cancer	CTUh	6.55E-07	2.96E-08	3.39E-07	2.97E-12	4.93E-09	6.18E-08	8.95E-11	-3.40E-07

3.4 Interpretation: contribution analysis, sensitivity analysis and uncertainty analysis

This paragraph elaborates on the impact results obtained for the climate change indicator and aims to identify the contribution that the different phases of the window production process have on the total impact.

The impact on climate change of 1 m^2 of a wooden window has a value of 6.64E+01 kg CO_2 eq/m^2 for the modules A1-A3, 3.44 kg CO_2 eq/m^2 for the transportation phase and 2.75 kg CO_2 eq/m^2 for the installation phase. For module C1 the total impact is 7.05E-04 kg CO_2 eq/m^2, for module C2 it is 5.47E-01 kg CO_2 eq/m^2, instead for module C3 it is 4.00 kg CO_2 eq/m^2 and for module C4 it is equal to 4.65E-02 kg CO_2 eq/m^2. The related impact for module D is -7.08 kg CO_2 eq/m^2.

In the total impact of the climate change the production of double glazing contributes for 46.46% and the energy consumption in the production phase has a total impact of 22.54%. It is also important to evidence the contribution of the overall raw materials, excluded the glass and wood, that counts for 11.99%.

All the impacts contribution are illustrated in *Figure 11* in kg CO_2 equivalent, instead in *Figure 12* in %. From them can be observed that the production of glass is the most impacting activity of the window.

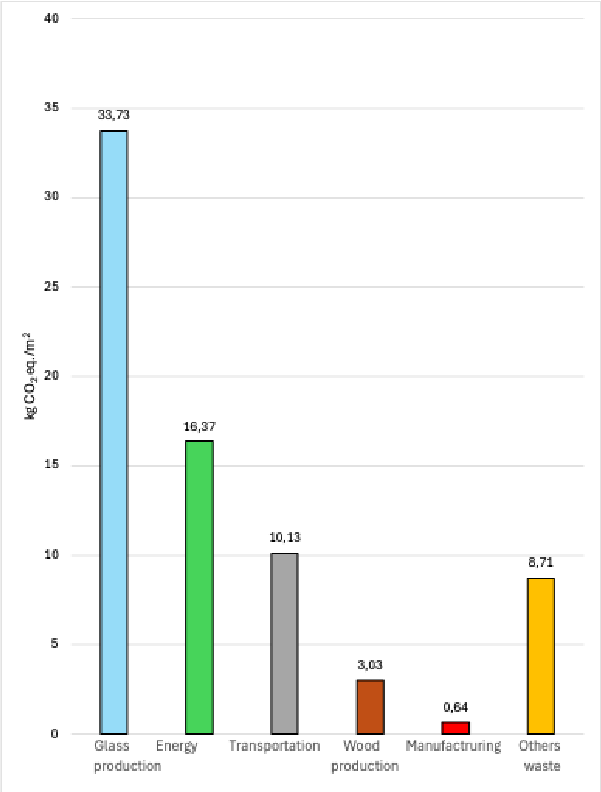

*Figure 11: Contribution in kg CO_2 eq. per m²
of wooden window.*

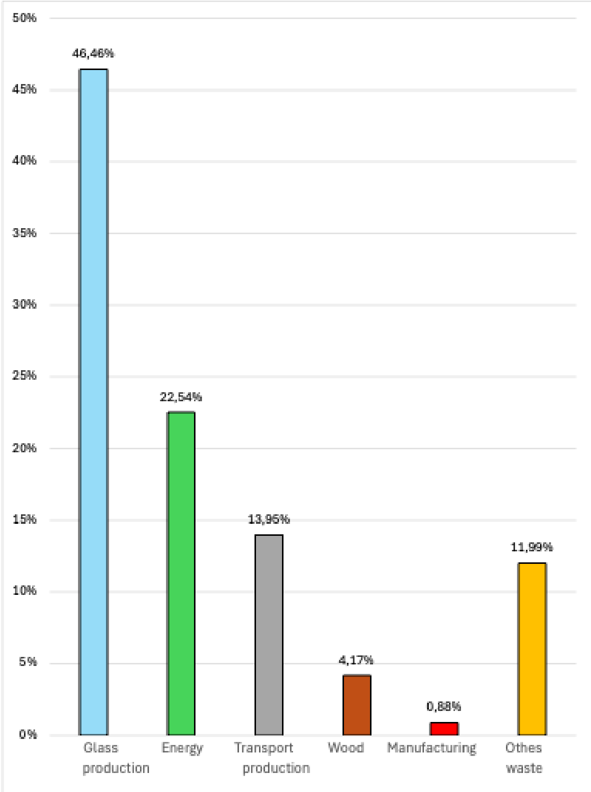

*Figure 12: Contribution in % CO_2 eq. per m²
of wooden window.*

The presence of packaging results in a benefit (negative impact) due to the characterization factors for the biogenic carbon present in the corrugated board.

3.5 Analysis and interpretation of GWP biogenic results

After completing the LCA of the wooden window the analysis is now focused on the results obtained for the Global Warming Potential – (GWP biogenic) impact category. This indicator is particularly relevant for bio-based products, as it accounts for the uptake and release of biogenic CO_2 over the product life cycle.

In the case study the EoL scenario of the wooden components of the window assumes that 95% of the wood is recycled (module C3), while the remaining 5% is sent to landfill (module C4). The resulting GWP biogenic values for the all modules are as follows: A1-A3: -2.47E+01 kg CO2 eq; A4: 2.26E-03 kg CO_2 eq; A5: 3.14E-02 kg CO_2 eq; C1:9.17E-06 kg CO_2 eq; C2: 3.74E-04 kg CO_2 eq ; C3: -1.88E+01 kg CO_2 eq; C4: 1.23E-04 kg CO_2 eq and for the last module D: -6.90E+00 kg CO_2 eq.

