

Draft Document

Normative module for the Life Cycle Assessment (LCA) of high-TRL bio-based systems.

Public consultation start date: 1st of October 2026

Public consultation end date: 1st of November 2026



**Funded by
the European Union**

CONTENTS

FOREWORD	4
1. INTRODUCTION	5
2. TERMS AND DEFINITIONS	6
3. LCA for high-TRL bio-based system	8
3.1. Goal and scope definition	8
3.2. Life Cycle Inventory (LCI)	8
3.2.1. Foreground LCI	8
3.2.2. Background LCI	9
3.3. Life Cycle impact Assessment (LCIA)	9
3.3.1. Dynamic carbon footprint	9
3.3.2. Other life cycle impact assessment methods	17
3.3.3. Circularity indicators	18
SUPPLEMENTARY INFORMATION	21
REFERENCES	22

LIST OF ACRONYMS

Acronym	Description
BbS	Bio-based Systems
CDR	Carbon Dioxide Removal
CF	Characterization Factors
CCI	Climate Change Impact (tool)
DyPLCA	Dynamic Process-based Life Cycle Assessment
EC	European Commission
EF	Environmental Footprint
EPD	Environmental Product Declaration
GHG	Greenhouse Gases
GTP	Global Temperature Potential
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
iRF	Integrated Radiative Forcing
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCI	Material Circularity Index
SLCF	Short-Lived Climate Forcers
TRL	Technology Readiness Level

FOREWORD

The development of the Normative Life Cycle Assessment of high-TRL bio-based system module represents a preliminary step towards enabling the international trade of bio-based products. This work is carried out within the framework of LCA4BIO, a Horizon Europe initiative bringing together a consortium of ten partners from seven different countries. The project aims to develop and validate a new set of improved, harmonized, precise, reliable and applicable assessment methodologies to properly evaluate environmental impacts and circularity in bio-based systems, methodologies that can be applied in certification schemes and thus enable the international trade of this type of product.

Different stakeholders across the bioeconomy value chain were involved through a co-creation process designed to capture their requirements and test the adequateness of the methodologies under development. This co-creation approach materialized in a series of dedicated workshops where the methodological proposals were presented, discussed and refined together with the stakeholders.

The result of this iterative, participatory process is the present draft, which will now be submitted to public consultation. This consultation stage is intended to open the proposed methodologies to broader scrutiny from the sector, gather additional feedback from certification bodies, industry actors and other interested parties, and ultimately validate the standard before its finalization.

1. INTRODUCTION

In recent years, the European Commission (EC) has approved several policies, such as the new Circular Economy Plan and the Bioeconomy Strategy, aimed at supporting circular bio-based systems (BbS) to reduce the dependence on non-renewable resources and to facilitate the green transition of European industry. For this reason, more applicable and realistic environmental assessment methods are needed to determine the best available technologies and validate the improved performance of bio-based products compared to their fossil-based counterparts. However, the existing methodologies present certain limitations when applied to both emerging and already available in the market BbS. In this context, LCA4Bio project addresses the development, improvement and harmonization of suitable and reliable Life Cycle Assessment (LCA) methodologies to support the certification of high-TRL BbS.

Specifically, the LCA4Bio consortium has developed a normative module that brings together the methodological advances achieved throughout the project and provides a step-by-step description of the proposed procedure for conducting LCA of high-TRL (≥ 8) BbS. Additionally, it supports practitioners in selecting the appropriate assessment approach according to the intended application, ranging from certification to research-oriented analyses.

The methodological framework adopted in this draft follows ISO 14040 and ISO 14044 framework. ISO 14040 is the international standard that establishes the principles and methodology framework for LCA, including its four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results. On the other hand, ISO 14044 provides more detailed requirements and guidelines for the implementation of each LCA phase, including aspects such as data quality, impact categories and result reporting.

2. TERMS AND DEFINITIONS

2.1 System and Resource Foundations

Bio-based Systems (BbS) and Bio-based Products: Systems and derived products fully or partially generated from biomass, which encompasses biological material of organic origin excluding materials embedded in geological formations or transformed to fossilized equivalents. They serve as renewable alternatives to traditional fossil-based production routes within the circular bioeconomy.

Fossil-based Products: Materials, chemicals, or energy resources derived from non-renewable geological reserves, primary petroleum, natural gas, and coal. Their extraction and combustion irreversibly release long-term sequestered carbon into the short-term active biosphere-atmosphere system.

Non-renewable Resources: Natural resources that exist in finite quantities and cannot be replenished by natural processes on a human timescale once consumed. These include mineral ores, nuclear fuels, and fossil energy carriers.

Biogenic Carbon / CO₂ Capture: The biological process by which biomass (plants, algae, etc.) removes carbon dioxide from the atmosphere through photosynthesis during its growth phase. In bio-based systems, this captured carbon remains stored within the product's molecular structure for a duration that depends on the product's lifespan and its circularity (recycling/reuse loops) before eventual release at the end-of-life. Accurate assessment of this capture requires dynamic modeling to distinguish it from fossil-based carbon emissions

2.2 Life Cycle Assessment Framework & Systems

Life Cycle Assessment (LCA): A standardized, multi-step analytical methodology (ISO 14040/14044) used to compile and evaluate the inputs, outputs, and potential environmental impacts of a product or service system throughout its life cycle. It systematically covers phases from raw material acquisition through production and use to end-of-life (EoL) treatment.

Process Unit (PU): The smallest elemental building block or discrete step identified in a life cycle inventory model for which input and output data are quantified (e.g., a specific chemical reactor, separation column, or drying process).

Elementary Flows: Material or energy inputs drawn from the environment without prior human transformation, or material/energy outputs released directly into the environment without subsequent human processing.

Foreground System: The collection of processes, operations, and supply steps that are directly affected, controlled, or modeled by the LCA practitioner using direct primary data (e.g., process-specific mass and energy balances).

Background System: Upstream and downstream processes connected to the foreground system through supply chains (e.g., national electricity grids, regional transportation, bulk chemical supplies) where primary data are unavailable and secondary background databases (such as ecoinvent) are applied.

Environmental Product Declaration (EPD): A standardized, third-party verified document (based on ISO 14025) that provides transparent and comparable information about the life-cycle environmental impact of a product. In the context of LCA4Bio, EPDs serve as a key instrument for the certification of high-TRL bio-based systems, translating complex LCI and LCIA results into verified environmental performance indicators for stakeholders and international trade.

