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Function-based allocation for recycling and waste-to-energy systems: A unit-process framework for attributional LCA

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Abstract

Purpose

Providing comparable attributional footprints of multifunctional recycling systems and their products is a long-running and controversial issue in LCA. This study proposes a function-based allocation approach for multi-input–multi-output recycling systems that yields functionally aligned cradle-to-gate footprints for recyclates and explicit footprints for waste-treatment and energy products. We ask how composition-based, function-based allocation can be operationalised in attributional recycling LCAs while respecting ISO 14040/44.

Methods

We develop a conceptual framework that functionally separates recycling systems into waste treatment (WT) and resource provision, further split into material provision (MP) and energy provision (EP). Based on article-level recyclability factors and the measured composition of the material streams, we derive composition-based recyclable-material shares for each fraction and use them to allocate burdens between WT, MP and EP. Process yields are reported as performance indicators and mass-balance checks, but are not used as allocation keys.

Results and discussion

A numerical example shows that the proposed allocation yields cradle-to-gate recyclate footprints that predominantly reflect material provision, while burdens for treating non-recyclables are assigned to WT and EP footprints. System inefficiencies (losses of recyclable material) become quantitatively visible and are attributed back to recyclates, creating clear incentives to improve yields and design for recycling. Compared with simple mass allocation and generic end-of-life approaches, the method resolves problems of the known inconsistent allocation approaches, avoids hidden double counting, and maintains the summation rule across recyclates, waste-treatment services and energy outputs.

Conclusions

The function-based allocation approach enables comparison of recyclate and virgin-material footprints at consistent system boundaries, subject to separate verification of substitutability, and makes the WT service of recycling systems explicitly quantifiable. It can directly support procurement, eco-design, benchmarking and policy instruments that rely on cradle-to-gate footprints for secondary materials, and can be integrated with existing frameworks such as Product Environmental Footprint (PEF) method or Environmental Product Declarations (EPD) programmes.

Recommendations:

Within recycling systems, the four-step procedure operationalises the physical-relationship allocation permitted under ISO 14044, replacing the interpretive latitude of generic recycled-content approaches with a reproducible, composition-based method that improves cross-study comparability. At the inter-life-cycle level, function-based cradle-to-gate outputs can complement existing frameworks such as the Circular Footprint Formula. Harmonised default data for recyclability and exergy parameters, and extension to chemical recycling, are priorities for future work.

1 Introduction

Life Cycle Assessment (LCA) is an established method for assessing environmental impacts of products and services across their life cycles and is widely applied to waste-management and recycling systems (ISO 2006a; Pryshlakivsky and Searcy 2021; Wang et al. 2023). When applied to end-of-life recovery recycling systems, such as recycling, LCA requires explicit allocation choices that influence the results (Nicholson et al. 2009), because recycling processes can be shared between product systems: they simultaneously treat discarded products and provide secondary resources to subsequent product systems, particularly in open-loop recycling systems (van der Harst et al. 2016; Rigamonti et al. 2020).

This study distinguishes two functions provided by end-of-life recovery systems: waste treatment (WT) and resource provision. WT refers to the management of discarded products in a manner compatible with environmental and regulatory requirements. Resource provision comprises material provision (MP) in material-recycling pathways and, where applicable, energy provision (EP) in energy-recovery pathways, including waste-to-energy (WtE) processes. The simultaneous provision of these functions makes end-of-life recovery systems multifunctional and raises the question of how environmental burdens should be assigned (Finnveden et al. 2009). This multifunctionality manifests at two distinct levels: between successive product life cycles, when secondary materials or recovered energy re-enter subsequent product systems, and within individual unit processes, when a single sorting, recycling, or energy-recovery operation generates several co-functions simultaneously. Both levels require distinct allocation solutions, as discussed in Section 2.1.

A range of established approaches addresses multifunctionality in waste-management LCA, including system expansion, substitution, cut-off system models, system-level methods such as the 50/50 method and the Circular Footprint Formula (CFF), and mass allocation (Lindfors et al. 1995; Wernet et al. 2016; European Commission 2021). These approaches operate either across successive product life cycles or between output streams of individual processes. None of these approaches by itself provides a physically grounded unit-process-level partitioning of WT, MP and EP based on the composition, configuration and recovery performance of the recycling system under study. A complementary line of work has advanced the allocation of burdens across successive product life cycles in open-loop recycling by accounting for changes in the functional quality of secondary materials (Rodrigues and Kulay 2026). This inter-life-cycle perspective addresses a different question than pursued here: the

present study focuses on the intra-system partitioning of burdens. Typically applied unit-process allocation often relies on generic physical or economic proxies that may obscure recyclability, recovery losses or physical process relationships (Chen et al. 2010; Pelletier et al. 2015).

