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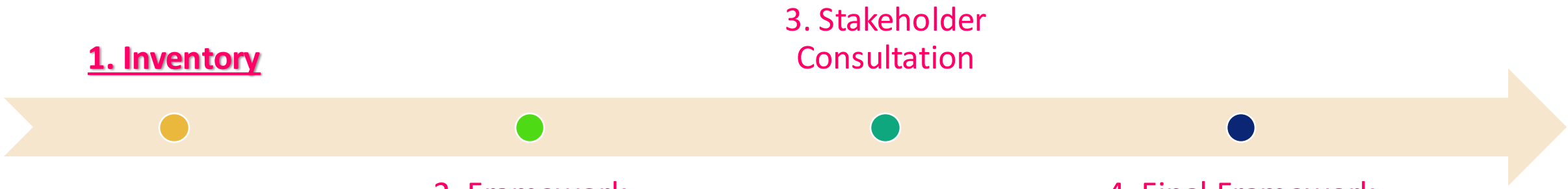
Circularity and Long-term Carbon Storage

Seunghye Lee, Alonso Albalate Ramirez
Yvonne van der Meer, Martin Junginger
29 October 2026

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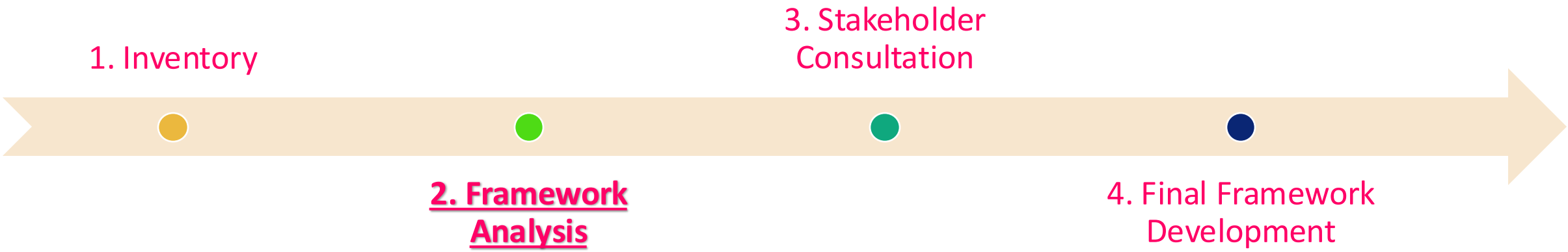


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Review relevant standards/documents and conduct interviews to identify key **"contested issues"** and challenges in LCA methodologies

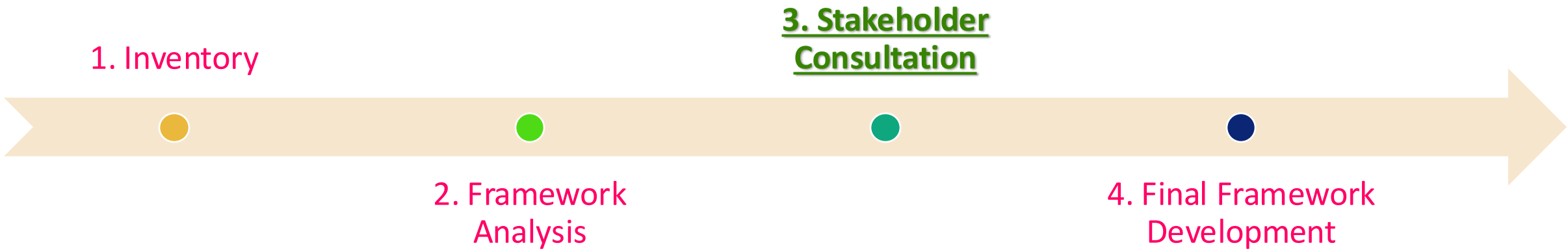
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Analyze key “contested issues” and develop strategies to address the identified challenges in LCA methodologies.

Draft a holistic LCA framework with recommendations for key challenges.

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Engaging researchers, industrial actors, and policymakers to validate the draft framework and addresscomments/feedback received.

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1. Inventory

2. Framework Analysis

3. Stakeholder Consultation

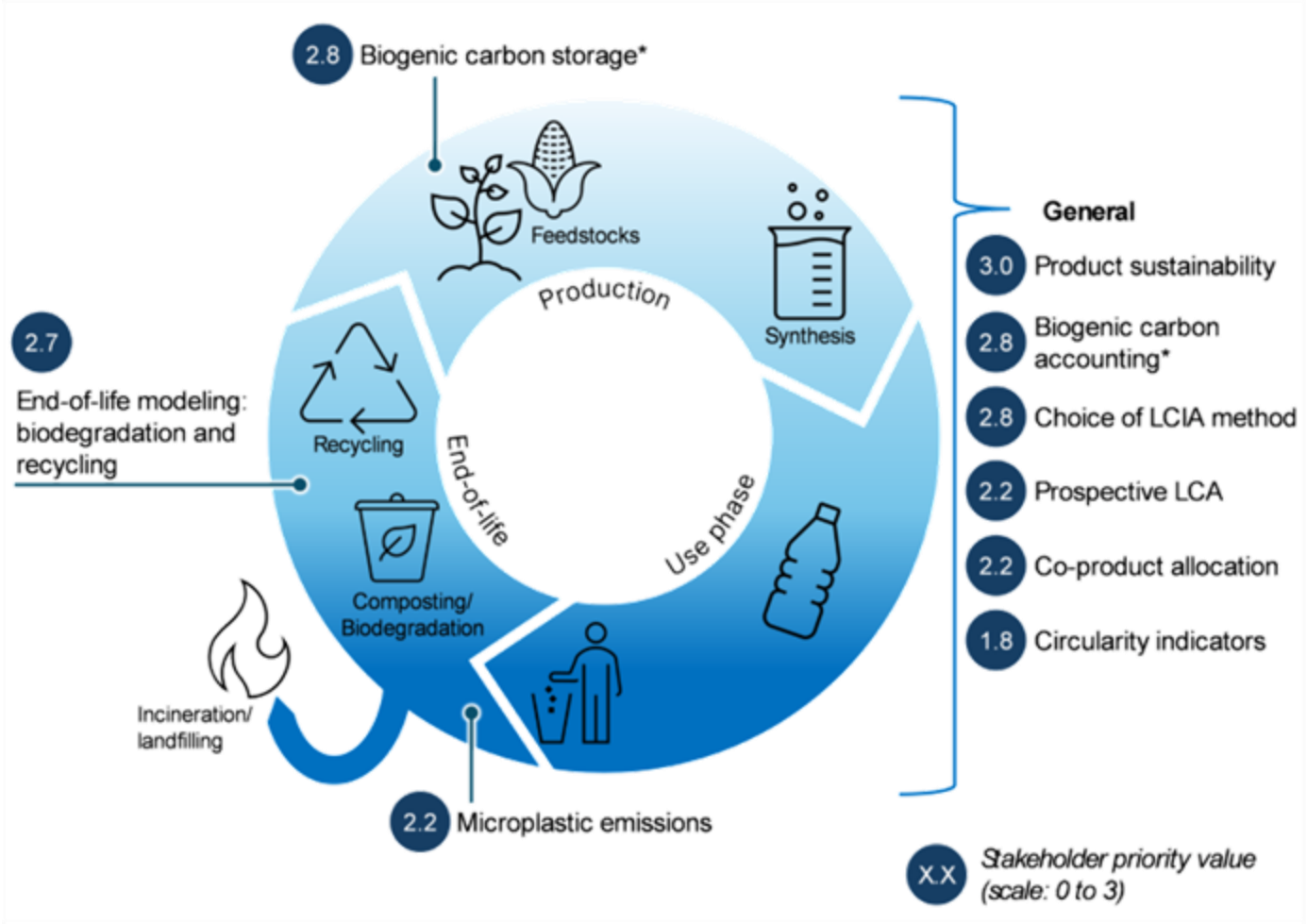
4. Final Framework Development

Finalize the framework based on stakeholder feedback and devise guidelines and recommendations.