2.3 Temporalization and Dynamic Carbon Accounting

Dynamic Carbon Footprint: An advanced carbon accounting approach that incorporates the exact timing of GHG emissions, uptake events, and removals across the product life cycle rather than assuming all releases occur at time zero. This temporal differentiation provides a more realistic assessment of climate impacts, particularly for long-lived systems, biomass growth, or delayed EoL emissions.

CCI-tool (Climate Change Impact Tool): A specialized analytical framework designed to process temporalized life cycle emission inventories and calculate dynamic climate change metrics, such as cumulative radiative forcing and global mean surface temperature change over flexible time horizons.

Climate Change, Global Warming Potential (GWP), Carbon Dioxide Removal (CDR), and Global Temperature Potential (GTP): Climate change refers to long-term alterations in global climate dynamics driven by greenhouse gas (GHG) emissions. GWP measures the cumulative radiative forcing of a GHG over a fixed horizon (typically 100 years: GWP100) relative to CO₂, GTP assesses the resulting change in global mean surface temperature at a chosen point in time, and CDR refers to activities that permanently remove CO₂ from the atmosphere.

Integrated Radiative Forcing (iRF): A dynamic climate metric that quantifies the cumulative radiative forcing (energy imbalance) caused by a substance in the atmosphere over a specific time horizon. Unlike static Global Warming Potential (GWP), the iRF accounts for the exact timing of emissions and removals, making it a more precise indicator for evaluating the temporary carbon storage benefits and the short-lived climate forcers (SLCF) characteristic of bio-based value chains.

2.4 Technology Readiness and Environmental Metrics

Technology Readiness Level (TRL): A standardized metric used to assess the maturity and deployment status of a specific technology on a scale from 1 (basic principles observed) to 9 (actual system proven in operational environment). Low-TRL (typically <8) refers to emerging technologies under laboratory or pilot validation, whereas high-TRL (≥8) denotes commercially deployable or fully operational industrial systems.

Environmental Impacts: Adverse or beneficial changes caused to ecosystems, human health, or natural resource stocks resulting fully or partially from human activities and process flows. In LCA, these impacts are quantified by converting inventory data into standardized impact metrics.

Characterization Factors (CF): Science-based conversion factors derived from environmental impact models that translate quantified inventory flows (e.g., mass of a pollutant emitted) into common impact units (e.g., kg CO₂-equivalent for climate change).

3. LCA FOR HIGH-TRL BIO-BASED SYSTEM

This document provides methodological recommendations for conducting LCA of high TRL ($TRL \geq 8$) BbS, where technologies are close to or already at commercial deployment. It supports practitioners in selecting the appropriate assessment approach according to the intended application for certification purposes, three main topics are considered: (i) dynamic carbon footprint, (ii) other environmental impacts, such as toxicity, land use, water use, biodiversity impacts and ecosystem services, and (iii) circularity. The document introduces three methodological tiers that progressively increase the level of temporal detail and modelling complexity for dynamic carbon footprint.

3.1. Goal and scope definition

The goal and scope definition sets the basis for the whole assessment. Since this document focuses on commercially mature bio-based systems ($TRL \geq 8$), the functional unit, system boundaries and methodological choices should reflect real operating conditions and support decision-making in industrial contexts. Depending on the intended application, users can select one of three methodological tiers for carbon footprint assessment.

- **Tier 1 is the first step towards BbS certification.** This certification method could be applied for five years. The Tier 1 method is compatible with the French RE2020 regulation; however, it addresses some of its shortcomings and provides more accurate results. This is particularly the case for wood-based products, for which the effect of CO₂ capture is now included in the climate change impact calculation. Moreover, the EoL time horizon is not imposed (in RE2020, the EoL is fixed at 50 years).
- **Tier 2 aims to provide BbS certification after five years of applying Tier 1**, when dynamic approaches to climate change impact calculation are expected to become more widely adopted. The Tier 2 method considers both the inventory and its temporal dimension for the foreground system. Biomass production is included in the foreground system, while the background system remains static. The CCI tool can be used to calculate dynamic climate change indicators in addition to GWP100. Dynamic climate change indicators, such as global mean temperature change and cumulative radiative forcing, are calculated as a function of time, without imposing a fixed time horizon. This allows for a clearer understanding of both the magnitude of the impact and when it occurs.
- **Tier 3 is intended for in-depth research on BbS.** Its aim is to understand how the system behaves and to identify mitigation levers across the entire life cycle. It applies a fully dynamic LCA at both the LCI and LCIA levels, which requires purpose-built calculation tools. As Tier 3 is primarily intended for research activities, so the dynamic LCIA is not developed further in this document.

3.2. Life Cycle Inventory (LCI)

3.2.1. Foreground LCI

The foreground LCI consists of the processes that are under the control of, or directly related to, the system under study. In addition, data can be categorized as either primary or secondary. Primary data consist of information collected directly through surveys, measurements, or experiments specific to the system under study. Such data are generally considered highly reliable, as they reflect actual operating conditions. In contrast, secondary data are obtained from literature reviews or databases. They are usually based on averages or estimates and are used when the collection of primary data is not possible.

LCA of high-TRL systems can be performed for different purposes. Two main objectives for the environmental assessment of bio-based systems can be distinguished: (1) Environmental Product Declaration (EPD)-oriented

LCA and (2) LCA for understanding environmental performance, eco-design, and communication.

In the case of an EPD approach, mixed inventory data (provided by producers) and environmental impact data (based on the Environmental Footprint method) are provided and subsequently used throughout the cascade of processes. By definition, the EPD approach relies on static LCA, including both static LCI and static LCIA.

Moreover, most widely used LCA software is designed for static LCA. For carbon footprint assessment, the temporalization of the LCI can be considered at different levels of detail and complexity, depending on the objective of the LCA.

Tier 1 applies to climate change impact assessment and consists of correcting static LCA results to better account for delayed emissions and/or CO₂ capture.

Tier 2 considers the foreground system with the temporal distribution of activities and processes, including upstream biomass production. The background inventory remains static. This dynamic approach provides more accurate results than Tier 1. It can be applied to any impact category using either static or dynamic LCIA methods. However, within this document, Tier 2 is defined and applied specifically to dynamic climate change impact assessment.