Building on this gap, we propose a function-based allocation approach that operationalises the polluter-pays principle at unit-process level and exhaustively partitions burdens across WT, MP and EP using physical relationships, without substitution credits. Beyond its methodological contribution, the approach aims to provide a stable basis for procurement decisions, benchmarking, and policy instruments such as Product Environmental Footprints (PEF) or Environmental Product Declarations (EPD). We illustrate its effects using a fictitious packaging-waste recycling system and compare it with mass-based allocation at the sorting stage combined with or without substitution of recovered energy. Specifically, we examine (i) whether function-based allocation can provide functionally aligned attributional footprints for WT, MP, and EP while preserving the summation rule, and (ii) how the results, including the visibility of system inefficiencies, differ from the reference approach.

2 Methods: Function-based physical allocation framework

2.1 Methodological requirements

Recycling and WtE systems are multi-input–multi-output systems that combine waste treatment (WT) with material provision (MP) and/or energy provision (EP). This creates allocation questions both between successive product life cycles and within individual unit processes (Fig. 1).

Regarding the first issue in Fig. 1, the allocation between life cycles, well-established system-level approaches, such as the 50/50 method and the Circular Footprint Formula (CFF), distribute burdens between successive product life cycles (Schrijvers et al. 2016; Wang et al. 2023). The 50/50 method applies an equal split between life cycles by convention (Lindfors et al. 1995; Wang et al. 2023), whereas the CFF uses rule-based parameters reflecting recycled content, end-of-life recycling, material quality, energy recovery, and market conditions (European Commission 2021; Huysman et al. 2026). While the CFF can account for recycling rates, quality factors, and market conditions, neither the 50/50 method nor the CFF by itself derives a unit-process-level partitioning from the actual composition, configuration, and recovery efficiency of the recycling system under study (Nessi et al. 2021). Ekvall et al. (2020) reviewed twelve approaches for modelling recycling between product life cycles and emphasised that their suitability depends on the goal and application of the study. A comparative overview of inter-life-cycle approaches is provided in the Supporting Information (SI) in A-1. Although the suitability of individual approaches remains contested and context dependent, there is broad consensus that parameter choices substantially affect product-level results and may limit reproducibility and comparability across differently modelled recycling systems (Wang et al. 2023; Huysman et al. 2026). Consequently, system-level recycling models do not by themselves determine which life cycle should bear burdens associated with non-recyclable material at unit-process level.

For this remaining attributional question, the polluter-pays principle provides a useful normative reference point: the costs of waste management should be borne by the original waste producer or the current waste holder (Treaty on the Functioning of the European Union, Article 191(2); Directive 2008/98/EC, Article 14). In the interpretation adopted here, burdens arising from co-collected items that do not meet applicable recyclability criteria are assigned to WT and, hence, to the waste-producing life cycle rather than to MP. This includes non-recyclable items resulting from product design or disposal behaviour. This differs from cut-off approaches, which define the boundary between life cycles before, within or after recycling and assign each product the burdens arising within its own life cycle. In the ecoinvent cut-off system model, recyclable material enters the receiving system burden-free, while recycling activities are generally assigned to the system using the recyclate (Wernet et al. 2016; ecoinvent 2024). For mixed collection streams, however, cut-off does not generate a separate attributional footprint for WT or distinguish sorting and separation burdens associated with co-collected non-recyclable items from those associated with MP. Recyclability is instead classified at the level of the collected stream, rather than used to functionally partition burdens at individual unit processes.

A related attributional approach, allocation at the point of substitution (APOS), distributes burdens between co-products using market-based information as they enter subsequent product systems (Weidema et al. 2013; Schrijvers et al. 2021). While APOS can provide a coherent inter-life-cycle convention, it does not specify how burdens are physically partitioned within a given process between WT, MP and EP, and its coordinated application across independently reported product footprints, especially for open-loop recycling is often impractical. APOS is therefore not directly suited to the unit-process-level function separation pursued here.