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The relevant methodological challenges identified include:

1. Biogenic carbon accounting
2. Prospective LCA
3. Co-product allocation (mass, energy, economic)
4. Impact assessment methods (which to choose)
5. Circularity
6. End-of-life modeling
7. Microplastics



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Biogenic Carbon Accounting

BioBased Circular

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TNO innovation for life

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ULTRA-BIO biogenic carbon accounting proposal – practical solution

Don't neglect the complexity but don't add unnecessary complexity

1. Follow the -1/+1 philosophy , adopt 100 years time horizon
   - Carbon stored >100y: permanent storage
2. Delayed effect of CO_2 emission: linearly discounted (PAS 2050, option 2)
3. Carbon sequestration:

   a) Annual crop: directly apply -1, report DLUCs and any risks of iLUC

   b) Biogenic carbon in waste/recycled feedstocks: apply linearly discounted credits based on the length of the use phase

   c) Forest and perennial crops: apply -1 as baseline **+ mandatory** report additional information: tree species, rotation periods, forest managements and sustainability certificates, ***or*** carbon stock changes (LULUCF)

Biogenic Carbon

If the carbon is stored in the bio-based products & materials for long..

- Should/can it be incentivized? How?
- -1/+1 approach
- 100-year storage counts as permanent storage
- Linear discount between year 1-100

Method – PAS 2050 (option 2), ILCD 2010

PAS: Publicly Available Specifications

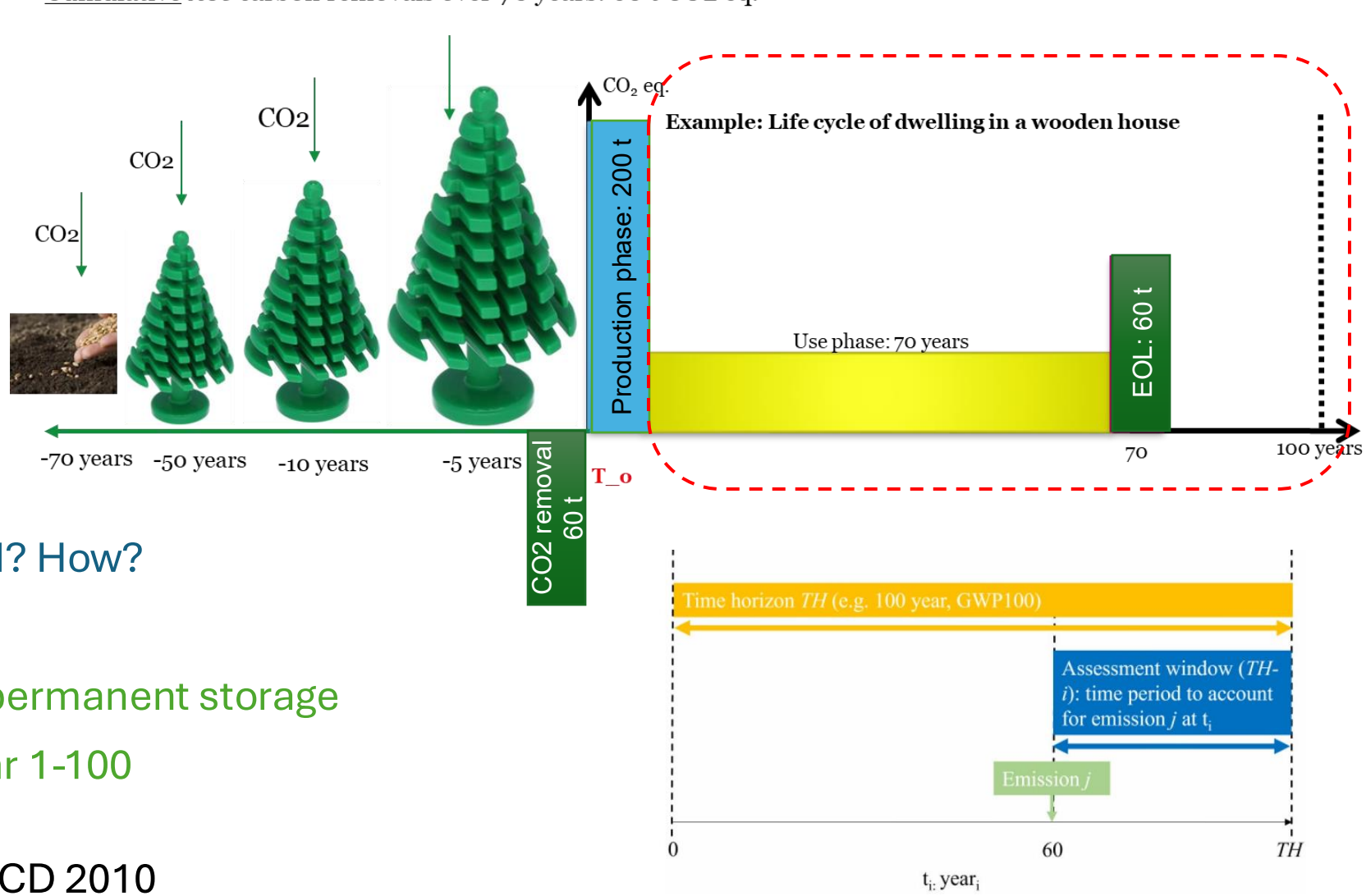


Fig. 4 Definitions of different temporal parameters: time horizon and flexible assessment window. An example shows these parameters for an emission *j* occurred in year 60 ($i=60$)

Figure source: De Jong et al., 2025, *From static to dynamic: Reviewing the application and potential of dynamic LCA to bio-based systems*

Biogenic Carbon – Delayed emissions

Linear discount

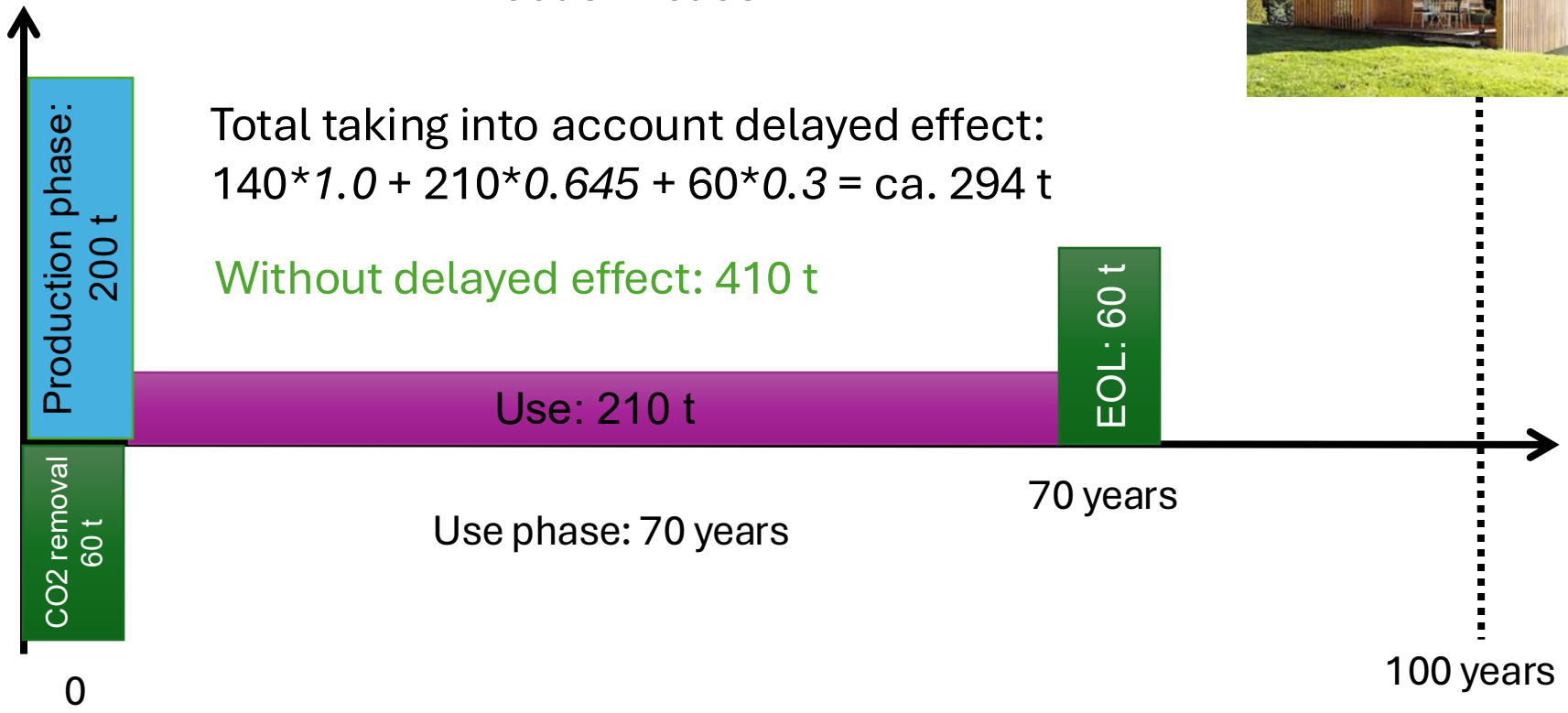
$$\frac{\sum_{i=1}^{100} x_i \cdot (100 - i)}{100}$$