The strongly negative contribution observed in module A1-A3 is attributable to the uptake of atmospheric CO_2 during tree growth, which is stored in the wooden biomass and accounted as biogenic carbon sequestration according to the static approach prescribed by EN 15804 + A2. Modules A4 and A5, as well as C1 and C2, show small positive contributions, which are associated with energy use and emissions from transport, installation, dismantling and waste transport activities. These processes do not directly involve the biogenic carbon stored in the wood and therefore have only marginal effects on GWP biogenic.
The C3 module (recycling) shows a substantial negative contribution, indicating that the recycled wood continues to store biogenic carbon in secondary material applications, in this way delaying its release to the atmosphere. This behaviour is consistent with the scientific literature, which highlights that recycling of wood products can prolong carbon storage within the technosphere and reduce short-term biogenic CO_2 emissions (Piccardo and Gustavsson, 2021). Conversely, the contribution of module C4 (landfill) is small and positive. This limited impact reflects both the emissions associated with waste treatment operations and the fact that a significant fraction of the carbon contained in wood disposed in landfills can remain stored for long periods under anaerobic conditions, as demonstrated by experimental and modelling studies on wood degradation in landfills (Ximenes et al., 2019). Finally, the negative value observed in module D results from material or energy substitution effects enabled by recycling processes, in accordance with EN 15804 rules.

To verify that the accounting approach applied to biogenic carbon corresponds to the static −1/+1 approach, an alternative scenario was modeled in which the wood of the window is assumed to be sent 100% to incineration at end of life (module C4), with no recycling or long-term storage. In this scenario, the GWP biogenic results are for C3: -4.66E-04 kg CO_2 eq; C4: 2.05E+01 kg CO_2 eq and for module D: -5.17E-02 kg CO_2 eq. In this case, module C4 becomes the dominant contributor, with a positive GWP biogenic value of approximately 20.5 kg CO_2 eq, corresponding to the release of biogenic CO_2 during the combustion of wood and the oxidation of the carbon contained in the biomass. The sum between A1-A3 and C4 does not result in a perfectly neutral balance (-4.19 kg CO_2 eq). This deviation from zero does not indicate an inconsistency in the model, but rather reflects the assumptions embedded in the life cycle inventory data. In particular, wood does not consist entirely of carbon and inventory datasets account for a carbon content lower than 100%, as well as for incomplete oxidation during incineration, with part of the carbon remaining in solid residues or being emitted in forms other than CO_2 (Piccardo and Gustavsson, 2021). Consequently, the obtained results confirm that the applied biogenic carbon accounting follows a static approach, characterized by instantaneous uptake and release without consideration of temporal dynamics, while remaining consistent with the physical and chemical assumptions underlying the ecoinvent database.

4. DYNAMIC ACCOUNTING METHOD OF BIOGENIC CO_2: NAVELLO WOODEN WINDOW CASE STUDY

4.1 Extract static biogenic CO_2 flows from the LCA

The dynamic approach adopted in this thesis follows the framework proposed by (Levasseur et al., 2013), in which:

- Emissions are represented as time-dependent functions;
- The atmospheric persistence of CO_2 is modelled using the Bern carbon cycle impulse response function;
- Climate impact is calculated as time-integrated radiative forcing.

This approach is aligned with the DLCA methodology discussed by (Su et al., 2017), who highlighted the importance of incorporating time-varying parameters into LCA when long life cycles are involved.

The analysis starts from LCI results instead of the pre-characterized LCIA indicators. Then temporal information is explicitly assigned to biogenic carbon flows. In this way, a time-dependent emission profile is constructed and subsequently processed through the atmospheric impulse response function to quantify the evolution of atmospheric CO_2 over time.

DLCA requires the explicit temporal distribution of carbon exchanges in order to evaluate their evolving contribution to climate change (Levasseur et al., 2013).

So once completed the LCA model in OpenLCA software, two categories of outputs were available:

- *Impact assessment indicators (LCIA results)*

  It is derived from the impact assessment results and reflects the rules, allocation procedures and modelling conventions defined on EN 15804 and associated Environmental Footprint methodologies. It is therefore a static climate indicator, not a physical carbon balance.
- *Life-cycle inventory flows (LCI results)*

  It is obtained by summing, from the inventory results, the "carbon dioxide, non-fossil" exchanges across modules A1-A5 and C1-C4, excluding module D. This represents a mass-balance measure of the net atmospheric exchanged and provides the right starting point for DLCA.

The static climate change indicators reported in paragraph 3.3.11 are based on LCIA results and therefore reflect the specific characterization rules and modelling conventions of EN 15804 and related Environmental Footprint methodologies. However, the computation of dynamic biogenic CO_2 cannot depend on these pre-characterized indicators, because DLCA requires the physical quantities of CO_2 exchanged with the atmosphere in each year of the modeling horizon. So dynamic calculation was performed using inventory results that constitute the direct input needed to model CO_2 atmospheric persistence and time-dependent climate effects (Levasseur et al., 2013).

The biogenic CO_2 exchanges were grouped considering the following steps:

- Production and construction: A1-A3, A4, A5;
- End-of-life: C1,C2,C3,C4.

In *Table 29* are reported the inventory results of the mixed EoL, for each module, excluding the module D.

Table 29: Static biogenic CO_2 balance (mix scenario).

MODULES	kg OUTPUT	kg INPUT	kg Net	Modules sum
A1-A3	+1.02E+01	-2.68E+01	-1.65E+01	-1.64E+01
A4	+3.37E-02	0	+3.37E-02	
A5	+8.64E-02	0	+8.64E-02	
C1	+2.04E-05	0	+2.04E-05	+5.82E+00
C2	+3.86E-03	0	+3.86E-03	
C3	+4.79E+00	0	+4.79E+00	
C4	+1.03E+00	0	+1,03E+00	
SUM_STATIC				-1.06E+01

The resulting static net balance equals: **-10.58 kg $CO_{2,eq}$**. This negative value indicates that, over the entire life cycle considered, the amount of biogenic carbon stored in the wooden window during biomass growth exceeds the total biogenic CO_2 released during the production, use, and EoL stages.

4.2 Definition of time parameters

Two key temporal parameters were defined:

- *Reference Service Life* (RSL) of the window: 40 years;
- *Time Horizon* (TH): 100 years, aligned with conventional practice (GWP100).

The dynamic inventory is therefore modelled from t = 0 (production year) to t = 100.