3.2.2. Background LCI

The background system includes processes upstream and downstream of the foreground system and encompasses the evaluation of processes such as the production of materials required by the system. Typically, LCI data for the background system primarily consists of secondary data. Although the use of secondary data may increase uncertainty in LCA results, it often represents a practical solution when faced with complex and time-consuming process of collecting primary data.

The Ecoinvent database is the most widely recognized background database used in LCA studies. The database covers a diverse range of sectors and contains more than 26,000 datasets modelling human activities and processes.

3.3. Life Cycle impact Assessment (LCIA)

3.3.1. Dynamic carbon footprint

3.3.1.1. *Tier 1 methodology for certification*

This methodology can be used with inventory data or with EPD data. The methodology is inspired by the French regulation RE2020 (Guide RE2020, 2025) in the sense that it combines static and dynamic elements. The methodology proposed in this document improves the result accuracy in comparison with RE2020, especially for wood-based products, and for systems with late emissions.

The following rules should be applied under the Tier 1 methodology.

Rule 0: Biogenic carbon must be considered using cradle-to-grave system boundaries, consistent with the –1/+1 approach.

Rule 1: By convention, **time zero ($t = 0$) is set at the beginning of the use stage**, when the product is delivered. Time before $t = 0$ is represented as negative time.

Rule 2: A time horizon of 100 years is selected for the impact assessment.

Taking this into account, the time frame can be divided in two zones (**Figure 1**):

Zone (1): All emissions occurring before $t = 0$ during the production stage are considered at $t = 0$ and are

therefore treated as static. An exception is made for wood-based products, for which carbon uptake is accounted for over the growth period preceding $t = 0$.

Zone (2): The use and EoL stages (0–100 years), during which the impact is adjusted to account for the timing of emissions. Rapid EoL emissions, such as those resulting from incineration, can be considered to occur at $t = \text{EoL}$. For long-term emissions, such as those resulting from decomposition in landfills, the temporal distribution of emissions can be considered to obtain more accurate results.

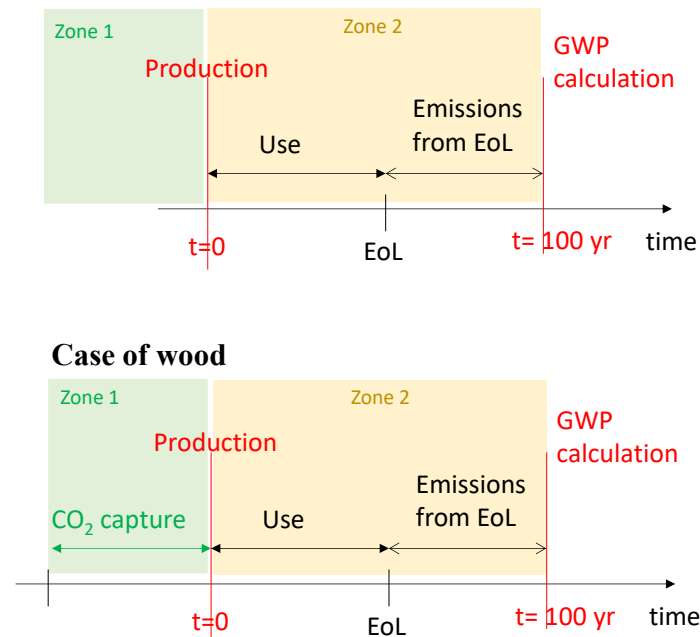


Figure 1. Life cycle time scale and fixed points $t=0$ (beginning of use stage) and $t=100$ for GWP calculation. Zone 1 is the “production”, considered at $t=0$ (except for wood production). Zone 2 is “use” and “end of life” stages.

An easy-to-use tool was developed in excel to calculate climate change impact (GWP100). It can be used with EPD data or with LCA inventory (elementary flows). Corrections of static LCA results are implemented for CO₂, CH₄ and the two most used refrigerants (HFC-32 and HFC-125). All correction factors and characterization factors implemented in the tool have been calculated with CCI-tool (Tiruta-Barna, 2021; Tiruta-Barna, 2026).

The **Dynamic Climate Change Tier 1 Tool** is available in Zenodo repository <https://zenodo.org/records/20735324>, which also provides a complete worked **example** based on data from EPD at <https://zenodo.org/records/23067900>.

Data requirements

- Inventory and/or EPD inventory and impact results as GWP100 kg CO₂-eq.
- Amount of CO₂ captured by biomass growth for wood-based products.
- CO₂ emissions, CH₄ emissions, refrigerants emissions during the use stage. These data can be as amount of gas emitted in kg, or as individual GWP100 result in kg CO₂-eq. Ideally, individual data for each gas are preferred for the result accuracy.
- For end of life, emissions could spread over a given time period, e.g. in case of landfilling. CO₂ and CH₄ emissions can be estimated from different methodological guides, e.g. IPCC – waste. Use amount of each gas in function of time.

Methodology for CO₂ capture, wood - Zone (1)

This section describes the methodological procedure used to account for CO₂ captured during the growth of wood biomass. In case of wood, it is useful to consider CO₂ capture when capture occurs for more than 5 years.

- 1) Amount of CO₂ captured (from, e.g., C content of the material used)
- 2) Distribute this amount evenly over the time of wood growth. Depending of the tree, if it is stem, or round wood.

This distribution can be year by year, or for larger time intervals, e.g. 5 years, 10 years. Consider a time scale, place each interval, and consider the middle of the interval as value of time for the capture step, like in the example below (**Figure 2**).

Use the correction factor corresponding at the capture time to multiply the impact value (kg CO₂-eq) or the amount in kg CO₂, to obtain the GWP100 for this capture time.

Verify that the result is indeed a negative value (CO₂ capture).

Example: Suppose the capture of 50 kg CO₂, with a growth time (time of biomass growth until harvesting) of 25 years, from year -25 to year 0. **Figure 2** shows two examples of distributing the amount (50 kg) over the time of the capture (25 years).