Weighting factors:
Production: *1.0*
Use phase: *0.645*
EOL: *0.3*

$$\frac{1}{70} * \frac{\sum_{i=1}^{70}(100 - i)}{100} = 0.645$$

Example: Life cycle carbon balance of dwelling in a wooden house





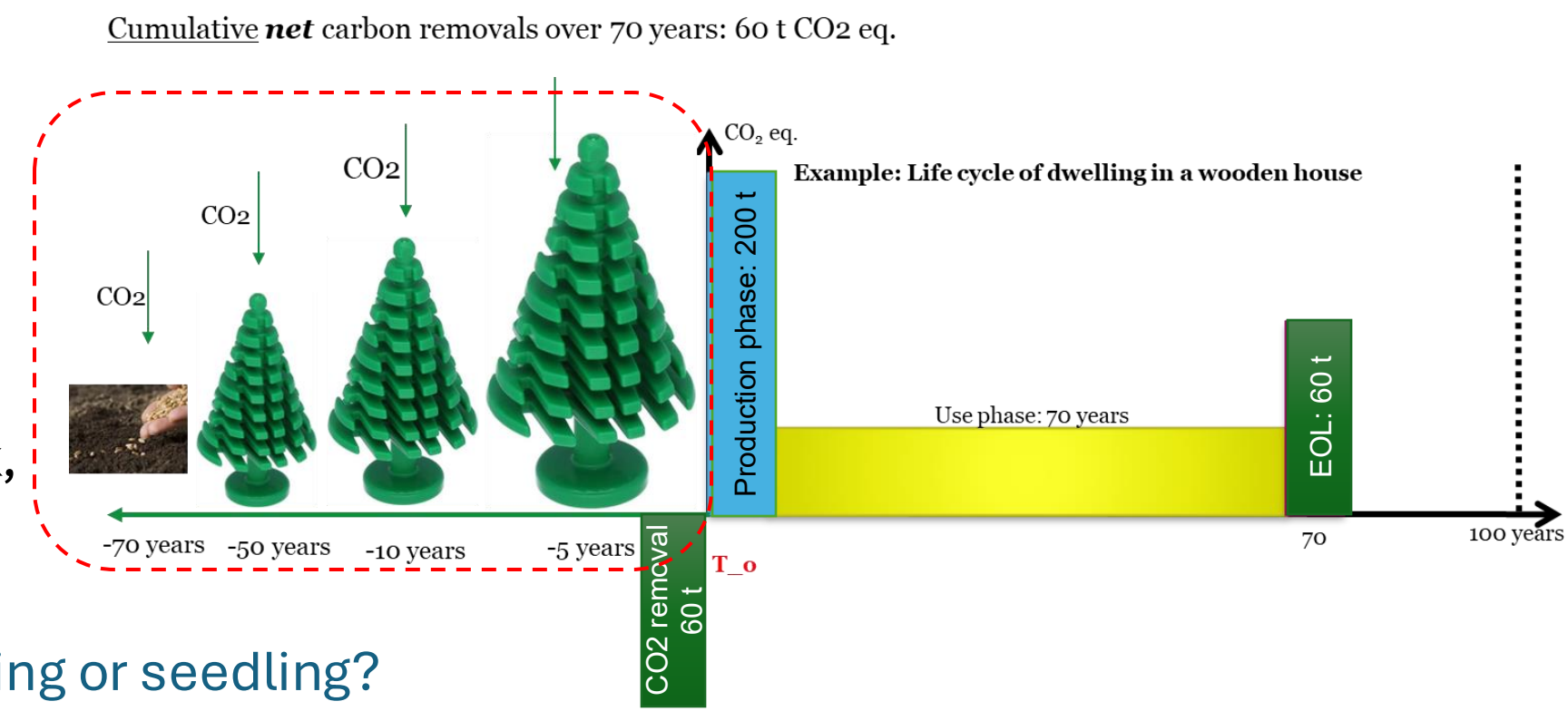
Total taking into account delayed effect:
140**1.0* + 210**0.645* + 60**0.3* = ca. 294 t

Without delayed effect: 410 t

Method – PAS 2050 optional step, ILCD 2010

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Biogenic Carbon



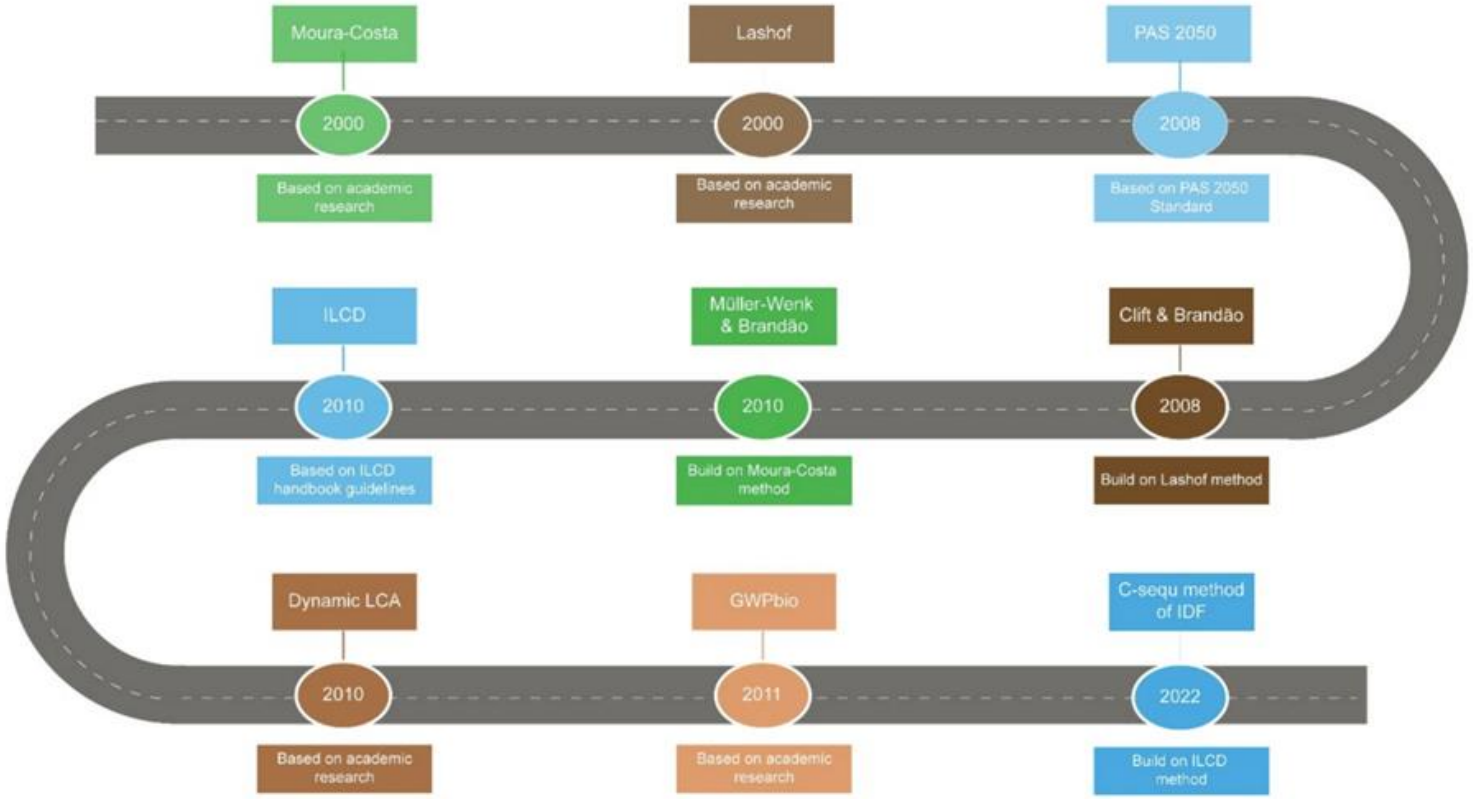
What about when it takes long to grow the feedstock, like forest and perennial crops?