These observations motivate the central proposition of the present framework: The polluter-pays principle is used here as a normative heuristic for assigning burdens associated with normatively non-recyclable material to the waste-generating life cycle. This process-level resolution is necessary to derive recyclate footprints that are functionally aligned with conventional cradle-to-gate footprints of virgin materials.

The second issue in Fig. 1 concerns multifunctionality at unit-process level. Individual processes, such as sorting plants, may generate several output streams that are further recycled, energy-recovered, or treated as residual waste. Multifunctionality at this level does not necessarily require burden partitioning when the goal of a study is to assess the combined functional output of a system. In such cases, the system can be expanded to include all relevant co-functions; here, this refers to *actual* system expansion, in which the functional unit is expanded rather than displaced products being modelled through substitution (Heijungs et al. 2021; Schrijvers et al. 2021). Alternative system configurations can then be compared using an equivalent basket of functions (Ekvall et al. 2025). This system-level perspective is well suited to comparing alternative recovery configurations, but does not by itself yield separate attributional footprints for individual outputs, such as a specific recyclate grade or a waste-treatment service.

ISO 14044 prioritises avoiding allocation through subdivision or actual system expansion over allocation procedures. Amendment 2 to ISO 14044 additionally describes a substitution-based interpretation of system expansion, although the distinction between actual system expansion and product substitution remains contested (ISO 2020; Heijungs et al. 2021). Substitution is frequently used to address multifunctionality in waste-management LCA and can avoid explicit partitioning of process burdens (Rigamonti et al. 2020; van der Harst et al. 2016). Allocation is often associated with attributional LCA and substitution with consequential LCA, but this distinction is an oversimplification (Finnveden et al. 2009; Rigamonti et al. 2020). Substitution is well established in consequential LCA, because it supports its inherent nature, but it can also be applied coherently in attributional LCA when credits and corresponding burdens are consistently assigned across co-products, thereby preserving the total burden of the multifunctional system (Ekvall and Weidema 2004; Provost-Savard and Majeau-Bettez 2024). Substitution modelling requires explicit assumptions regarding the substituted product system, including the recovery efficiency, the functional equivalence between recovered and displaced products, and the expected response of competing production systems (Rigamonti et al. 2020; Vadenbo et al. 2017).

However, the limitation identified here is specific to attributional LCA and stand-alone product footprints. While substitution is well suited to comparing counterfactual scenarios, it represents burdens displaced to external product systems rather than burdens of the physical process under study. Unless corresponding burdens are assigned within a coordinated model of interconnected product systems, substitution credits do not exhaustively partition observed burdens and may be claimed more than once across independently reported footprints. Amendment 2 of ISO 14044 identifies substitution as a “straightforward choice for energy products” (ISO 2020). Here, a credit for avoided electricity or heat generation shall represent displaced energy production and does not determine how the physical WtE-process burdens are partitioned between WT and EP. If retained in a stand-alone product footprint, an additive attributional accounting requires the recovered energy to carry a balancing burden equal to the credited burden of displaced energy production. Otherwise, the recyclate producer may claim the credit while the energy user treats the recovered energy as burden-free, resulting in incompatible footprint claims. Deriving separate, function-based attributional footprints therefore requires an explicit within-system allocation rule (Brander and Wylie 2011; Ekvall et al. 2020; Pelletier et al. 2015; Rigamonti et al. 2020; Schrijvers et al. 2021). Accordingly, the first requirement of the proposed allocation framework is:

Requirement 1

For the derivation of separate WT, MP, and EP footprints at unit-process level, all observed process burdens shall be exhaustively allocated within the system boundary. Substitution shall not be used to derive within-system functional partitioning.

Where subdivision or actual system expansion cannot be applied, ISO 14044 gives preference to allocation based on relevant physical relationships (ISO 2020; Pelletier et al. 2015). However, the ISO standard does not specify which physical relationship should govern this allocation, nor how it should be

operationalised for multifunctional recycling and WtE processes; this interpretive latitude is left to the practitioner and, as a result, is resolved inconsistently across studies (Azuaje et al. 2025). At unit-process level, the burdens of sorting, recycling, and recovery arise from the physical handling, separation or treatment of material streams. Allocation keys should reflect measurable properties of material and energy flows. Economic keys may be useful for other purposes but vary with market conditions rather than physical process relationships (Frischknecht 2000; Pelletier et al. 2015). A commonly applied physical allocation basis at unit-process level is output mass. However, mass alone does not distinguish between recyclable and non-recyclable material content, nor does it provide a rule for separating WT, MP, and EP within a recovery pathway (Schrijvers et al. 2016; Azuaje et al. 2025). Recyclate footprints derived from mass allocation alone may therefore combine burdens associated with resource provision and waste treatment, limiting their functional alignment with cradle-to-gate footprints of virgin materials. A physically grounded allocation basis must therefore go beyond mass and reflect the recyclability of the material streams themselves, which is reflected in the second requirement.