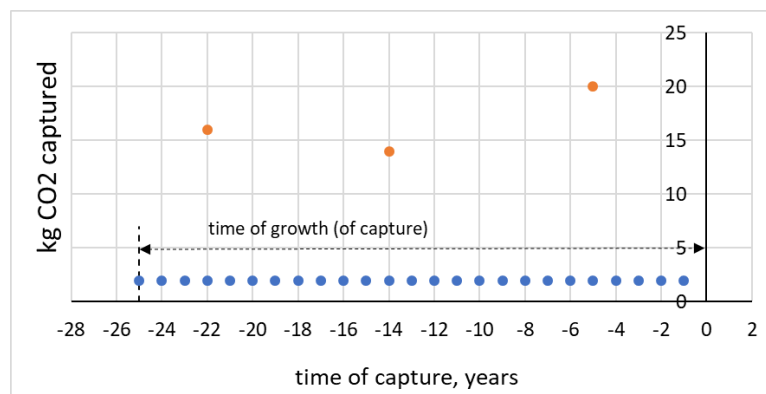


Figure 2. Example of data time series with different granulometries in time (timesteps)

Blue dots show the case when the amount captured is provided each year: 2 kg each year, from -1 to -25 (included).

Orange dots show the case when 3 time-intervals are considered:

- Years [-1, -10] with $2 \times 10 = 20$ kg CO₂ captured, placed at time -5
- Years [-11, -17] with 2×7 kg = 14 kg CO₂ captured, placed at time -14
- Years [-18, -25] with 2×8 kg = 16 kg CO₂ captured, placed at time -22

Tool utilization, sheet “tool CO₂ capture”

Figure 3 shows the tool calculation for the example proposed in Figure 2, with a time step of 1 year. The next **Figure 4** shows the case of using 3 intervals (identified by different colors).

A small difference is observed for net results: -54.99 vs 54.98 kg CO₂-eq.

Remark: More the timestep of the distribution is small, more the result is precise.

do not modify these columns		Put the CO2 amount captured, in kg	Result in kg CO2-eq (GWP100)	
		recommended one datapoint each maximum 10 years	-54.99383841	
CO2 capture year of capture	correction coefficient	amount, kg	result in kg_CO2 eq	
0	-1.00		0	
-1	-1.01	2	-2.015629774	
-2	-1.02	2	-2.031223649	
-3	-1.02	2	-2.046782183	
-4	-1.03	2	-2.06230592	
-5	-1.04	2	-2.077795389	
-6	-1.05	2	-2.093251108	
-7	-1.05	2	-2.108673582	
-8	-1.06	2	-2.124063301	
-9	-1.07	2	-2.139420746	
-10	-1.08	2	-2.154746382	
-11	-1.09	2	-2.170040667	
-12	-1.09	2	-2.185304045	
-13	-1.10	2	-2.200536949	
-14	-1.11	2	-2.215739801	
-15	-1.12	2	-2.230913016	
-16	-1.12	2	-2.246056994	
-17	-1.13	2	-2.261172129	
-18	-1.14	2	-2.276258802	
-19	-1.15	2	-2.291317388	
-20	-1.15	2	-2.306348252	
-21	-1.16	2	-2.321351748	
-22	-1.17	2	-2.336328224	
-23	-1.18	2	-2.351278018	
-24	-1.18	2	-2.366201462	
-25	-1.19	2	-2.381098876	
-26	-1.20		0	
-27	-1.21		0	
-28	-1.21		0	
-29	-1.22		0	
-30	-1.23		0	
-31	-1.23		0	
-32	-1.24		0	
-33	-1.25		0	
-34	-1.26		0	
-35	-1.26		0	
-36	-1.27		0	
-37	-1.28		0	
-38	-1.29		0	
-39	-1.29		0	

Figure 3. Tool utilization with a year-timestep

do not modify these columns		Put the CO2 amount captured, in kg	Result in kg CO2-eq (GWP100)	
		recommned one datapoint each maximum 10 years	-54.97875829	
CO2 capture year of capture	correction coefficient	amount, kg	result in kg_CO2 eq	
0	-1.00		0	
-1	-1.01		0	
-2	-1.02		0	
-3	-1.02		0	
-4	-1.03		0	
-5	-1.04	20	-20.77795389	
-6	-1.05		0	
-7	-1.05		0	
-8	-1.06		0	
-9	-1.07		0	
-10	-1.08		0	
-11	-1.09		0	
-12	-1.09		0	
-13	-1.10		0	
-14	-1.11	14	-15.51017861	
-15	-1.12		0	
-16	-1.12		0	
-17	-1.13		0	
-18	-1.14		0	
-19	-1.15		0	
-20	-1.15		0	
-21	-1.16		0	
-22	-1.17	16	-18.69062579	
-23	-1.18		0	
-24	-1.18		0	
-25	-1.19		0	
-26	-1.20		0	
-27	-1.21		0	
-28	-1.21		0	
-29	-1.22		0	
-30	-1.23		0	
-31	-1.23		0	
-32	-1.24		0	
-33	-1.25		0	
-34	-1.26		0	
-35	-1.26		0	
-36	-1.27		0	
-37	-1.28		0	
-38	-1.29		0	
-39	-1.29		0	

Figure 4. Tool utilization with different time intervals for data input in calculation

For CO₂ emissions, the input data may be provided either as emission inventories (kg CO₂) or as climate change impacts expressed as GWP100 (kg CO₂-eq). In both cases, users should use the "Emissions CO₂" worksheet and enter the available data at the corresponding year of emission.

For CH₄ emissions, two calculation options are available depending on the available data. If methane emissions are reported as inventory data (kg CH₄), users should complete the "Emissions CH₄, kg" worksheet by entering both the emission amounts and their corresponding emission times. Emissions may be recorded on an annual basis or aggregated over longer time intervals, in which case the total emitted amount should be assigned to the midpoint of the interval. If methane emissions are already expressed as GWP100 values (kg CO₂-eq), the "Emissions CH₄, kg CO₂-eq" worksheet should be used, following the same procedure for assigning emission

values to their corresponding emission times.

For the two most commonly used refrigerants in buildings, HFC-32 (difluoromethane) and HFC-125 (pentafluoroethane), dedicated worksheets are provided within the tool. Users should use the "Emission HFC-32" or "Emission HFC-125" worksheet to calculate the corrected GWP100 values while accounting for the timing of emissions.

For all other greenhouse gas emissions expressed as GWP100 (kg CO₂-eq), including aggregated datasets such as those commonly reported in Environmental Product Declarations (EPDs), users should use the "Emission General kg CO₂-eq" worksheet. This worksheet adjusts the reported climate change impact by incorporating the emission timing, ensuring consistency with the dynamic climate change assessment methodology. This approach is particularly useful when only impact results, rather than detailed life cycle inventories, are available.