- Is T_0, point of harvesting or seedling?
- Forest is always managed at the landscape level
- Need to make sure that forest management is in place so that the stock and flow keep a balance.
- Apply -1 as baseline & **report additional information**: tree species, rotation periods, **sustainability/forest managements certificates** or **carbon stock changes (LULUCF)**

More ~~complicated~~ advanced solutions are also available..
(see also an overview of the methods in De Jong et al. 2026)

$$DCF(t) = \int_{t-1}^{t} a \times C(t)dt$$

- Delayed effect based on dynamic characterization factors (e.g. ESCIB, ALIGNED, based on Levasseur et al., 2012)
- - Rotation /+ Delayed effect: GWP_bio (Guest et al., 2013)
- - 1?



This illustration indicates the origin and development timeline of impact assessment methods for evaluating biomass C sequestration. Methods with similar foundations are represented in the same color with varying shades to reflect their shared origins

Picture source: Methods for quantifying and incorporating biomass carbon sequestration by trees in life cycle assessments

Other issues related to ‘cradle’, land use (or land management) and land use changes

- For agricultural crops: Soil carbon content changes
- LULUCF from IPCC: multiple carbon pools + tiered approach
- More questions can be asked, e.g.: natural emissions and anthropogenic emissions?

Complicated systems → complicated solutions

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Circularity Indicators

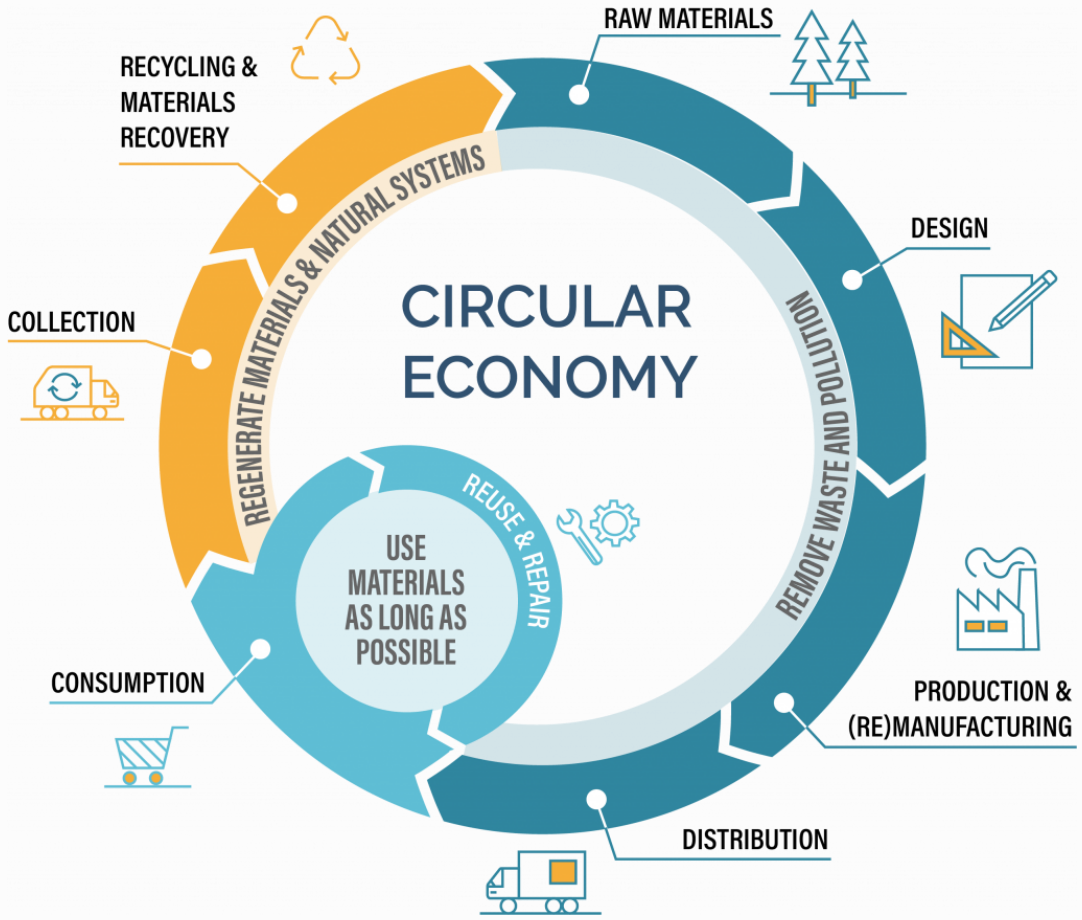
Presenter: Alonso Albalate Ramirez

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Circular Economy as a means towards Sustainability

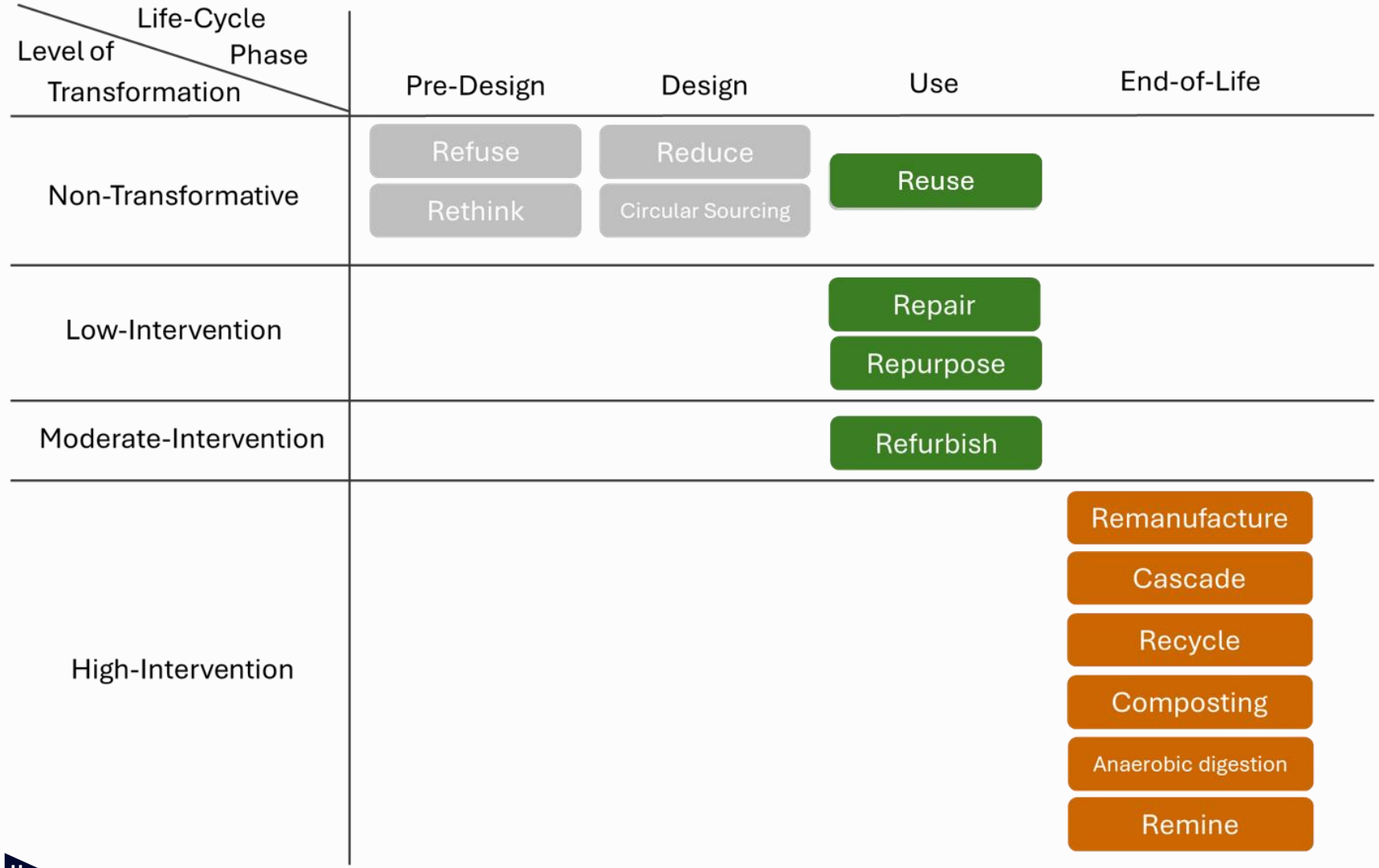
- The transition towards CE requires more than technological innovation; it demands methodological coherence in the way circularity is defined and assessed.

- ISO 59004/59010 defines thirteen **Circular Resource Management Actions (CRMA)**. These strategies define how materials are managed to retain value within the system and reduce dependence on primary resource extraction.