4.3 Dynamic emission profile and results

An annual emission history g(t) (kg CO_2/year) was conducted by assigning each static biogenic CO_2 flow to the year in which it occurs:

- *Production stage* (t = 0): g(0) = ∑(A1-A3, A4, A5) = -1.64E+01 kg CO_2.
  All biogenic CO_2 flows occurring in A1-A5 were assigned to year 0 because they occur at the start of the product system (manufacturing + transport to site + installation).
- *Use stage* ($0 < t < t_{EoL}$): 0 kg CO_2.
  No biogenic CO_2 emissions/removals were assumed during the use phase.
- *End-of-life stage* ($t_{EoL} = 40$): +5.82E+00 kg CO_2.

This profile captures the temporal separation between sequestration and emission, which is the key element adressed by DLCA.
In the spreadsheet, this structure is implemented considering in one column g(t) CO_2 (t), which at t = 0 is equal to -1.64E+01 kg CO_2 (biogenic uptake credited in A modules) and at t = 40 is +5.82E+00 kg CO_2 (biogenic release in C modules). The remaining years, until 100, are set to zero.

4.4 Different end-of-life scenarios

The scenario analysis focuses exclusively on the biogenic carbon fraction associated with the wooden components of the window. Different EoL treatments for wood were considered in order to evaluate how alternative carbon-management strategies influence the dynamic climate results. The EoL modelling of non-biogenic materials, such as glass and metallic elements, was kept constant across all scenarios. This assumption ensures

that any variation in the results can be attributed only to differences in the management and timing of biogenic carbon flows.
The dynamic method was applied to four alternative EoL scenarios for the wooden fraction:

- Mixed (95% recycled and 5% goes to landfill);
- 100% Incineration;
- 100% Recycling;
- 100% Landfill.

By isolating the biogenic component the analysis allows a better interpretation of the temporal effects associated with carbon storage and delayed emissions in wood-based products.

By applying the methodology described in Chapter 2.5 for the *mixing* scenario EoL, the dynamic result is **-12.43 kg $CO_{2,eq}$**. Comparing the stating value and the one obtained now, emerge that the temporal delay between uptake and emission strongly reduces the effective warming impact, which is related with the timing of carbon sequestration and release.

The *incineration* scenario starts with the inventroy results presented in *Table 30*.

Table 30: Static biogenic CO_2 balance (incineration scenario).

MODULES	kg OUTPUT	kg INPUT	kg Net	Modules sum
A1-A3	+1.02E+01	-2.68E+01	-1.65E+01	-1.64E+01
A4	+3.37E-02	0	+3.37E-02	
A5	+8.64E-02	0	+8.64E-02	
C1	+2.04E-05	0	+2.04E-05	+2.06E+01
C2	+3.86E-03	0	+3.86E-03	
C3	+2.06E+01	0	+2.06E+01	
C4	+1.50E-03	0	+1.50E-03	
SUM_STATIC				+4.18E+00

By applying the dynamic calculation steps the result obtained is **-2.36 kg $CO_{2,eq}$**, which indicates a net climate benefit within the 100-year TH.
This result can be explained by the temporal separation between carbon uptake and release. The biogenic carbon absorbed during biomass growth is accounted at the

beginning of the life cycle (t = 0), while its release through incineration at the end of the service life. Due to the atmospheric decay, described by the IRF, a portion of the emitted CO_2 does not persist in the atmosphere for the entire assessment period. So the time-integrated atmospheric perturbation is lower than an equivalent fossil CO_2 emission, leading to a negative dynamic climate indicator.

For the *recycing* scerario the starting data are indicated in *Table 31*.

Table 31: Static biogenic CO_2 balance (recycling scenario).

MODULES	kg OUTPUT	kg INPUT	kg Net	Modules sum
A1-A3	+1.02E+01	-2.68E+01	-1.65E+01	-1.64E+01
A4	+3.37E-02	0	+3.37E-02	
A5	+8.64E-02	0	+8.64E-02	
C1	+2.04E-05	0	+2.04E-05	5.04E+00
C2	+3.86E-03	0	+3.86E-03	
C3	+5.04E+00	0	+5.04E+00	
C4	+1.50E-03	0	+1.50E-03	
SUM_STATIC				-1.14E+01

After performing the dynamic method the overall impact is **-12.96 kg $CO_{2,eq}$**. Recycling delays carbon release further increasing temporary atmospheric removal and producing a strong negative dynamic import. This highlights the benefits of carbon strorage duration in wood products.

For the last scenario, 100% *landfill*, the invontory results are shown in *Table 32*.

Table 32: Static biogenic CO_2 balance (landfill scenario).

MODULES	kg OUTPUT	kg INPUT	kg Net	Modules sum
A1-A3	+1.02E+01	-2.68E+01	-1.65E+01	-1.64E+01
A4	+3.37E-02	0	+3.37E-02	
A5	+8.64E-02	0	+8.64E-02	
C1	+2.04E-05	0	+2.04E-05	6.35E-02
C2	+3.86E-03	0	+3.86E-03	
C3	+5.71E-02	0	+5.71E-02	
C4	2.54E-03	0	+2.54E-03	
SUM_STATIC				-1.63E+01

Applying the Levasseur steps, the overall dynamic impact is **-16.36 kg $CO_{2,eq}$**. Landfill maximizes long-term carbon storage resulting in the largest negative dynamic impact. This confirms that delayed or avoided emissions dominates dynamic climate performance, a result not visible in static LCA. This behavior can be explained by the long-term carbon storage assumed in the landfill scenario. In this case, a large fraction of the biogenic carbon remains stored in the waste material beyond the 100-year assessment horizon. So the delayed or avoided emissions dominate the dynamic climate performance.

In contrast, the recycling scenario involves additional processing stages and partial carbon release that reduce the net storage benefit. The reprocessing of wood materials requires transport and treatment operations, which generate emissions and shorten the effective duration of carbon storage within the considered system boundary.

Therefore, under the assumptions of the dynamic model adopted in this study, landfill results in the highest negative dynamic, so the best case. It is important to note that this conclusion is strictly related to biogenic CO_2 timing and does not reflect the overall environmental performance of landfill compared to other waste management strategies.

