

Circularity Analysis Tool for Biomass REsource Valorisation Impact Analysis

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Two indicators for environmental performance of residue valorisation

The CAT-BREVIA tool facilitates quantitative comparison of environmental performance of allocating residual biomass streams to different valorisation pathways and waste management options. Effects are quantitatively estimated for two indicators:

- Degree of circularity: an indicator for resource use efficiency that takes into account the yield to food, energy carriers and biobased materials.
- Consequential greenhouse gas (GHG) emissions effect, which accounts for substitution of primary materials/feedstocks by the (residual) material (like substitution of natural gas by biomethane) and other GHG emissions and mitigation effects up to the point of substitution.

The scope of the tool is limited to two sustainability dimensions

because (a) these dimensions are considered essential for sustainably meeting growing demands for food, feed and biobased valorisations within the constraints of limited renewable resources, and (b) they can be quantified consistently across all valorisations. Nevertheless, authors are aware that **sustainable development is characterized by a wide range of criteria**. Depending on the specific context and priorities, many other criteria may be relevant. For example

- o Environmental benefits associated with the biodegradability of certain bioplastics favours the production of bioplastics,
- o There may be a strong preference for maintaining nutrients in crop residues for the soil if legislative constraints limit the ability to compensate for nutrient losses resulting from the reallocation of crop residues.

These – and various other sustainability dimensions – are not captured by the selected indicators but may be taken into account in more comprehensive multi-criteria decision-making processes for the selection of valorisations.

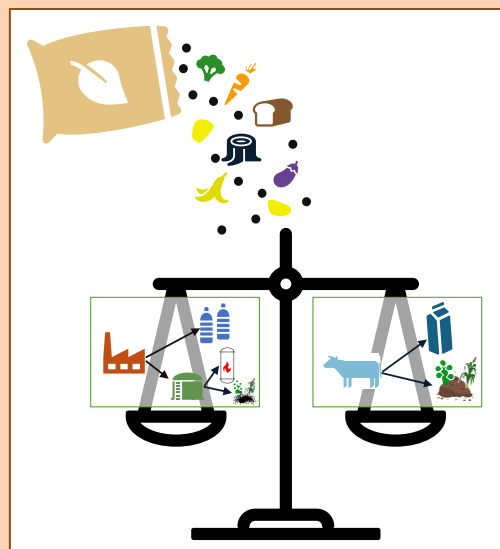
This factsheet first provides a general introduction to the indicator *degree of circularity* (page 2) and indicator *consequential GHG emissions effect* (page 3), followed by recommendations for the assessment of situation-specific effects (page 4). Assumed modelling heuristics[¶] for diverse valorisations are described in dedicated factsheets.

To facilitate rapid assessments, the tool contains a database with information about average/typical compositions[¶] of diverse biomass materials, residual flows and processed products.

[¶] *Disclaimer: The method relies on heuristics and parameter values derived from reference studies that are often limited in scope and/or based on average values. Consequently, its valorisation to individual case studies may involve some inaccuracy and uncertainty due to the inherent generalizations and averaging assumptions.*

Yield factors were for diverse valorisations – especially for agricultural valorisations – derived from performance figures for mainly Dutch production systems. These may deviate from practical averages in other geographic regions. Upon request the authors may consider adoption of yield factors for other areas or production systems (provided that necessary data are available).

The CAT-BREVIA tool is subject to ongoing development and refinement. New insights can lead to adjustments of pathway parameter values. Likewise, GHG emission factors for both inputs and substituted products are periodically updated. As a result, the calculated outcomes may differ slightly between tool versions. Therefore, results generated using different versions of the CAT-BREVIA tool should not be compared directly.



The tool, including accompanying factsheets that describe the modelling approaches and underlying assumptions for a range of common and alternative valorisations, is available at: <https://circular-biomass-valorisation.com/quantification>. Examples of case studies can be found on <https://circular-biomass-valorisation.com/cases>.

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The CAT-BREVIA tool was developed based on public funded research projects, supported by the Dutch Ministry of Agriculture, Fisheries Food security and Nature[#] and from EU^{##}.

[#] In diverse BO projects the foundational method for indicator 'degree of circularity' was developed, including quantitative elaboration of diverse common valorisation pathways (feed for diverse livestock and other agricultural uses including organic waste management options. In the KomCirc project the method was applied for diverse specific pathways (including parameterisation of dedicated alternative valorisation pathways and other biomass streams).

The KomCirc project received financial support from the Knowledge and Innovation Agenda agriculture, water, food. Within the KIA, the business community, knowledge institutions and government are working together on innovations for safe and healthy food (and a green living environment) for 9 billion people in a resilient world.