Circular Resource Management Actions (CRMA):

Product sustainability and EoL characteristics



System-level actions

Functional sustainability characteristics:

- Function retention
- Long service life
- Repairability
- Ease of maintenance

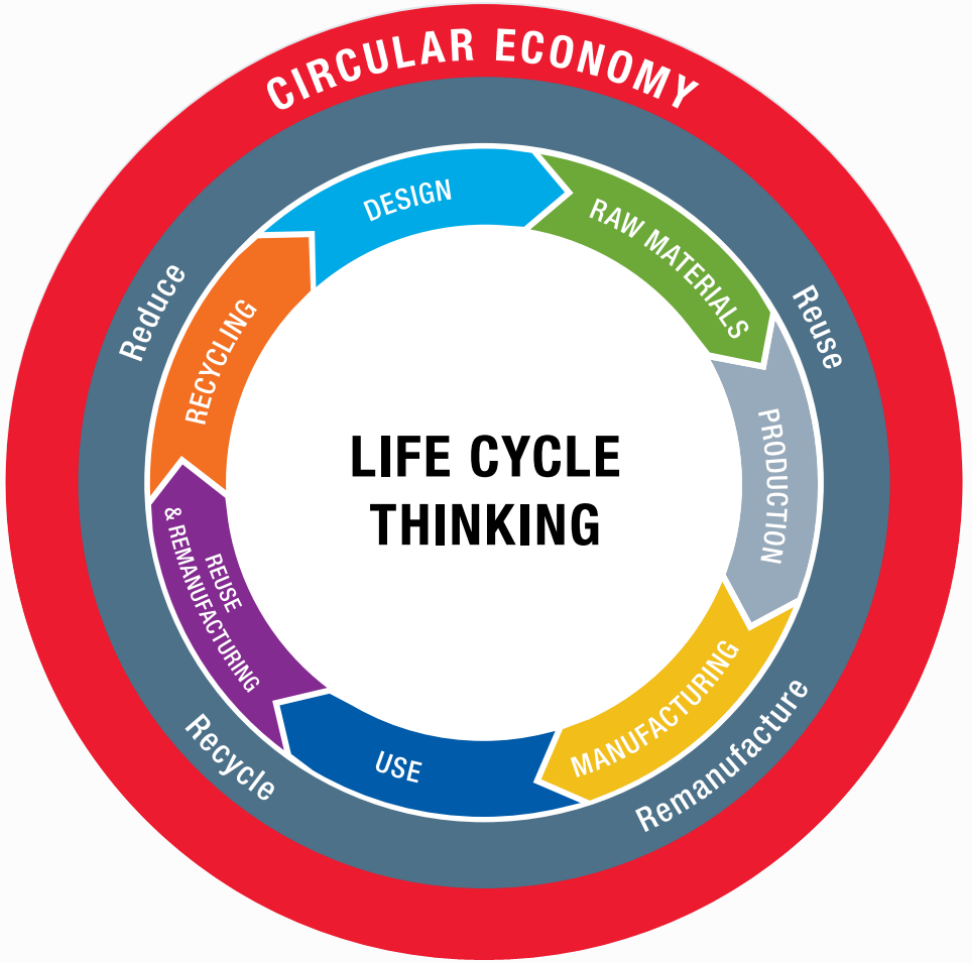
Functional End-of-Life characteristics:

- Component separability
- Recyclability
- Biodegradability
- Downcycling feasibility
- Non-toxic degradation products

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Life Cycle Assessment & Circular Resource Management Actions

- Applying LCA to circular economy strategies requires specific modelling decisions that are often overlooked in practice.
- While circularity describes how materials are retained within economic systems, LCA evaluates whether such retention effectively translates into environmental benefits.
- This means that circular design intentions must be translated into explicit modelling choices if LCA results are to remain robust and decision-relevant.



Modelling circular products and systems in LCA

Methodological challenges and practical recommendations

GENERAL RECOMMENDATIONS

System boundaries across multiple life cycles
Include successive loops where relevant and feasible. Make assumptions about future destinations and material quality explicit.

Allocation across life cycles
Follow applicable mandatory rules. Otherwise, apply the ULTRA-BIO 50/50 recommendation within its defined scope.

Circular situation	Methodological challenge	Practical LCA recommendation
Complex circular systems	**Uncertain pathways across loops** Multiple destinations, quality changes and secondary material markets	**Document material pathways** Track destinations, recovery yields and substitution assumptions; test uncertain scenarios.
Extended use-phases	**Comparing equivalent service** Lifetime, maintenance and use-phase impacts may differ	**Use a service-based functional unit** Compare equivalent service over a common period; include maintenance and use-phase impacts.
Multi-material products	**Representing recovery constraints** Disassembly, separation and infrastructure affect feasible routes	**Model realistic recovery scenarios** Use regional data for disassembly and recovery; distinguish current conditions from future scenarios.
Biogenic carbon storage	**Tracking carbon across cycles** Storage duration, transfers and timing of emissions	**Apply consistent carbon accounting** Follow ULTRA-BIO Biogenic Carbon guidance; track uptake, transfers and releases consistently.

Translate circular strategies into explicit, transparent LCA modelling choices

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What do we miss with LCA impact results alone?

Making circular performance explicit alongside environmental impacts

Circular situation	Additional information to make explicit	Example indicators
Complex circular systems	**Extent of material circulation** Secondary inputs, recovery and material losses	MCI
Extended use-phases	**Duration of resource retention** Additional lifetime across uses and loops	Longevity indicator
Multi-material products	**Design enabling recovery** Ease of disassembly	Ease-of-disassembly indicator
Biogenic carbon storage	**Carbon retention across cycles** Amount and duration of storage	BCS100

Circular performance + Environmental impacts | Interpret benefits and trade-offs together

These aspects may be represented in the LCA model without being explicit in its impact results.

Circularity Indicators – Recommendations

For complex circular systems → **Material Circularity Indicator (MCI)**

For capturing the **overall material circularity performance**, where increasing system complexity and material circulation pathways are often highly simplified in LCA models **(EMF, 2019)**.

For extended use phases → **Longevity Indicator (LI)**

To **quantify extended material retention time within the use phase** enabled by repair or recycling processes, including additional product or material lifetime gained through circular loops **(Franklin-Johnson et al. 2016)**.

For multi-material products → **Ease-of-Disassembly Indicator (EDIM)**

To **show product design aspects that are fundamental** for enabling refurbishment, repairability, and recycling but are not represented in standard LCA impact assessment **(Vanegas et al. 2018)**.

To quantify biogenic carbon → **Biogenic carbon stored for over 100 years (BCS100)**

For **capturing the total biogenic carbon stored over 100 years (kg C) across successive cycles**, including both previous and subsequent product life cycles, thereby avoiding multifunctionality issues **(Corona-Bellostas et al. 2022)**.

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Ease-of-Disassembly Indicator (EDIM)

Circularity Indicators – Recommendations

Other circularity indicators can be selected based on:

1. Their material-flow perspective.
2. The degree of differentiation between bio-based and non-biobased resources.
3. Applicability to a circular strategy.

Follow the work published by:
(Perez-Hernandez et al. 2022)

https://doi.org/10.1016/j.spc.2025.11.004

FLOW PERSPECTIVE	GENERIC CAIs NO DISTINCTION BETWEEN BIO- AND NON-BIO-BASED RESOURCES	BIO-INCLUSIVE CAIs EXPLICITLY DIFFERENTIATE BIO- AND NON-BIO-BASED RESOURCES	BIO-EXCLUSIVE CAIs DESIGNED EXCLUSIVELY FOR BIO-BASED RESOURCES	
INFLOW	[7] QC VRE D ER C-F RIR ME	[3] **CD BF FCR**	[3] BUE BUI BCI	[13]
OUTFLOW	[3] FRS LFIPF CR	[1] WOI	[11] **NCI NRI INC ONC TNP-BF TNP-BG FC WC CEEC CEEBG CEEUBG**	[15]
LOOP	[22] CEI CIC EDIM LI PLCM RDI RPI CST EOL-RIR CI EOL-RR MI NTUM PRecI PReuI RIS RR TRP RECOV-R CMUR CIRC(T) NF-EOL-RR	[2] CM CUSI	[5] **BUF** C-BCS N-RI R-FWSC-PIERATTI **S4NR**	[29]
HOLISTIC	[9] CC CEIP **CMT** SCI UOR PCI LMA **MCDM-FP CLCF**	[17] **CTI CET HSI MCI** MCI-Razza **MRS** MCI-Rocchi **SIAT** TESA-MR **TESA-AC TESA-AD MCI-Karayilan CI-SSbDC** CSCI C-I **WBCI ISO-59020**	[3] BCS100 CF R-FWSC-PALETTO	[29]
	[41]	[23]	[22]	

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Circularity vs Life Cycle Assessment

CI should **NOT** be understood as a replacement for LCA, but rather as a complementary tool that improves the interpretation, communication, and monitoring of circular performance in bio-based materials and products.