4.5 Influence of service life on dynamic biogenic CO_2 results

To evaluate the influence of service life assumptions on the dynamic assessment of biogenic CO_2 the calculation was repeated considering two more RSL values: 30 years and 50 years, in addition to the base case study of 40 years. Since DLCA explicitly accounts for the timing of carbon release, variations in service life are expected to significantly influence climate outcomes.

After performing all the calculations, the results obtained for each EoL scenario considering a RSL = 30 years are reported in *Table 33*.

Table 33: Comparison between static and dynamic biogenic CO_2 results (RSL = 30 years).

RSL = 30 years		
SCENARIO	STATIC	DYNAMIC
Mixed	-10.58 kg $CO_{2,eq}$	-11.94 kg $CO_{2,eq}$
Incineration	+4.18 kg $CO_{2,eq}$	-0.64 kg $CO_{2,eq}$
Recycling	-11.36 kg $CO_{2,eq}$	-12.54 kg $CO_{2,eq}$
Landfill	-16.34 kg $CO_{2,eq}$	-16.35 kg $CO_{2,eq}$

When the service life is shortened to 30 years EoL, so the emissions occur earlier within the 100-year TH. Also in this case the largest difference between static and dynamic results is observed in the incineration scenario, where the dynamic result becomes negative, indicating a net climate benefit within the considered TH due to the temporal separation between carbon uptake during biomass growth and its delayed release at EoL.

Compared to the 40 year case, the earlier release of biogenic carbon reduces the benefit associated with temporary storage. The landfill and recycling scenarios remain strongly negative, since a substantial fraction of carbon remains stored beyond the modelling horizon, but the cooling effect is slightly reduced for recycling.

Now considering a RSL = 50 years, the results obtained are listed in *Table 34*.

Table 34:Comparison between static and dynamic biogenic CO_2 results (RSL = 50 years).

RSL = 50 years		
SCENARIO	STATIC	DYNAMIC
Mixed	-10.58 kg $CO_{2,eq}$	-12.94 kg $CO_{2,eq}$
Incineration	+4.18 kg $CO_{2,eq}$	-4.15 kg $CO_{2,eq}$
Recycling	-11.36 kg $CO_{2,eq}$	-13.40 kg $CO_{2,eq}$
Landfill	-16.34 kg $CO_{2,eq}$	-16.36 kg $CO_{2,eq}$

In this case the biogenic carbon release is shifted forward in time. This delay allows a greater portion of the emitted CO_2 to decay within the 100-year horizon due to the impulse response function of the carbon cycle. All scenarios show a more favorable (more negative) dynamic results compared to the 30 and 40-year scenarios.

4.6 Evaluation of the results

When comparing the three service life assumptions (30, 40, and 50 years) a consistent and physically meaningful trend emerges in the dynamic results. As the RSL increases, the release of biogenic carbon at EoL is progressively shifted forward in time within the 100-year TH. This temporal displacement directly affects climate impact, since emissions occurring later contribute less to cumulative radiative forcing due to the atmospheric decay described by the impulse response function of the carbon cycle (Levasseur et al., 2013). The effect of service life is particularly pronounced in the incineration scenario. For a service life of 30 years, the dynamic result is close to neutrality (-0.64 kg $CO_{2,eq}$), instead extending the service life to 40 and 50 years leads to increasingly negative results (-2.36 and -4.15 kg $CO_{2,eq}$ respectively). This behavior illustrates how delaying the release of biogenic CO_2 reduces its time-integrated atmospheric persistence and therefore lowers the overall climate impact within the selected assessment horizon.

A similar but less pronounced trend is observed in the mixed and recycling scenarios. In the mixed scenario, the dynamic impact becomes progressively more negative as service life increases, shifting from -11.94 kg $CO_{2,eq}$ at 30 years to -12.94 kg $CO_{2,eq}$ at 50 years. The recycling scenario follows the same trend, with dynamic results that goes from -12.54 kg $CO_{2,eq}$ to -13.40 kg $CO_{2,eq}$ as service life increases. These two scenarios have similar results since the mixed scenario consider that 95% of wood goes to recycling. These results confirm that cases characterized by delayed emissions or extended material use benefit from longer service lives when evaluated dynamically.

In contrast, the landfill scenario shows negligible sensitivity to service life assumptions. In fact, dynamic results remain almost constant across the three cases, practically -16.36 kg $CO_{2,eq}$, indicating that long-term carbon storage dominates the system behavior. As the biogenic carbon remains stored beyond the 100-year assessment horizon, the precise timing of EoL has a limited influence on the cumulative climate impact.

Overall, this comparison confirms that service life is a key parameter in the dynamic assessment of biogenic carbon. So increasing the durability of wood-based products delays carbon release and reduces cumulative radiative forcing. These findings reinforce the importance of explicitly accounting for temporal dynamics when assessing the climate performance of long-lived bio-based construction products.

4.7 Graphical analysis of dynamic LCA

Figures 13, *14*, and *15* illustrate the evolution of instantaneous radiative forcing over the 100-year assessment horizon for the four EoL scenarios, distinguished by different colors in the legend. The figures are presented in order of increasing service life and correspond respectively to 30, 40 and 50 years. The curves clearly show the temporal behavior of biogenic carbon uptake and release and highlight the strong influence of service life duration on dynamic climate performance.