^{##} In EU Agriloop project, the method was extended with the indicator 'consequential GHG emission effect' and some alternative valorisations, including bioplastics and microbial proteins. The Agriloop project has received funding from the European Union's Horizon Europe research and innovation programme under the grant agreement No. 101081776, the UK Research and Innovation (UKRI) fund under the UK government's Horizon Europe funding guarantee, the Swiss State Secretariat for Education, Research and Innovation (SERI) and from the National Key Research and Development Program of China (NKRDPC).

Core principles of the methodology for the Degree of circularity

The CAT-BREVIA tool estimates and compares the yield of the valorisation of bio-materials in different 'valorisations pathways' to final products (food, energy carriers and biobased materials). The calculations are based on mass balance equations, describing conversion efficiencies per macronutrient (proteins, lipids, carbohydrates, etc.).

The analysis of a valorisation pathway includes all significant effects, including those arising from residual streams generated within the pathway. For example, for feed valorisations, the assessment considers not only the production of animal-derived food products but also the contribution of the resulting manure to feed and food production through its use as a fertilizer.

The *degree of circularity* is calculated as the ratio of the energy content of the end products relative to that of the input material (as – often hypothetically – food), with some adjustments (explained below).

The net increase of the *degree of circularity* resulting from the reallocation of a material from a reference valorisation pathway to an alternative valorisation pathway is defined as the difference between the *degrees of circularity* associated with the two pathways.

Formula for indicator degree of circularity

The *degree of circularity* is calculated with following formula (upgraded from Broeze et al., 2024):

$$\text{Degree of circularity (\%)} = \frac{\sum_{\text{products } k} (\sum_{\text{components } j} (\sum_{\text{components } i} (A_{j,k} \times y_{i,j,k} \times K_{j,k} \times \Delta H_{c,j}^0 \times m_i)))}{\sum_{\text{components } i} (K_{i,\text{food}} \times \Delta H_{c,i}^0 \times m_i)}$$

where the expression in the denominator expresses the value of the material and the nominator refers to the produced product(s) in a valorisation pathway. Meaning of the variables:

- m_i stands for the mass share of macro-nutrient i in the material on dry matter basis (kg/kg).
- $y_{i,j,k}$ stands for the yield factor of macro-nutrient i to component j in product k (kg/kg).
Often (like in extraction processes) $y_{i,j,k} = 0$ for all $j \neq i$; in conversion processes $y_{i,j,k} \neq 0$ is possible for $j \neq i$.
- $\Delta H_{c,i}^0$ stands for the specific heat of combustion of macro-nutrient i (MJ/kg).
- $A_{j,k}$ is an appreciation factor for component j in product k , intended for expressing different preferences for product categories (food, energy carriers and biobased materials), including different valuation per macro-nutrient in food.

Adjusted appreciation of proteins in food

Considering the specific nutritional importance of proteins in food, beyond their energetic value, and the generally lower agricultural yields of protein crops compared to energy crops, an additional weighting factor is assigned to proteins in food.

Proteins require about 3 to 5 more land than carbohydrates (m² land per kg product). This is reflected in market prices: protein generally have higher prices than carbohydrate products. The actual price ratio varies, dependent on (international) trade and power relations and political situation.

A land productivity ratio of approximately 4 for carbohydrate production relative to protein production can be converted into an energy yield ratio of approximately $4 \times 17.2/23.9 \approx 3$, based on typical specific heats of combustion of 17.2 MJ kg⁻¹ for carbohydrates and 23.9 MJ kg⁻¹ for proteins.

Accordingly, while the tool values other components according to their specific heats of combustion, proteins in food are assigned a value equal to three times their specific heat of combustion.

Differentiated appreciation factors for final product categories: food, energy carriers and biobased materials

- Food is – based on societal preferences – considered here as the reference.
- Generally, valorisation for production of energy carriers is considered lower-value than for food production. This (societal) preference is reflected by lower or comparable prices for feedstocks for anaerobic digestion or biofuels production (compared to food and feed for livestock). Furthermore, energy carriers (like biomethane and biofuels) are commonly generated with substantially higher (energetic) efficiency from feedstocks than the conversion of livestock feed into food products. Based on these considerations energy carriers are assigned a lower appreciation factor (25%) compared to food products in the tool.
- Biomaterials can be utilized multiple times throughout their life cycle, e.g. through recycling and incineration (with potential of energy recovery) at the 'end-of-life'. Therefore, a higher appreciation factor is assigned to biomaterials compared to

energy carriers. Based on typical recycling rates for bioplastics found in literature (between 60 and 90%), here biomaterials are appreciated at 3x the value for *energy carriers*.