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End-of-Life modelling

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End-of-Life options – Contested issues

Modelling of End-of-Life options for bio-based products.

- EoL modelling remains a key methodological challenge in life cycle assessment (LCA) of bio-based products, particularly for bio-based plastics.
- These systems involve multiple EoL pathways whose environmental performance depends on material properties, the availability of waste management infrastructure, and underlying modelling assumptions.



Figure. Different End-of-Life options for bio-based products. Adapted from EUBP 2024.

End-of-Life options – Contested issues

- Additional complexity arises from biodegradability, which is highly dependent on specific environmental conditions.
- **Biodegradability** is not an intrinsic property exclusive to bio-based materials, as certain fossil-based polymers also exhibit biodegradable characteristics under specific conditions.

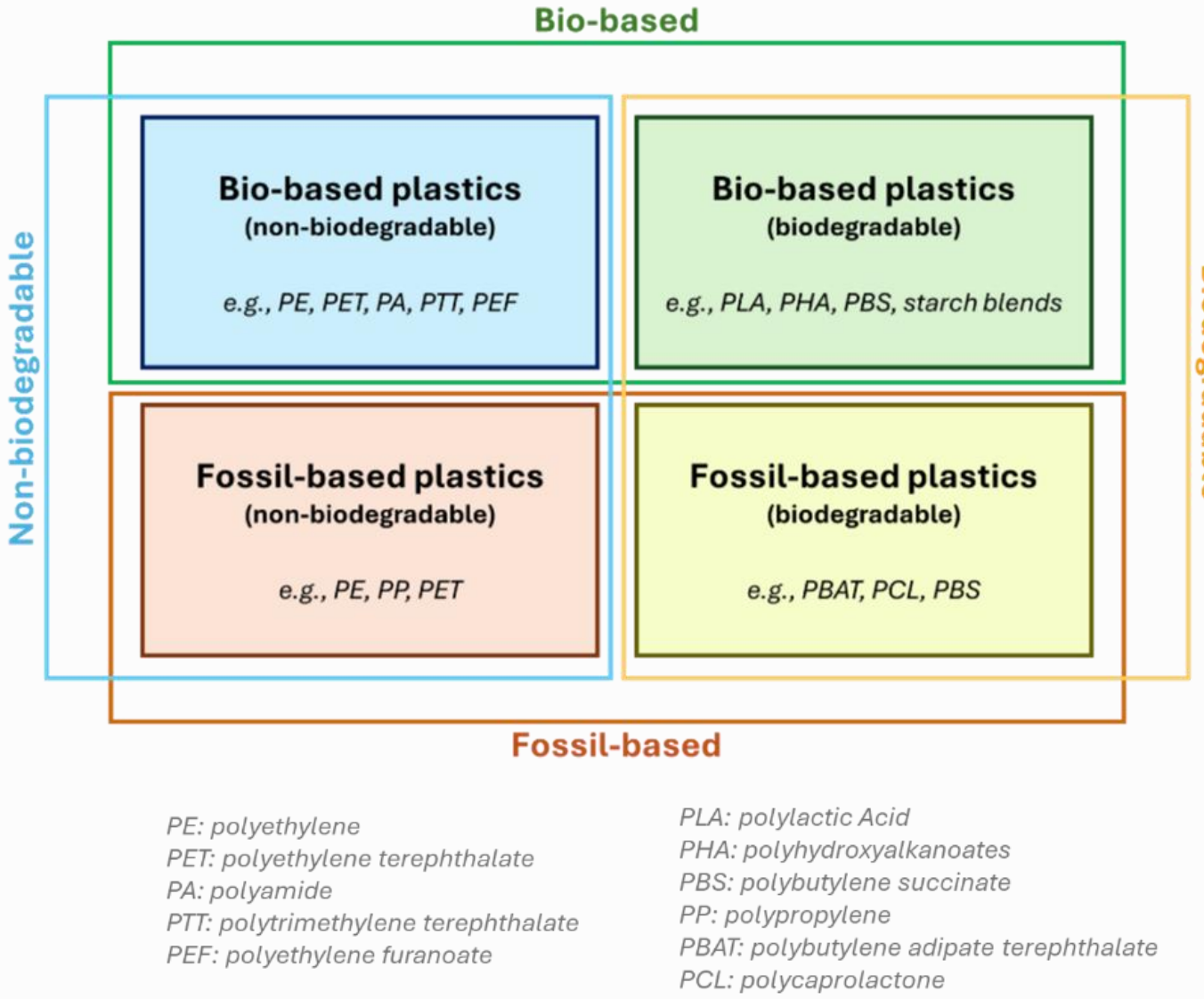


Figure. Examples of biodegradable and non-biodegradable plastics. Adapted from EUBP 2022.

End-of-Life options – Contested issues

Plastic littering and leakage

- Due to the “eco-friendly” stigma, improper consumer handling of non-biodegradable bio-based plastics can lead to **littering**.
- Some plastics are not properly managed at EoL, finding their way into the environment, leading to **leakage**.
- To effectively reduce plastic leakage and littering, practitioners must be able to detect the material flows within their own industry and supply chain.





Modeling of End-of-Life Options

Recommendations

End-of-Life options – Recommendations

Ensure technological feasibility.

- ❑ Only model an EoL pathway when there is evidence that the material is compatible with the selected treatment technology.
- ❑ Avoid assuming ideal circular routes that are not currently available or technically feasible.
- ❑ Clearly distinguish between current and future (prospective) waste management scenarios (*e.g.*, chemical recycling).

Use region-specific waste management conditions.

- ❑ Align collection, sorting, recycling, and treatment assumptions with the local waste management system.
- ❑ Consider regional infrastructure, technology availability, and actual treatment practices.
- ❑ Avoid using generic EoL scenarios that do not reflect the geographical context.

End-of-Life options – Recommendations

Prioritize material-specific inventory data.

- ❑ Use material-specific datasets whenever available.
- ❑ Avoid generic degradation factors or proxy datasets unless their representativeness can be justified.
- ❑ Develop dedicated inventories when existing datasets are not sufficiently representative.

Base biodegradation assumptions on evidence.

- ❑ Use experimentally measured biodegradation rates whenever possible.
- ❑ Prioritize values obtained from recognized standards or full-scale operational data.
- ❑ Explicitly document assumptions and uncertainty when default values are applied.

Biodegradation

Recommendations

End-of-Life options – Contested issues



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Bio-plastic littering and leakage

Alignment

Plastic leakage – Recommendations

Stakeholder feedback changed the recommendation from a generic default to a context-sensitive approach.

Previous approach

- ❑ Region-specific primary data should represent littering and leakage.
- ❑ If no specific data is available, the Plastic Leak Project framework (PLP) is recommended.
  - **Littering rate of 2%** for packaging**, single-use plastic,** or any on-the-go plastic waste, and **0%** for more **durable** types of plastic waste.
  - **Leakage** can be modeled using loss rates from municipal waste treatment data provided by the World Bank.

Stakeholder Feedback

Rates depend on:

- Polymer and product type
- Region and waste system
- EoL technology
- Pathway to the environment

No single rate can represent all EoL systems and regional waste-management conditions.

Revised Recommendation

Use process-specific loss and release rates

1. Primary data
2. Context-specific proxies
3. Generic assumptions

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Plastic leakage – Recommendations

1 **PRIMARY DATA**

Measured data for the polymer, facility, and End-of-Life process

$$\textbf{Plastic leakage} = \textbf{activity} \times \textbf{loss rates} \times \textbf{release rate}$$

2 **CONTEXT SPECIFIC PROXIES**

Comparable polymer, technology, or regional data

Document the source, applicability, and uncertainty

3 **GENERIC ASSUMPTIONS**

Last-resort screening with sensitivity analysis

Update the model when better evidence becomes available

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Plastic littering – Recommendations

1 **PRIMARY DATA**

Measured data for the polymer, facility, and End-of-Life process

2 **CONTEXT SPECIFIC PROXIES**

Comparable polymer, technology, or regional data

Document the source, applicability, and uncertainty

3 **PLASTIC LEAK PROJECT ASSUMPTIONS**

Littering rate of **2% for packaging**, single-use plastic, or any on-the-go plastic waste, and **0% for more durable types of plastic waste.**