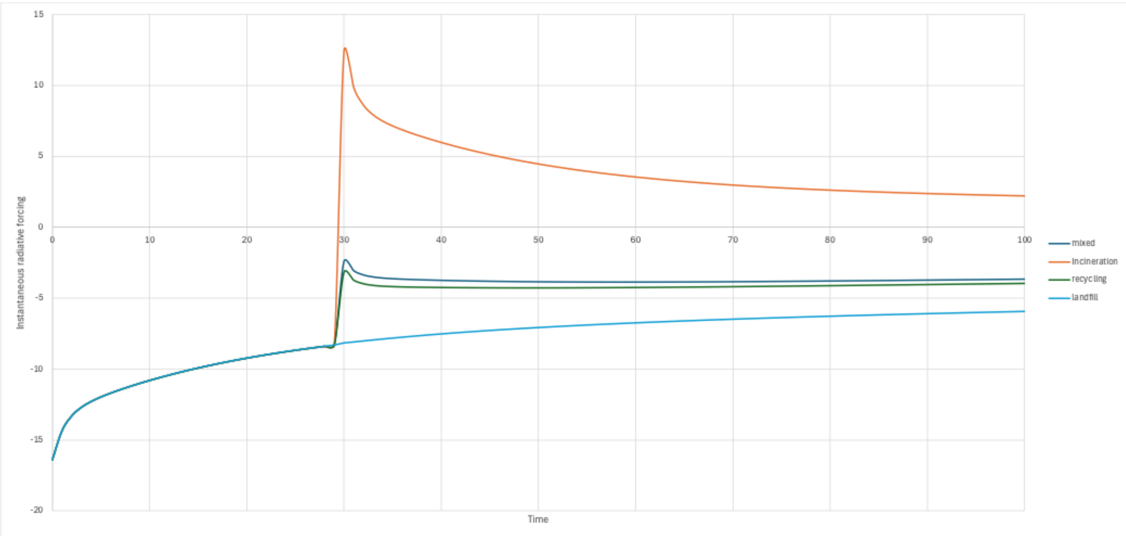

Figure 13: Instantaneous global warming impact of a wooden window for four EoL scenarios calculated using the DLCA approach, considering a RSL = 30 years.

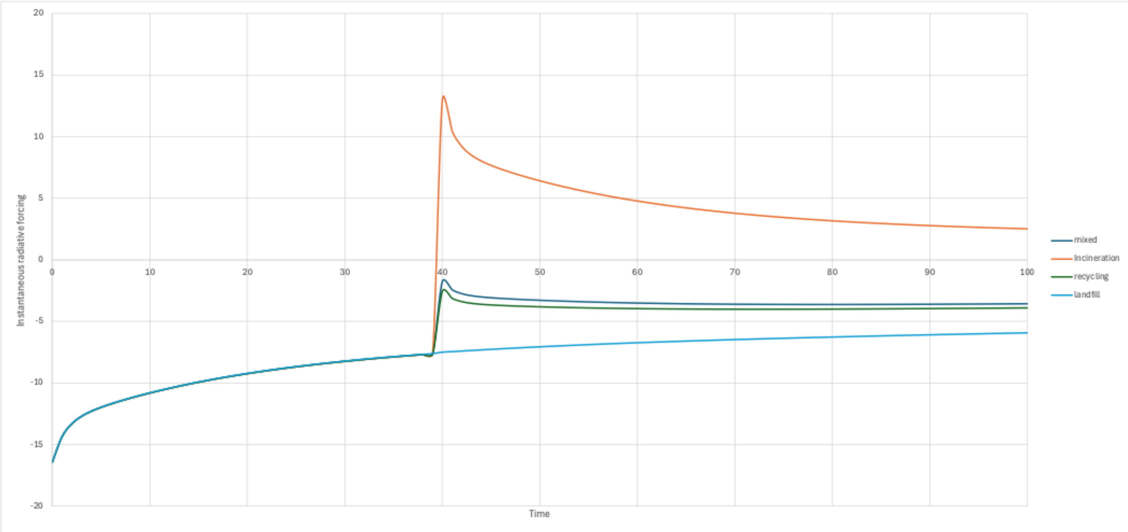

Figure 14: Instantaneous global warming impact of a wooden window for four EoL scenarios calculated using the DLCA approach, considering a RSL = 40 years.

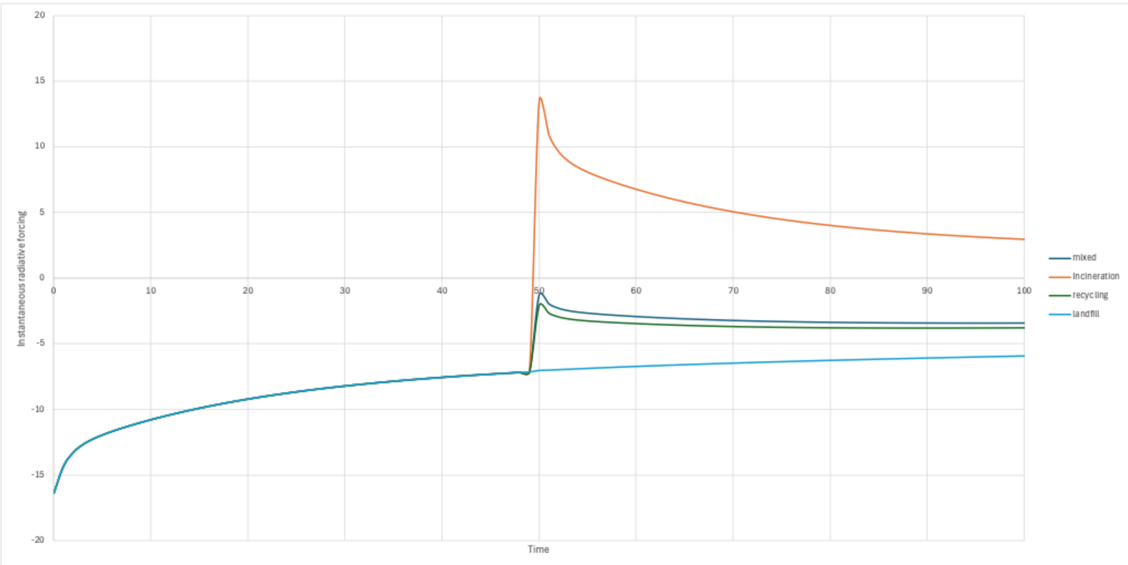

Figure 15: Instantaneous global warming impact of a wooden window for four EoL scenarios calculated using the DLCA approach, considering a RSL = 50 years.

In all cases, the curves show a similar behavior characterized by an initial negative impact at the beginning of the TH followed by a peak at the EoL stage. The initial negative values correspond to the biogenic carbon uptake that occurs during biomass growth and accounted at the production stage (t = 0). The uptake temporarily reduces atmospheric CO_2 concentration, so produces a negative radiative forcing contribution.