3.3.1.2. Tier 2 methodology for certification after 5 years of performing Tier 1

All processes in the foreground system can be considered with their occurrence time. The foreground system must include (**Figure 5**):

- the biomass with the growth period
- the processes associated with biomass cultivation and harvesting
- manufacturing of biobased products
- the use stage of the product with its eventual refurbishment or other related processes
- the product's end-of-life with the related processes

Considering the biomass growth and delayed emissions ensures an accurate result, more accurate than static LCA or Tier 1 method.

If some processes last for years, as for example CO₂ capture by trees, others can be considered as punctual in time, at a given year (e.g. manufacturing at $t = -1$ yr, tree harvesting at $t = -3$ yr, end-of-life incineration at $t = 80$ yr...). The time step in this method is 1 year. It is not necessary to differentiate in time processes which take place closer than 2 years. For example, if the distance in time between process A and B is of 1.5 years, it is possible to place A and B at the same time.

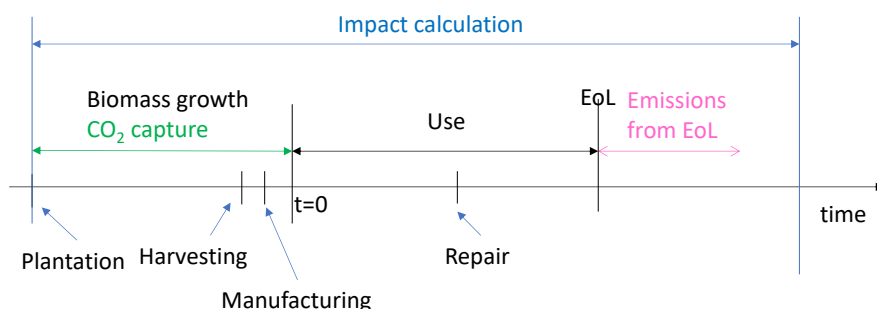


Figure 5. Foreground system of BbS for Tier 2 LCA methodology and the timescale

There is no imposed lifetime or time horizon. Time $t=0$ corresponds to the start of the use stage.

The impact indicators are calculated in function of time and not at a given time horizon (e.g. 100 years). The

recommended indicators are:

- global mean temperature change (in °C or K),
- cumulated radiative forcing (in W yr m⁻²)

The necessary data are inventory amounts as retrieved from an LCA software, i.e. elementary (or biosphere) flows, in kg. The LCI results (in terms of biosphere flows) have to be separated by key processes, e.g. in case of **Figure 5**, for plantation lifecycle, growth, harvesting (lifecycle), repair (lifecycle), end of life (lifecycle). If the LCA software doesn't provide results organized by processes, separate runs are necessary by process of interest to obtain its LCI.

The dynamic climate change indicators are calculated with the CCI-tool. It is available as calculator on-line at <https://www.insa-toulouse.fr/cci-tool/> or its python code can be downloaded as a package, available on the same site. Users download the template file from the CCI-tool website and fill it in with their own inventory data. It is possible to complete manually for each substance (fastidious) or to copy the inventory from a result file retrieved from LCA software. In this case, the only operation is to place the data column (representing a process) at the desired time. **Figure 6** shows a result file from BrightWay2 software, for 2 processes. Note that all biosphere flows are listed. In case the nomenclature is those from Simapro software, the user doesn't need to separate the 'air' emissions from the other compartments. In the category "natural resource", check that CO₂ complete name is "Carbon dioxide, in air"; if not, change the name into "Carbon dioxide, in air" (as in figure below). In case the LCA software output doesn't contain the same names for the emission compartments as Simapro, like in the example obtained with Brightway2, the raw LCI file must be sorted for the Air emissions, and change the name of compartment from e.g. ('air', 'urban air close to ground') "in "Air".