Remark: subjective elements in indicator degree of circularity

The appreciation factors currently implemented in the method are – as explained above – underpinned by sound methodological reasoning. Nevertheless, the applied appreciation factors – most notably the valuation of energy and biomaterials relative to food – rely on assumptions/choices linked to context-dependent and temporally variable considerations, such as societal perceptions of value and prevailing market price ratios, rather than from fundamental physical evidence or biophysical principles.

The approach used to set the appreciation factor for energy carriers relative to food inherently results in lower *degree of circularity* scores for energy conversion valorisations than for those with animal feed valorisations for most materials. If the societal appreciation of bioenergy would be higher, this could be represented by assigning a higher appreciation factor to bioenergy. Under such circumstances, the *degree of circularity* indicator would generate more differentiated outcomes, with certain materials exhibiting higher degree of circularity values when utilized as animal feed, while others would achieve higher values when directed toward energy production pathways.

Furthermore, the proposed recycling factor for biomaterials is intended for use in prospective scenario analyses that assume substantial adoption of circular bioeconomy practices. Under current conditions, this factor does not adequately reflect existing waste management systems, as the recycling of bioplastics has not yet been widely institutionalized. However, when circular bioeconomy systems mature and recycling infrastructure becomes more established, the proposed factor is expected to provide a realistic representation of recycling performance.

The appreciation factors may be revised upon request, when justified by robust rationale.

Core principles of the methodology for Consequential GHG emission effect

The CAT-BREVIA tool estimates *consequential GHG emission effect* in accordance with common consequential greenhouse gas emission quantification guidelines. The following effects are taken into account:

- avoided GHG emissions through the substitution of primary materials with generated products (such as commonly used animal feed, electricity or fossil fuels),
- carbon sequestration (in material or in the soil),
- up to the point of substitution and for products (including produced residuals) that do not substitute a material:
 - GHG emissions associated with used energy and other processing inputs,
 - emissions of other greenhouse gases:
 - CH₄, with a Global Warming Potential (GWP) of 27 kg CO₂ equivalents (CO₂e) per kg,
 - N₂O, with a GWP of 273 kg CO₂e per kg.

For dedicated situation-specific scenario analysis, effects of additional operations – like energy use in specific processing operations and/or transport – can be added to the calculated effect.

The net *consequential GHG emission effect* of reallocating a material from a reference valorisation pathway to an alternative valorisation pathway is defined as the difference between the *consequential GHG emission effect* of the two pathways.

Note: The inclusion of all consequential effects in this method differs fundamentally from attributional greenhouse gas (GHG) emission accounting ('carbon footprinting'). Main differences:

- In carbon footprinting, greenhouse gas (GHG) emission reductions or removals associated through the production of circular products from waste streams or from co-products without economic value should not be taken into account, in order to avoid double counting. For example, the low GHG emission intensity associated with renewable energy generation is attributed to the user of that energy rather than to the supplier of the waste/residue stream. In contrast, consequential assessment accounts for all system-wide effects, including changes in renewable energy generation resulting from waste management and other affected processes.
- Likewise, in product carbon footprinting the average GHG emission factors for electricity should be used, whereas in consequential analyses marginal GHG emission factors are preferred.

In product carbon footprinting the GHG emissions associated to primary production should be included. In contrast, the consequential analyses considered here assess the effects of reallocating a material from a common valorisation pathway to an alternative valorisation pathway.

GHG emission factors

GHG emission factors – for both used inputs and the for the products assumed to be substituted – are key determinants of the outcomes of GHG emission accounting. A brief description of the methodological choices is provided here; specific references for each data point are documented within the tool.

GHG emission factors for electricity

In consequential analyses on redirecting a stream to another 'destination' preferable marginal emission factors for electricity are used. These are – in contrast to grid-average emission factors – not widely available. Determining marginal emission factors for electricity is inherently complex, as it requires understanding of decision-making processes across multiple actors and timescales, including long-term energy policy development, real-time power generation scheduling, and the dynamic composition of the energy mix. As a work-around, average emission factor for generated fossil-based electricity (derived from ember-energy.org¹) are used as a proxy for marginal emission factors.

The referenced source provides emission factors per unit of generated electricity. Emission factors for electricity consumption were derived from these values by correcting for transmission and distribution losses (these loss factors were derived from World Bank²).