The differences between the scenarios occurs at the EoL emissions moment. When the service life is 30 years, the release of biogenic CO_2 occurs earlier within the 100-year TH, resulting in a peak of instantaneous radiative forcing around year 30. When the service life increases to 40 and 50 years, the peak is shifted forward in time. This reflects the delayed release of stored carbon and is a key element of the DLCA framework, as later emissions contribute less to cumulative climate impact due to atmospheric decay processes.

The incineration scenario, the orange line, shows the highest positive peak in all three graphs, as the stored biogenic carbon is rapidly released to the atmosphere at EoL through combustion. In contrast, the recycling scenario, represented by the green curve, produces a smaller perturbation because part of the carbon remains temporarily stored in secondary wood products. The mixed scenario, in dark blue, follows a similar trend to recycling but with a slightly higher impact due to the 5% of wood assumed to be sent to incineration. Finally, the landfill scenario, in light blue, shows a continuous negative profile throughout the TH, reflecting the long-term storage of biogenic carbon in landfill conditions, which limits the release of CO_2 within the 100-year assessment period.

Comparing the three figures also highlights the influence of service life on the temporal distribution of climate impacts. As the service life increases from 30 to 50 years, the emission peak shifts further along the time axis and the magnitude of the instantaneous perturbation decreases slightly over the remaining assessment horizon. This behaviour confirms that extending the durability of wood-based products delays carbon release and reduces the effective climate impact within the considered time horizon, which is one of the key insights provided by dynamic LCA approaches.

5. COMPARISON BETWEEN STATIC AND DYNAMIC APPROACHES

5.1 Comparison of results across end-of-life scenarios

This chapter compares the results obtained using the conventional static approach and the dynamic accounting method applied to the Navello wooden window case study. The aim is to highlight how the inclusion of time in the assessment affects the biogenic carbon flows and the resulting climate change impact.

Table 35 summarizes the comparison between the static results obtained from the LCA model and the dynamic results calculated using the DLCA approach, for different service life durations (30, 40 and 50 years) and for the four EoL scenario considered for this study.

Table 35: Comparison between static and dynamic GWP results for different service life durations.

SCENARIO	STATIC	DYNAMIC (30 y)	DYNAMIC (40 y)	DYNAMIC (50 y)
Mixed	-10.58 kg $CO_{2,eq}$	-11.94 kg $CO_{2,eq}$	-12.43 kg $CO_{2,eq}$	-12.94 kg $CO_{2,eq}$
Incineration	+4.18 kg $CO_{2,eq}$	-0.64 kg $CO_{2,eq}$	-2.36 kg $CO_{2,eq}$	-4.15 kg $CO_{2,eq}$
Recycling	-11.36 kg $CO_{2,eq}$	-12.54 kg $CO_{2,eq}$	-12.96 kg $CO_{2,eq}$	-13.40 kg $CO_{2,eq}$
Landfill	-16.34 kg $CO_{2,eq}$	-16.35 kg $CO_{2,eq}$	-16.36 kg $CO_{2,eq}$	-16.36 kg $CO_{2,eq}$

One of the most relevant differences between the static and dynamic approaches concerns the influence of product service life on the calculated climate impacts.
In the static method, the duration of the service life does not affect the final GWP result, because the timing of emissions is not considered in the characterization process.
In contrast, the dynamic approach explicitly captures the effect of delayed emissions. Increasing the service life shifts the release of biogenic carbon further into the future, reducing its contribution to atmospheric radiative forcing within the selected time horizon.

The largest differences between the two approaches are observed for the *incineration* scenario. In the static assessment, incineration shows a positive value, instead in the dynamic results the impact becomes significantly lower and negative. This occurs because the release of the stored biogenic carbon is delayed, reducing its contribution to cumulative radiative forcing within the 100-year TH.

Also for the *mixed* waste treatment and *recycling* scenarios the dynamic results are more favorable compared to the static results, although the difference is less pronounced than in the incineration case.

The *landfill* scenario shows the most negative results in both approaches. This outcome is mainly related to the long-term storage of carbon in the landfill environment, which limits the amount of biogenic carbon released to the atmosphere within the considered TH.

Overall, the comparison highlights that the inclusion of temporal dynamics significantly modifies the interpretation of climate impacts for wood-based products.

5.2 Interpretation of dynamic climate response

Figure 16 illustrates the cumulative radiative forcing over the 100-year TH for the reference service life of 40 years. The four EoL scenarios considered are distinguished by different colors in the legend.

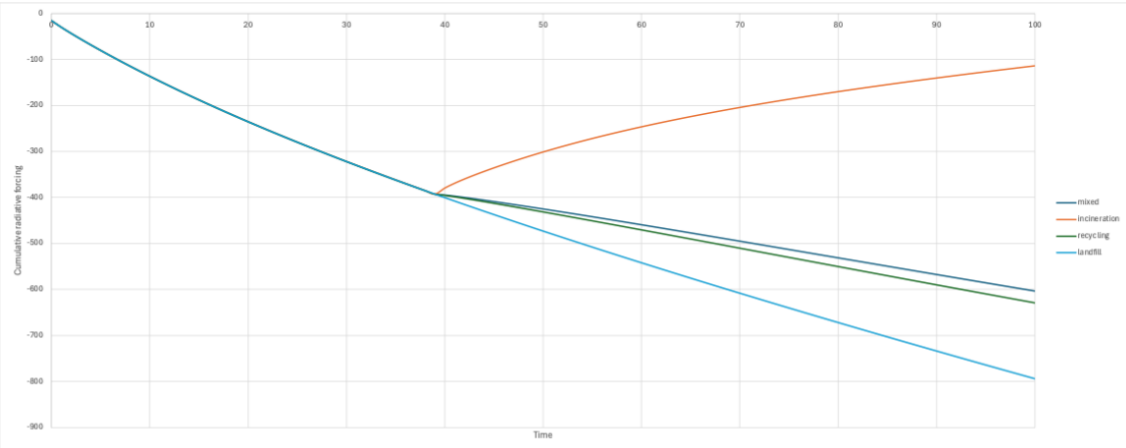

Figure 16: Cumulative radiative forcing over the 100-year horizon for RSL = 40 years.