Fichier	Accueil	Insertion	Mise en page	Formules	Données	Révision	Affichage	Aide	Power Pivot	Outils	Notes	ce que vous voulez faire	
S16													
	A	B	C	D	E	F	G	H	I	J	K	L	M
		name	categories	type	unit	database	Process A	Process B					
1	0	1,4-Butanediol	('air', 'urban air close to ground')	emission	kilogram	biosphere3	1.78348E-10	2.74199E-12					
3	1	1-Pentanol	('air', 'urban air close to ground')	emission	kilogram	biosphere3	1.88882E-13	7.04623E-13					
4	2	1-Pentene	('air', 'urban air close to ground')	emission	kilogram	biosphere3	3.25623E-12	6.95614E-13					
5	3	2,4-D	('soil', 'agricultural')	emission	kilogram	biosphere3	1.8035E-09	1.19467E-08					
6	4	2-Aminopropanol	('air', 'urban air close to ground')	emission	kilogram	biosphere3	1.62468E-13	6.97408E-13					
7	5	2-Methylpentane	('air', 'urban air close to ground')	emission	kilogram	biosphere3	2.91703E-10	1.46156E-11					
8	6	2-Methyl-1-propanol	('air', 'urban air close to ground')	emission	kilogram	biosphere3	6.18784E-13	2.33083E-12					
9	7	2-Methyl-2-butene	('air', 'urban air close to ground')	emission	kilogram	biosphere3	1.00304E-16	1.11559E-16					
10	8	2-Nitrobenzoic acid	('air', 'urban air close to ground')	emission	kilogram	biosphere3	3.8685E-13	1.62858E-12					
11	9	2-Propanol	('air', 'urban air close to ground')	emission	kilogram	biosphere3	4.36751E-08	1.77021E-09					
12	10	3-Methyl-1-butanol	('air', 'urban air close to ground')	emission	kilogram	biosphere3	0	0					
13	11	4-Methyl-2-pentanone	('air', 'urban air close to ground')	emission	kilogram	biosphere3	8.20527E-12	2.86138E-12					
14	12	Abamectin	('soil', 'agricultural')	emission	kilogram	biosphere3	2.85557E-12	1.76779E-11					
15	13	Acenaphthene	('air', 'urban air close to ground')	emission	kilogram	biosphere3	0	0					
16	14	Acetate	('soil', 'agricultural')	emission	kilogram	biosphere3	7.13844E-10	2.67924E-09					
17	15	Acetaldehyde	('air', 'urban air close to ground')	emission	kilogram	biosphere3	6.32864E-08	3.40379E-09					
18	16	Acetamide	('soil', 'agricultural')	emission	kilogram	biosphere3	1.4541E-13	1.70479E-13					
19	17	Acetic acid	('air', 'urban air close to ground')	emission	kilogram	biosphere3	1.57717E-06	7.43705E-09					
20	18	Acetochlor	('soil', 'agricultural')	emission	kilogram	biosphere3	2.5252E-11	3.25211E-12					
21	19	Acetone	('air', 'urban air close to ground')	emission	kilogram	biosphere3	8.42101E-08	3.84892E-09					
22	20	Adonifen	('soil', 'agricultural')	emission	kilogram	biosphere3	1.51845E-15	1.98158E-14					
23	21	Acrolein	('air', 'urban air close to ground')	emission	kilogram	biosphere3	7.04956E-11	1.56091E-11					
24	22	Acrylic acid	('air', 'urban air close to ground')	emission	kilogram	biosphere3	3.65883E-10	1.48147E-11					
25	23	Alachlor	('soil', 'agricultural')	emission	kilogram	biosphere3	7.16314E-13	2.25677E-12					
26	24	Aldehydes, unspecified	('air', 'urban air close to ground')	emission	kilogram	biosphere3	1.53069E-10	4.55643E-11					
27	25	Aldicarb	('soil', 'agricultural')	emission	kilogram	biosphere3	1.1874E-11	6.9903E-11					
28	26	Aldrin	('soil', 'agricultural')	emission	kilogram	biosphere3	2.19182E-10	3.18681E-11					
29	27	Aluminium III	('air', 'urban air close to ground')	emission	kilogram	biosphere3	2.57845E-06	3.62849E-08					
30	28	Ametryn	('soil', 'agricultural')	emission	kilogram	biosphere3	3.2683E-13	4.96952E-14					
31	29	Amidosulfuron	('soil', 'agricultural')	emission	kilogram	biosphere3	7.90501E-13	9.39548E-16					
32	30	Ammonia	('air', 'urban air close to ground')	emission	kilogram	biosphere3	3.61445E-06	2.52081E-07					
33	31	Ammonium carbonate	('air', 'urban air close to ground')	emission	kilogram	biosphere3	5.07481E-10	6.76739E-11					
34	32	Ammonium	('water', 'ground')	emission	kilogram	biosphere3	1.06433E-07	8.28345E-09					
35	33	Anhydrite	('natural resource', 'in ground')	natural resour	kilogram	biosphere3	4.06225E-07	4.36686E-10					
36	34	Aniline	('air', 'urban air close to ground')	emission	kilogram	biosphere3	2.1776E-12	7.25848E-12					
37	35	Anthranilic acid	('air', 'urban air close to ground')	emission	kilogram	biosphere3	3.00584E-13	1.26697E-12					
38	36	Anthraquinone	('soil', 'agricultural')	emission	kilogram	biosphere3	2.53849E-15	1.7487E-16					
39	37	Antimony ion	('air', 'urban air close to ground')	emission	kilogram	biosphere3	5.52928E-10	2.42408E-11					
40	38	AOX, Adsorbable Organic Halo	('water', 'ground')	emission	kilogram	biosphere3	0	0					

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
2					Date												
3					Timestamp	0	1	2	3	4	5	6	7	8	9	10	11
4	name	compartment	subcomp	"unit"													
5	Carbon dioxide, in air	Natural resource		kg / year	0.01238589											0.80832704	
6	Carbon dioxide, in air	Natural resource		kg / year	0.00664108											2.17043755	
7	1,4-Butanediol	Air		kg / year	1.78E-10											2.74E-12	
8	1-Pentanol	Air		kg / year	1.89E-13											7.05E-13	
9	1-Pentene	Air		kg / year	3.26E-12											6.96E-13	
10	2-Aminopropanol	Air		kg / year	1.62E-13											6.97E-13	
11	2-Methylpentane	Air		kg / year	2.92E-10											1.46E-11	
12	2-Methyl-1-propanol	Air		kg / year	6.19E-13											2.33E-12	
13	2-Methyl-2-butene	Air		kg / year	1.00E-16											1.12E-16	
14	2-Nitrobenzoic acid	Air		kg / year	3.87E-13											1.63E-12	
15	2-Propanol	Air		kg / year	4.37E-08											1.77E-09	
16	3-Methyl-1-butanol	Air		kg / year	0											0	
17	4-Methyl-2-pentanone	Air		kg / year	8.21E-12											2.86E-12	
18	Acenaphthene	Air		kg / year	0											0	
19	Acetaldehyde	Air		kg / year	6.33E-08											3.40E-09	
20	Acetic acid	Air		kg / year	1.58E-06											7.44E-09	
21	Acetone	Air		kg / year	8.42E-08											3.85E-09	
22	Acrolein	Air		kg / year	7.05E-11											1.56E-11	
23	Acrylic acid	Air		kg / year	3.66E-10											1.48E-11	
24	Aldehydes, unspecified	Air		kg / year	1.53E-10											4.56E-11	
25	Aluminium III	Air		kg / year	2.58E-06											3.63E-08	
26	Ammonia	Air		kg / year	3.61E-06											2.52E-07	
27	Ammonium carbonate	Air		kg / year	5.07E-10											6.77E-11	
28	Aniline	Air		kg / year	2.18E-12											7.26E-12	
29	Asiatic acid	Air		kg / year	3.01E-13											1.27E-12	
30	Antimony ion	Air		kg / year	5.53E-10											2.42E-11	
31	Arslene	Air		kg / year	4.27E-15											1.73E-16	
32	Barium II	Air		kg / year	3.60E-06											4.77E-10	

Figure 6. Top: A result file with raw LCI from an LCA software. The necessary columns to be copy/paste in the template file are highlighted in yellow. Bottom: the template file completed with the user's data

The user uploads this file with inventory data placed in time, completes the web interface with the timestep (1 year) and the desired timespan for impact calculation. For example, if the user wants to have impact results for 200 years after the zero point, the desired timespan is 200 years. Note that the past period (negative time) is added at 200. For example, if wood growth occurs from $t = -50$ to $t = 0$, and the timespan for calculation is 200, then the total period included in impact calculation is 250 years (from year -50 to +200).

The user will receive the calculation results by email, as csv (excel) data organized by columns: time value (yr), radiative forcing RF (W m^{-2}), cumulated radiative forcing iRF (W yr m^{-2}), temperature change GMTC ($^{\circ}\text{C}$ or K), cumulated temperature change iGMTC ($^{\circ}\text{C yr}$). Other two files contain detailed results by chemical species. The user can then use these data at his convenience, for graphical presentation of climate change indicators in function of time. More information on CCI-tool utilization is available on the web page at <https://www.insa-toulouse.fr/ccl-tool/>.