GHG emission factors for other materials

Greenhouse gas (GHG) emission factors for other inputs, substituted materials, and energy carriers were derived from established and reliable sources, including CarbonCloud³, the Joint Research Centre (JRC), and various specific references, most of which peer-reviewed. Note: Each reference factor was determined for a specific production system or supply chain configuration, or derived as the average of a selection of case studies, which may not fully represent the actual situation being assessed. Consequently, the use of secondary data may inevitably introduce a degree of uncertainty and potential inaccuracy into the assessment.

Subjective element: choice of substituted products

For many products, the substituted (primary) product can be identified relatively straightforwardly. For example, biogas (green gas) may be assumed to substitute fossil natural gas.

For food and feed valorisations, the selection of appropriate substituted products and their associated emission factors is less straightforward. This is due to the wide range of commonly used food and feed ingredients, as well as the substantial variation in their carbon footprints resulting from differences in production regions and production system characteristics. In the present methodology, substituted products were selected based on those often reported in the life cycle assessment (LCA) studies. Selected substituted products and associated emission factors are presented in the respective factsheets.

Upon request the authors may consider the inclusion of alternative substituted products in the tool.

¹ <https://ember-energy.org/data/yearly-electricity-data/>

² <https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS>

³ <https://carboncloud.com/>

Advanced use of the CAT-BREVIA tool: adding GHG emission associated to energy use and transport

The effects associated with energy consumption, other input materials, and transportation can be incorporated by the user, for example by applying the emission factors provided in one of the tool's worksheets. It should be noted that, for most predefined valorisations, typical energy and input requirements are already

incorporated within the tool. Therefore, users are advised to consult the valorisation pathway factsheet to avoid double counting of impacts.

Advanced use of the CAT-BREVIA tool: assess effects of fractionation with different valorisation pathways and/or waste management options per fraction

Advanced residue valorisation pathways may involve different 'destinations' for fractions of the material. Often, only a fraction is used in a high-value valorisation whereas a residue stream is directed to another valorisation pathway or a waste management option. A methodology for assessing such scenarios is described below.

Specifying compositional information per fraction

If in the scenario the composition of a stream directed to a valorisation pathway or waste management option differs significantly from that of the original material, the (estimated) composition should be added to the compositional dataset. This information is essential for accurately assessing the impacts associated with the respective valorisation pathway(s).

Estimating Degree of circularity

The *degree of circularity* for the combination of valorisations can be derived from the value for the individual fractions:

$$C_t = \frac{\sum_{\text{valorisations } i} (f_i \times C_i \times A_i)}{A_m}$$

where

- C_t is the calculated total *degree of circularity* of the combined set of valorisations.
- f_i is the mass fraction (in terms of dry matter) of the stream entering valorisation pathway or waste management option i . Preferably in the analysis the consequential effect of the total material is described (i.e. $\sum_{\text{valorisations } i} f_i = 1$). If a fraction is neglected (e.g. lost to waste water and not described in the

analysis) the sum of the described streams' mass fractions will be less than 1.

- C_i is the *degree of circularity* for fraction i in its valorisation or waste management option (calculated by the tool).
- A_i is the appreciation for fraction i in the reference valorisation pathway (= direct to food); this value is provided by the tool: estimated specific heat of combustion with correction for appreciation of proteins as explained above.
- A_m is the appreciation for the starting material m , again provided by the tool.

Estimating Consequential GHG emission effect

Also the *consequential GHG emissions effect* can be calculated based on mass-fraction averaging of the effects to the individual fractions:

$$G_t = \sum_{\text{valorisations } i} (f_i \times G_i)$$

where

- G_t is the calculated total *consequential GHG emissions effect* of the combined set of 'destinations' (kg CO₂e per kg material dry matter).
- f_i is the mass fraction (in terms of dry matter) of the stream entering valorisation pathway or waste management option i .
- G_i is the calculated total *consequential GHG emissions effect* of stream i in valorisation pathway i (kg CO₂e per kg material dry matter) as calculated by the tool.

When applicable, the specific emissions due to fractionation process and/or other additional operations can be added as explained above.

Recommended literature

- Broeze, J.; W. Elbersen; J. Voogt; H. Soethoudt (2024) Circulariteit van reststroombenutting. Wageningen Food & Biobased Research, Report 2584. DOI: 10.18174/672425. <https://edepot.wur.nl/672425>.
- Broeze, J., M. Rodriguez-Illera (2025) Third estimates of biomass residue volumes, composition, bio-based yields and environmental performances, EU-Agriloop project, Deliverable 1.6, <https://www.agriloop-project.eu/resources/documents/>.