The cumulative curves illustrate how the climate impact evolves over time as a result of both carbon uptake during biomass growth and carbon release at the EoL stage.

During the early years, the curves show a decrease in cumulative radiative forcing due to the uptake of biogenic carbon during tree growth and its storage within the wooden product. At the EoL stage (year 40), the release of the stored carbon causes an increase in radiative forcing, the magnitude of which depends on the specific treatment scenario. The different slopes of the curves after the EoL stage reflect the persistence of CO_2 in the atmosphere as described by the impulse response function used in the dynamic model. This representation highlights the advantage of the dynamic approach in capturing the time-dependent evolution of climate impacts, rather than providing a single aggregated indicator.

Overall, the comparison demonstrates that dynamic LCA provides a more detailed and physically better representation of the climate impacts associated with biogenic carbon flows. Dynamic modelling allows climate impacts to be analyzed in a more comprehensive and transparent way, particularly for long-lived wood-based construction products where carbon storage and delayed emissions play a crucial role (Hawkins et al., 2021).

6. LIMITATIONS AND FUTURE DEVELOPMENTS

6.1 Static accounting of biogenic carbon: conceptual limitations

The conventional static LCA framework presents several limitations when applied to systems involving biogenic carbon flows. The main limitation is the absence of an explicit temporal dimension in the accounting of GHG emissions and removals.

In static LCA, biogenic carbon uptake during biomass growth is typically balanced against emissions occurring at the EoL stage, often resulting in a net-zero contribution over the assessment horizon. This approach is based on a mass-balance principle in which increases and decreases in carbon stocks are accounted for without explicitly considering the timing of these processes (Leinonen, 2022).

While the mass balance principle ensures physical consistency in the accounting of carbon flows, it does not capture the climatic implications of temporary carbon storage. In the case of wood-based products, carbon absorbed during biomass growth can remain stored in the product during its service life before being released at the EoL stage. However, the static GWP method does not represent the temporal delay between carbon uptake and its subsequent emission.

Several studies have shown that even systems that are carbon neutral when evaluated over long time horizons may still produce a measurable climate impact when the temporal discrepancy between emission and regrowth is taken into account (Cherubini et al., 2012). Furthermore, the absence of temporal differentiation in conventional LCA may mask the potential climate benefits associated with delayed emissions from long-lived wood products (Hawkins et al., 2021).

Another limitation concerns the use of fixed characterization factors, such as GWP100, which aggregate the climate impact of emissions over a predefined time horizon but do not capture the temporal evolution of atmospheric CO_2 concentrations. As a result, the dynamic behaviour of the carbon cycle and the atmospheric persistence of carbon dioxide are not explicitly represented.

These limitations have motivated the development of dynamic LCA approaches, which aim to explicitly incorporate the timing of emissions and removals into climate change impact calculations.

6.2 Dynamic accounting of biogenic carbon: conceptual and applicative limitations

Although the dynamic approach provides a more detailed representation of the temporal behaviour of biogenic carbon flows, it also has limitations.

First, DLCA requires a detailed description of the temporal distribution of emissions and removals. This implies the need to define emission profiles over time, which may introduce additional uncertainty when empirical data are not available. In many cases, simplified assumptions regarding the timing of emissions, service life duration or EoL treatment must be adopted. As a consequence, the results of dynamic assessments can be highly sensitive to the assumptions made regarding the timing of emissions and removals. Parameters such as the assumed service life of the product, the distribution of emissions over time, and the EoL scenario can significantly influence the calculated climate impact.

Second, the results of DLCA are sensitive to modelling choices, such as the selected time horizon, the temporal resolution of the emission inventory and the assumptions made regarding carbon uptake and release processes. For example, different assumptions about product service life or EoL scenarios may significantly affect the calculated climate impacts.

Another limitation concerns the complexity of the modelling framework. DLCA requires the use of time-dependent inventories and climate models that account for the atmospheric persistence of GHG. In this study, atmospheric CO2 persistence was represented using the impulse response function derived from the Bern carbon cycle model. While this model is widely used in climate science, it represents a simplified approximation of the global carbon cycle and therefore introduces additional modelling uncertainty.

Finally, despite its scientific advantages, dynamic LCA is not yet widely implemented in existing LCA standards, databases, and software tools. Most environmental product declarations and LCA guidelines currently rely on static impact assessment methods such as GWP100. As a result, the application of dynamic LCA often requires additional calculations and methodological choices, which may reduce comparability between studies and limit its practical adoption in standardised LCA frameworks (Levasseur et al., 2013).

6.3 Limitations of case-study

Beyond the methodological aspects of static and dynamic approaches, some limitations affect the modelling of biogenic carbon in LCA.

One of the main challenges is the lack of harmonised international guidance for the accounting of biogenic carbon flows. Different LCA standards and protocols adopt different assumptions regarding carbon uptake, carbon neutrality and the treatment of temporary carbon storage. This has led to inconsistencies in the way biogenic carbon is considered across studies. In the case-study analysed in this thesis, the LCA was conducted following the European standard EN 15804, which provides specific rules for EPDs of construction products. While this standard ensures consistency in reporting within the construction sector, it is based on a conventional static accounting framework that does not explicitly consider the temporal dynamics of biogenic carbon flows.

Another source of uncertainty concerns the definition of system boundaries, for example the inclusion or exclusion of processes such as forest regrowth, which is not considered in this study, but it can influence the results of LCA.

The climate impact associated with biogenic carbon depends strongly on the fate of the material after use, such as incineration, recycling, landfill disposal, or reuse. However, future EoL scenarios are often difficult to predict and may change over time due to technological developments or policy changes.

In addition, the modelling of forest carbon dynamics is very complex. The amount and duration of carbon storage depend on factors such as forest management practices, growth rates, climatic conditions and ecosystem characteristics. Therefore, using simplified assumptions in LCA may not capture the complexity of real forest ecosystems.

6.4 Further developments and research perspectives

An important ongoing initiative aimed at improving the treatment of biogenic carbon in LCA is the Biogenic Carbon Project coordinated by the United Nations Environment Programme (UNEP) through the Life Cycle Initiative. The project started in response to the inconsistent accounting of biogenic carbon in LCA standards, leading to differences in the way climate impacts of bio-based systems are assessed.