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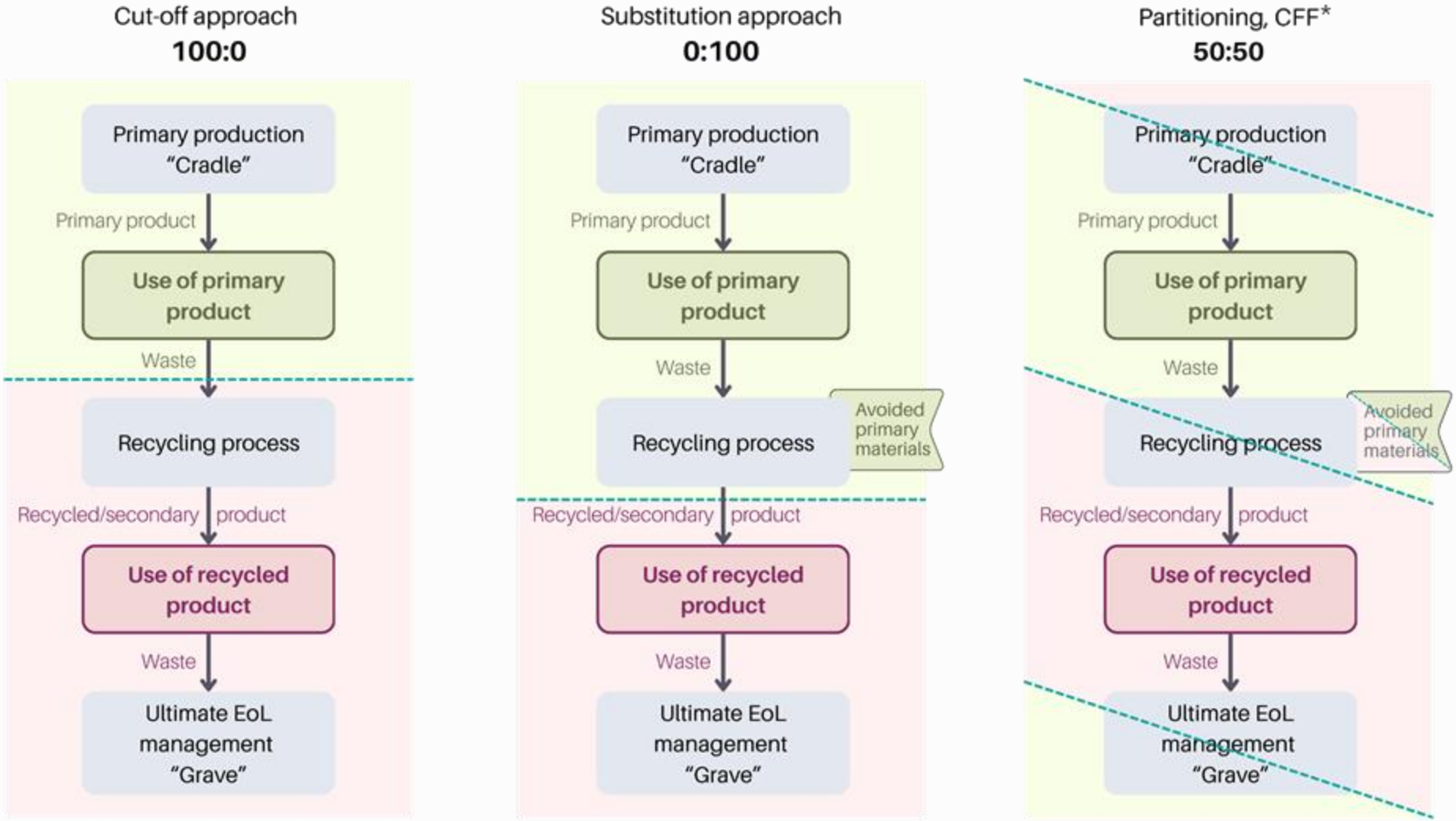
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Co-product Allocation & Biogenic Carbon

Alignment

Co-Product Allocation



Impacts or benefits allocated to primary product.
Impacts or benefits allocated to secondary product.
Limiting border for the system boundaries between the primary and secondary use of the product/material.

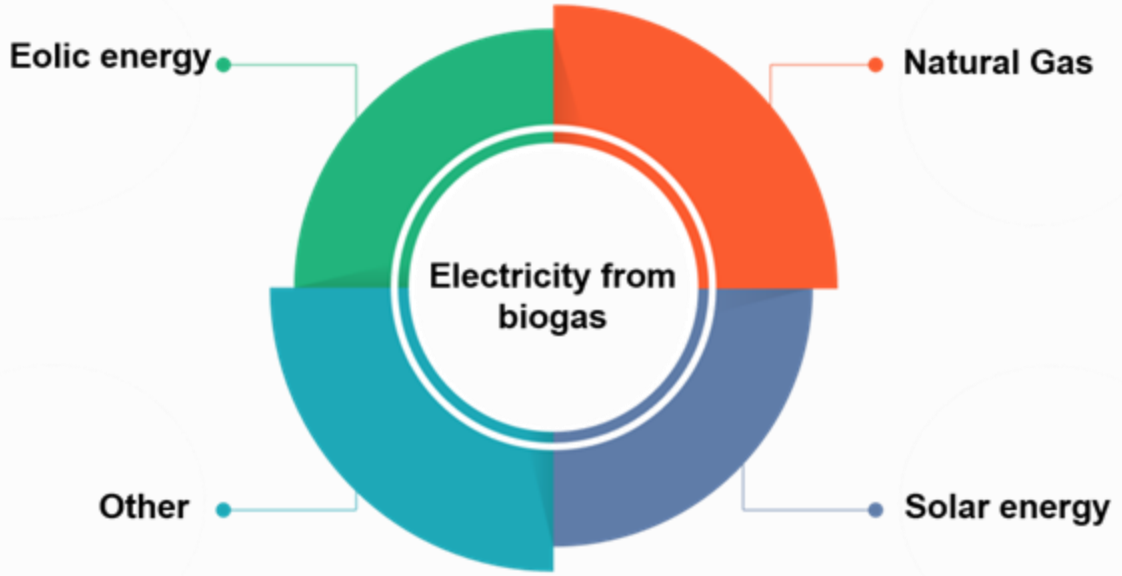
*Includes share of avoided material when necessary.
Source: Adaptation of the figure in Corona et al. 2019.

Co-Product Allocation – Recommendations

Alignment with regulatory compliance.

- For product-specific regulatory compliance (e.g., bioplastic-focused schemes), the allocation or substitution approach prescribed by the relevant regulatory framework shall be followed where applicable.

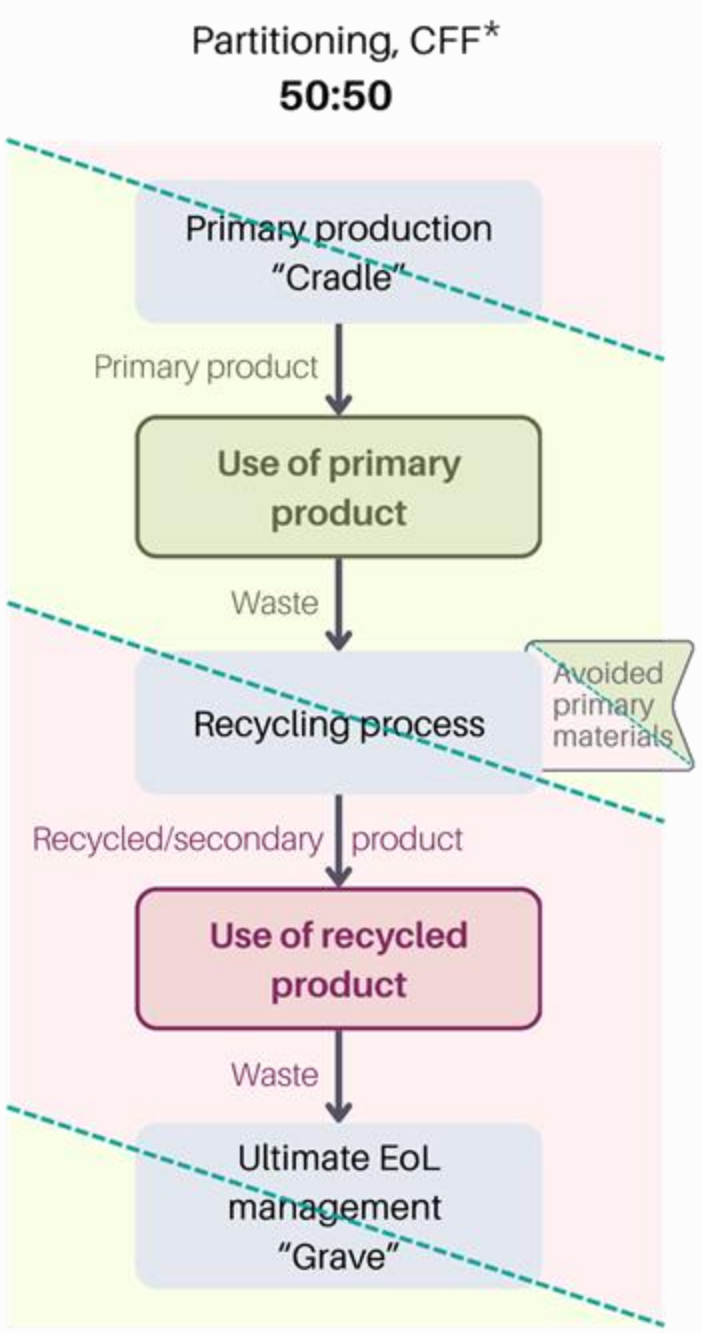
- **IF** a substitution method must be applied, a “basket approach”, reflecting a realistic mix of substituted products based on market shares, is recommended.