Example of results presentation for Tier 2 approach

Three main result files are provided by CCI-tool:

- radiative forcing for all calculated GHGs and temperature for all GHGs: the user can interpret the results by chemical species.

- four indicators (radiative forcing, cumulated radiative forcing, global mean temperature change and the cumulated temperature change) in function of time for the system (cumulated over all GHGs).

For the example in **Figure 6**, graphical presentation of radiative forcing, cumulated radiative forcing and global mean temperature change are shown in **Figure 7**.

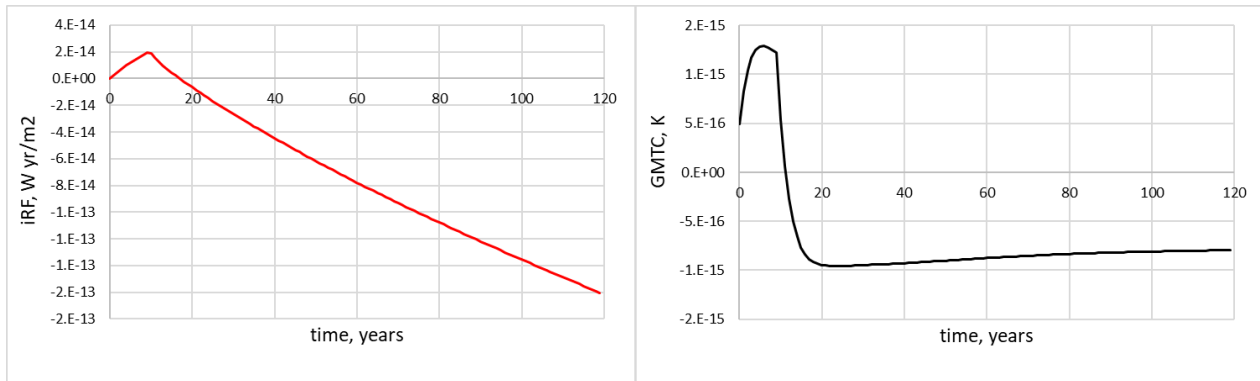


Figure 7. Example of results presentation - climate change impact indicators. Left: cumulated radiative forcing, Right: global mean temperature change

GWP at year 100 can be calculated from the iRF value at year 100 and the CO₂ AGWP100 ($8.91352 \cdot 10^{-14}$ W yr m⁻²):

$$\text{GWP@100} = \text{iRF} / \text{AGWP100}_{\text{CO}_2}$$

For the given example GWP@100 = - 1.52 kg CO₂-eq (vs -1.72 in static LCA)

In addition, an excel file with the different steps to build the template with temporalized inventory is available in Zenodo repository at <https://zenodo.org/records/23064315>.

For more details on the type of results and their presentation and interpretation, please refer to the related documents (Tiruta-Barna 2021, Tiruta-Barna 2026, deliverable LCA4BIO_D2.1 (Ch 3) <https://zenodo.org/records/17880614>)

3.3.2. Other life cycle impact assessment methods

Besides the climate change impact, there are also other impact categories to consider, in particular for BbS. The LCA4BIO consortium has already done an evaluation for certain LCIA method for relevant impact categories, with a focus on toxicity, water use, land use, biodiversity, and ecosystem services (**Table 1**).

Table 1. Selected Life Cycle Impact Assessment method for impact categories relevant for BbS, with characterization factors found in its supporting information excel file.

Impact category	Selected Life Cycle Impact Assessment method
Toxicity	Environmental Footprint 3.1
Land Use	Environmental Priority Strategies (EPS) v2020 method
Water Use	AWARE v1.2
Biodiversity impact	LC-IMPACT
Ecosystem services	LANCA v2.5

The characterization factors for these methods were collected in the supporting information 1 excel file included in Deliverable 2.3, which is available in Zenodo repository at <https://zenodo.org/records/23059357>. These can then be imported into LCA software to execute. Alternatively, they may already be present in LCA software or be available elsewhere.

For other impact categories, we have conducted no clear evaluation but the Environmental Footprint may then be the go-to-method in evaluations relevant for the European context and market.

3.3.3. Circularity indicators

Several various circularity indicators for biobased products, covering different scales, sectors, and circularity aspects can be found in literature. Some of them appear at least partly compatible with LCA. However, in general, direct application of the existing indicators within LCIA is still mostly not possible. Nevertheless, some of the indicators can be calculated by utilizing data collected over the LCI phase. This highlights the need for further methodological advancement to enable the integration of circularity assessment within LCIA and LCA of circular bio-based systems.

The high variety among the existing indicators means that the choice of the most suitable one(s) to be used for circularity assessment must be driven by the aspect that the decision-maker identifies as priority or strategy. Accordingly, instead of imposing one specific one-fit-all indicator, the mandatory requirement for the certification is to identify and calculate **at least one circularity indicator**. The **biocircularity compass tool** should be used to facilitate the identification of the most relevant indicator(s) among the set of suitable indicators. The biocircularity compass is suitable for various scales and various economic sectors, thus considering both different materials and products. The identification works similarly to a decision tree with four levels of decision, with a nested approach.

A breakdown of the four decision levels is provided below:

1. Wood: specify if the assessed system is about woody biomass.
2. Scale: select the scale of the assessed system (micro-, meso-, or macro-).
3. Circularity strategies: indicate the focal aspect(s) that stakeholders prioritize.
4. Sub-strategies: further narrow down the priorities to a sub-set of aspects within the strategies.

Circularity strategies are meant to reflect the existence of several different aspects that need to be measured when monitoring the circularity of biobased products. They are derived from the circular economy principles for biobased products proposed in Vural Gursel et al. (2022).

Sub-strategies help narrowing down the circularity aspect of interest within a certain strategy: each strategy has one or more sub-strategies with a more focused scope.

Indicators

31 unique indicators were identified and belong to the set included in the biocircularity compass. They are summarized in **Table 2** below.

Table 2. Set of indicators suitable for biobased products.