The overall objective of the project is to develop harmonised, scientifically robust and stakeholder-informed recommendations for modelling biogenic carbon flows in LCA. The initiative brings together experts from academia, industry, consulting organisations, governmental bodies and non-governmental organisations in order to analyse existing methodological approaches and identify possible pathways toward greater consistency in biogenic carbon accounting.

The project is structured as a multi-phase international collaboration. Phase 1, conducted between 2024 and early 2025, focused on reviewing existing methodological practices and identifying key areas where inconsistencies occur. The discussions were organised around four main thematic working groups addressing the most critical methodological issues in biogenic carbon accounting:

- temporal aspects of biogenic carbon flows;
- end-of-life modelling, including reuse and recycling;
- system boundary definitions;
- standards and barriers to methodological adoption.

The outcome of Phase 1 was the development of a technical report summarising the different options currently used to model biogenic carbon in LCA, highlighting areas of consensus as well as unresolved methodological questions.

Based on these results Phase 2 of the project (2025–2027) aims to transform the findings of the first phase into practical guidance for LCA practitioners. This stage includes a process of stakeholder consultation, iterative development of recommendations, pilot testing of proposed methodologies and the preparation of global guidance documents. The final objective is to provide internationally recognised recommendations that can support consistent and transparent modelling of biogenic carbon in LCA across different sectors.

The work carried out within this project reflects the growing need for improved methodological consistency in the assessment of bio-based products and systems. Future outcomes of the UNEP initiative may therefore contribute to further refinement and potential standardisation of dynamic approaches for representing the climate impacts of biogenic carbon.

Continued research and international collaboration will be essential to address the remaining methodological challenges and to ensure that LCA study provides robust and comparable information on the climate performance of bio-based products.

CONCLUSION

This thesis analyzes the role of biogenic CO_2 in the LCA of a wooden window produced in Italy by the Navello company, focusing on the comparison between static and dynamic approaches. Starting from a conventional cradle-to-grave LCA developed in OpenLCA and reported through an EPD, the study was extended by implementing the DLCA framework based on the methodology proposed by (Levasseur et al., 2013).

The results demonstrate that the consideration of time significantly influences the climate assessment of bio-based products. While conventional static LCA aggregates emissions independently of their temporal distribution, dynamic modelling explicitly accounts for the separation between carbon uptake during biomass growth and carbon release at EoL. By integrating the atmospheric impulse response function of CO_2 and calculating time-dependent radiative forcing, DLCA provides a more physically consistent representation of climate impact.
The comparison between static and dynamic indicators showed substantial differences in both magnitude and interpretation of the results. Under static accounting, the biogenic carbon balance remains constant regardless of service life duration, as the timing of emissions and removals is not considered. In contrast, dynamic results are influenced by both the service life of the product and EoL scenario. Extending the reference service life from 30 to 50 years improved dynamic climate performance, particularly in scenarios involving delayed emissions. This confirms that durability becomes a climate-relevant parameter only when temporal dynamics are explicitly considered.
Among the scenarios analysed, the landfill option showed the most negative dynamic climate impact due to the long-term storage of biogenic carbon, instead the other scenarios exhibited a strong sensitivity to the timing of emissions. This highlights the importance of considering the temporal distribution of carbon flows when evaluating the climate performance of wood-based products.

In the building sector the dynamic modelling enables a more objective and transparent assessment of climate impacts (Hawkins et al., 2021). The results of this thesis support this claim, showing that parameters such as product durability and EoL management become critical factors when evaluated dynamically.

Beyond the specific case study analyzed, this research contributes to the international discussion on the treatment of biogenic carbon in LCA. The accounting of biogenic carbon remains one of the most debated methodological issues in LCA, particularly in the construction sector where bio-based materials are increasingly promoted as climate mitigation solutions. In this context, the present work aligns with the ongoing activities of the UNEP Life Cycle Initiative, which aims to develop harmonized and scientifically robust recommendations for the treatment of biogenic carbon in LCA. By applying a dynamic modelling framework to a real industrial case study and transparently documenting the modelling assumptions, inventory data and scenario choices, this thesis provides an empirical example that may contribute to testing and evaluating future methodological guidelines under development.

An important conceptual aspect emerging from this work concerns the role of the assessment TH in climate impact evaluation. In most LCA studies, climate impacts are quantified using the GWP100 indicator, which aggregates radiative forcing effects over a 100-year period. However, this TH represents a methodological and policy convention rather than a strict representation of the physical persistence of CO_2 in the atmosphere. From a purely physical perspective, the total quantity of CO_2 released into the atmosphere remains the same regardless of whether emissions occur today or several decades later. Nevertheless, the timing of emissions becomes relevant in the context of climate mitigation strategies, which aim to limit temperature increase within the current century. Delaying emissions can therefore reduce near-term atmospheric concentration peaks and provide additional time for technological and policy transitions toward low-carbon systems.

At the same time, the introduction of temporal dynamics in LCA raises important methodological challenges. One of the main strengths of conventional LCA are its standardization and comparability across products and studies, supported frameworks such as PCRs, EPD programs and shared databases. The use of dynamic modelling introduces additional parameters, such as service life assumptions, forest rotation periods and emission timing, which may be uncertain and context dependent. Therefore, DLCA results may become more difficult to compare across studies. This raises an important methodological question for the LCA community: whether increasing the physical realism of climate modelling through dynamic approaches justifies the potential reduction in simplicity and comparability of the assessment framework.

Concluding, this thesis demonstrates that explicitly incorporating time into the assessment of biogenic carbon flows can improve the robustness and scientific consistency of climate impact evaluation for wood-based construction products. At the same time, the study highlights the importance of extending product service life, implementing responsible EoL strategies and adopting transparent modelling assumptions when evaluating the mitigation potential of bio-based construction systems. As methodological research continues to evolve, further harmonization efforts will be essential to ensure that dynamic modelling approaches can be effectively integrated into LCA practice while maintaining the comparability and usability of environmental assessments.

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