End-of-Life options - Recommendations

Allocation of environmental burdens and benefits

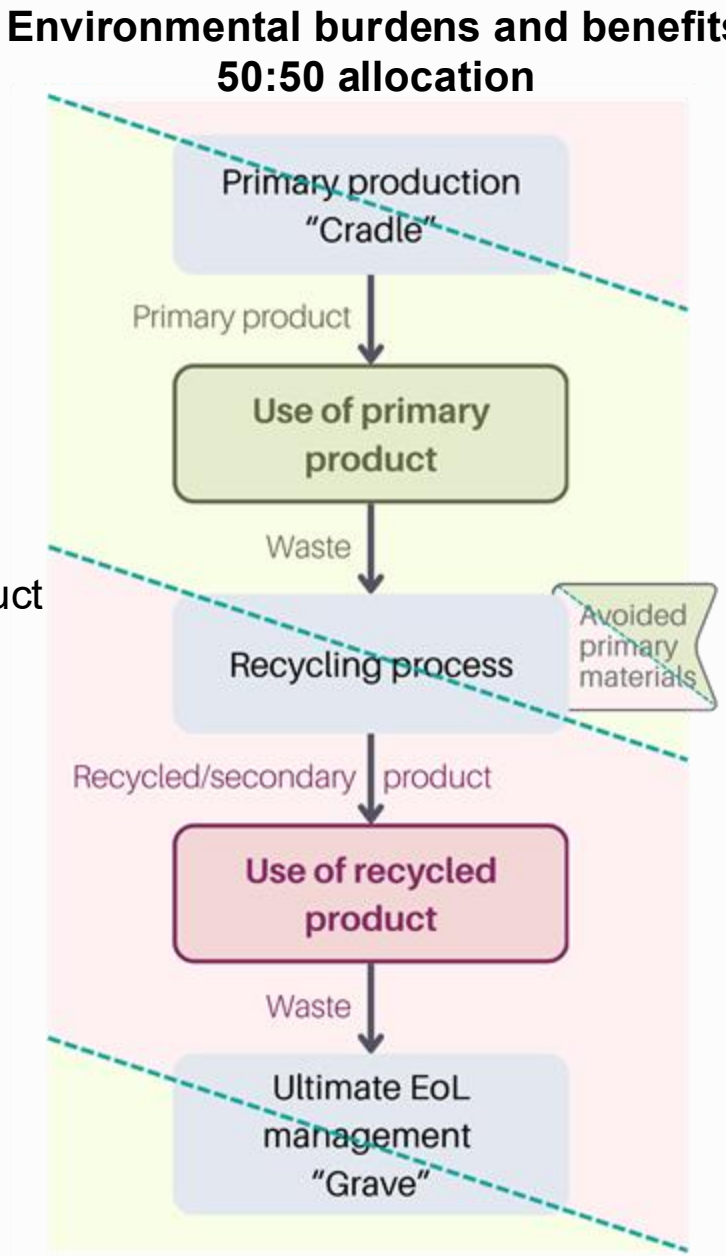
- LCA studies considering EoL strategies or multiple life cycles shall apply allocation of environmental credits/burdens across successive life cycles. The **50/50 method is recommended**, as it provides a balanced compromise between product life cycles.

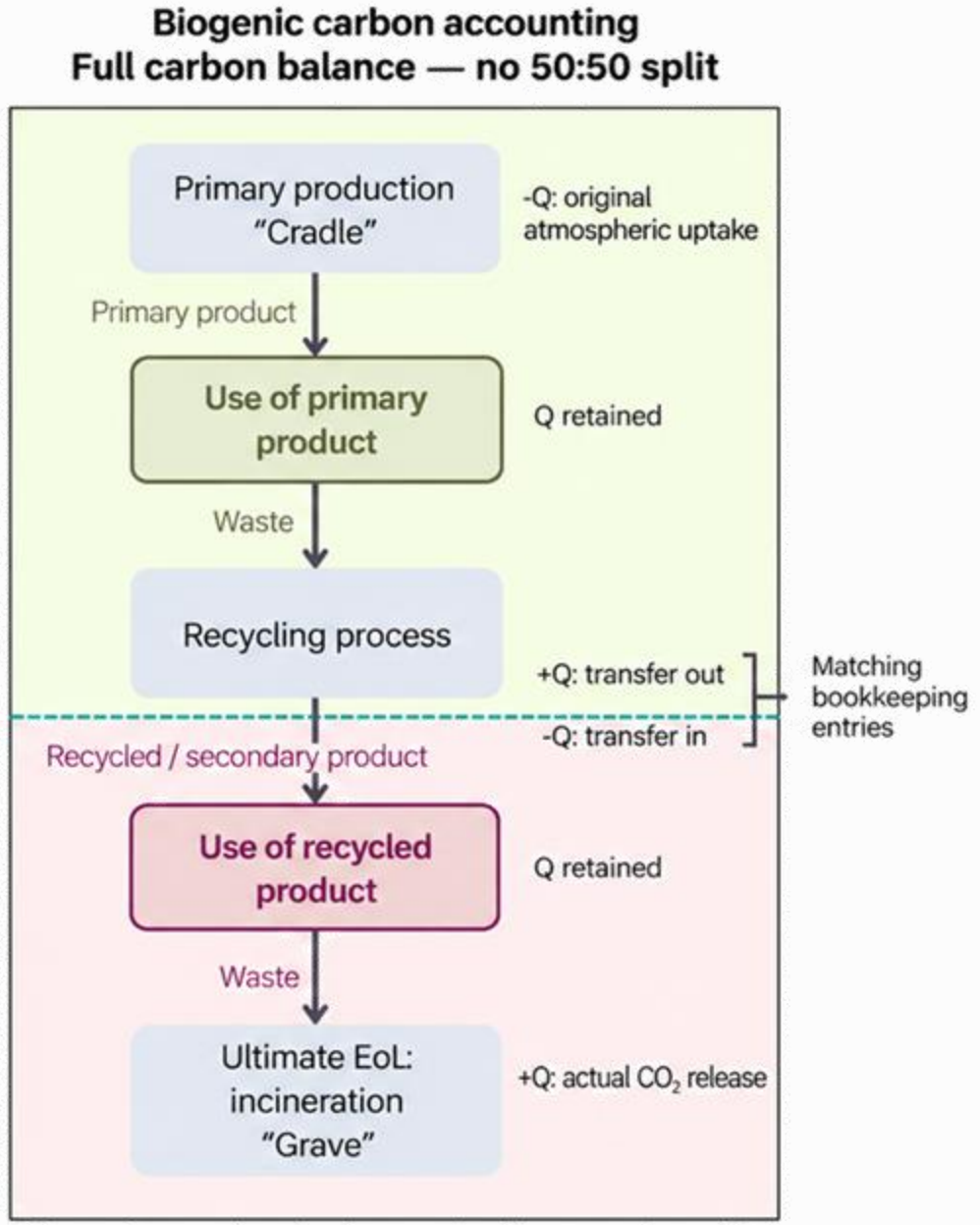


Impacts or benefits allocated to primary product.
Impacts or benefits allocated to secondary product.
Limiting border for the system boundaries between the primary and secondary use of the product/material.

Avoid 50/50 allocation to biogenic carbon.

- The 50/50 method shares recovery burdens and benefits between product systems, whereas **biogenic carbon follows the full carbon content through uptake, transfer and release** to maintain a consistent balance.





Impacts or benefits allocated to primary product.
Impacts or benefits allocated to secondary product.
Limiting border for the system boundaries between the primary and secondary use of the product/material.