Wood	Scale	Specific circular economy strategy of interest	CE sub-strategy	Indicator	Ref
Yes	Wood - meso	Economic viability	Economic viability	Creation of economic value based on the production of electricity/ thermal efficiency of woody biomass	1
No	Macro	Economic viability	Economic viability	Material productivity	2
No	Micro	Economic viability	Economic viability	Material productivity	2
No	Macro	Economic viability	Economic viability	Resource intensity index	2
No	Micro	Economic viability	Economic viability	Resource intensity index	2
No	Micro	High quality use and cascading of biomass	Preserving high value material qualities	Bioresource utilization index	3

Yes	Wood - meso	High quality use and cascading of biomass	Preserving high value material qualities	Percentage/ volume of wastes and residues that become new resources	4
No	Micro	Multidimensional circularity indicator	Multidimensional circularity indicator	Material Circularity Indicator (MCI) updated in 2019	5
Yes	Wood - meso	Recirculate	Reuse	Reuse I ₃ : Product life span before it is used for energy generation (years)	6
No	Macro	Recirculate	Refurbishment, reconditioning, remanufacturing	Average reused content of an inflow	2
No	Micro	Recirculate	Refurbishment, reconditioning, remanufacturing	Average reused content of an inflow	2
No	Macro	Recirculate	Refurbishment, reconditioning, remanufacturing	Percent actual reused product and component derived from outflow	2
No	Micro	Recirculate	Refurbishment, reconditioning, remanufacturing	Percent actual reused product and component derived from outflow	2
No	Macro	Recirculate	Durability and reliability	Average lifetime of product or material relative to industry average	2
No	Micro	Recirculate	Durability and reliability	Utility function of the MCI	5,7
No	Micro	Recirculate	Material recycling	Average recycled content of an inflow	2
No	Micro	Recirculate	Material recycling	Percent actual recycled product and component derived from outflow	2
No	Macro	Recirculate	Material recycling	Recycling rates (R) %	8 - 9
No	Micro	Recirculate	Overall ecosystem contribution	Material Circularity Indicator (MCI)	7
Yes	Wood - meso	Recirculate	Overall ecosystem contribution	Recycle I ₄ : The economic differential (%) gain from a more rational valorization of the valuable wood assortments	6
No	Micro	Regenerate	Carbon cycle support	Biogenic carbon storage (cBCS)	10
Yes	Wood - meso	Regenerate	Carbon cycle support	Carbon stock and CO ₂ absorption	1
Yes	Wood - meso	Regenerate	Sustainable sourcing	Amount of certified forest biomass and residues	4
Yes	Wood - meso	Regenerate	Sustainable sourcing	Amount of timber harvested/amount of replanting	4
No	Micro	Renewable resources and energy efficiency	Energy efficiency	Circular-Process Energy Intensity (CPEI)	11
No	Macro	Renewable resources and energy efficiency	Energy efficiency	Energy intensity (ISO)	2
No	Micro	Renewable resources and energy efficiency	Energy efficiency	Energy intensity (ISO)	2
No	Macro	Renewable resources and energy efficiency	Energy efficiency	Percent energy recovered from residual, non-renewable and non-recoverable resource outflows	2
Yes	Wood - meso	Renewable resources and energy efficiency	Energy efficiency	Ratio between the CO ₂ emissions saved by the timber sold for energy production and the total cubic meter collected	6
No	Macro	Renewable	Renewability	Average percent of energy consumed that is	2

		resources and energy efficiency		renewable energy	
No	Macro	Renewable resources and energy efficiency	Renewability	Average renewable content of an inflow	2
No	Micro	Renewable resources and energy efficiency	Renewability	Product renewability (PR)	11
No	Micro	Resource efficiency and waste management	Reduce waste	Circular-process waste factor (CPWF)	11
No	Micro	Resource efficiency and waste management	Resource efficiency	Circular-process feedstock intensity (CPFI)	11
Yes	Wood - meso	Resource efficiency and waste management	Resource efficiency	Ratio (on an annual basis) between the economic value of the wood harvested per cubic meter and the forest area (reduced)	6
Yes	Wood - meso	Social viability	Social viability	Number of jobs created by forestry employees	1

The bioeconomy compass utilizes was developed as a simple open access excel-based tool in which users are guided through a set of possible options for each level of decision The tool is stored in an open Zenodo repository that can be accessed at <https://zenodo.org/records/20431744>. Once the suitable indicator is identified the tool redirects to the indicator calculation sheet. The calculation sheet has a predetermined calculation workflow. It provides the formulas and lists and defines all required variables and units of measure. The user can insert the data specific to their project/system/product. The calculation sheet returns the calculated value for the identified indicator.

With this approach, at least **one strategy** and **one sub-strategy** must be identified and at least **one related circularity indicator** must be calculated.

SUPPLEMENTARY INFORMATION

This section lists the supporting files for applying the methodologies described in this document and indicates where each one can be accessed.

Dynamic Carbon Footprint

1. **Tier 1 Tool.** The tool is available on Zenodo at <https://zenodo.org/records/20735324>
2. **Tier 1 Example EPD.** Available on Zenodo at <https://zenodo.org/records/23067900>.
3. **Tier 2 CCI Tool.** Available on the INSA website <https://www.insa-toulouse.fr/cci-tool/>
4. **Tier 2 CCI Tool Guide.** Available on on Zenodo at <https://zenodo.org/records/23064315>

Other LCIA methods

5. Excel file 1 available on Zenodo at <https://zenodo.org/records/23059357>

Circularity indicators

6. **Biocircularity Compass Tool.** Available on Zenodo at <https://zenodo.org/records/20431744>

REFERENCES

ISO (2006). Environmental management - Life cycle assessment - Principles and framework (ISO Standard No. 14040:2006).

ISO (2006b). Environmental management - Life cycle assessment – Requirements and guidelines (ISO Standard No. 14044:2006).

Guide RE2020, Ministère Aménagement du territoire et Transition écologique, mai, 2025L. Tiruta-Barna (2021) A climate-goals-based, multicriteria method for system evaluation in Life Cycle Assessment, Int JLCA, 26, 1913–1931, <https://doi.org/10.1007/s11367-021-01991-1>

L. Tiruta-Barna (2026) Expanding the dynamic climate change impact model for dynamic LCA, based on the climate science, Int JLCA, accepted 2026.

Vural Gursel, I., Elbersen, B., Meesters, K. P. H., & van Leeuwen, M. (2022). Defining Circular Economy Principles for Biobased Products. Sustainability, 14(19), 12780. doi.org

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.