Requirement 2

Function-based allocation keys shall be grounded in measurable properties of the recycling system and its material and energy flows, combined with normative recyclability classifications where required. In the proposed framework, the allocation uses composition-based recyclability indicators for material outputs and exergy-based indicators for energy outputs.

In summary, Requirements 1 and 2 address the intra-system allocation problem in Fig. 1 and burdens of individual sorting, recycling, and energy-recovery processes can be partitioned between WT, MP, and EP; inter-life-cycle allocation remains outside the scope of the present framework.

2.2 Specific challenges of recycling chains

Beyond allocation challenges, the following requirements are framework-specific design choices adopted for the attributional context defined above. They are motivated by physical process relationships and the polluter-pays principle, but are not presented as generally prescribed allocation rules.

In practice, recycling chains exhibit several characteristics that complicate attributional modelling and allocation. For example, recycling systems typically receive heterogeneous waste streams whose composition varies by source, region, and time. Different shares of non-recyclable materials directly influence the composition of the residual stream, the achievable yields, the quality of the output and the process burdens. Heavily contaminated inputs require more intensive sorting and cleaning and generate higher quantities of residues. At the same time, recycling chains exhibit variability at multiple levels. At the modelling level, unit-process boundaries should follow the physical configuration of the recycling system. Sorting, recycling, and upgrading operations may be physically separate or integrated, depending on the actual plant configuration and the transfer of material streams between operations. At the technological level, even within the same technology class, sorting plants can differ substantially in

configuration, for instance, in the number and sequence of separation steps, the share of manual versus automated sorting, and the resulting output fractions. Across recycling systems, further structural differences arise from alternative upstream collection and pre-sorting configurations, such as separate collection, deposit-return systems, and mechanical recovery of packaging from mixed municipal waste (Picuno et al. 2021a, b). Thus, the third requirement is formulated:

Requirement 3

Unit processes shall be delimited according to physically distinguishable process units and their actual input–output relationships. The allocation shall reflect the composition, recovery performance, and residual streams of each process unit. Burdens from upstream operations with a single transferred material stream may be carried forward and allocated at the first downstream process generating multiple material outputs, provided that the stream is not materially transformed. Accordingly, differences in allocation results should reflect real differences in input composition, process configuration, and recovery performance, rather than artefacts introduced by incomplete or inconsistent process data.

In this study, items that are both detectable and separable by current state-of-the-art sorting technology and processable into a marketable recyclate within the applicable recycling system are referred to as recyclable items; all other items are grouped as non-recyclable items. In many regions, recyclability standards define which packaging qualifies as recyclable under the current state of the art, e.g. the minimum standard for determining the recyclability of packaging in agreement with the German Environment Agency (ZSVR 2025). Such standards are determined by measurable physical properties, such as detectability in near-infrared sorting, mechanical separability, and processability in established recycling pathways, rather than by economic value or market conditions. From the polluter-pays perspective, standards define the scope of the recycler's actual task: recovering recyclates from end-of-life waste that qualifies as recyclable under the applicable standard. Sorters and recyclers are not responsible for recycling non-recyclable packaging; rather, they provide a WT service that separates and forwards it to incineration, with resulting impacts attributed to the waste-producing life cycle rather than the recyclate. Normative recyclability standards thus provide the basis for this split. Although the WT function covers the complete collected waste stream (Section 1), the resulting WT footprint comprises only the burdens of treating the non-recyclable share (formalised in SI A-6.3). Instead, the treatment of the recyclable share is attributed to the resource consuming life cycle and, hence, to the MP footprint.

Requirement 4

The burdens from treatment of non-recyclable material shall be attributed to the WT footprint rather than the recyclate, with recyclability determined by the applicable normative standard.

An apparently straightforward alternative to this standard-based approach would be to use observed plant yields as allocation keys. However, observed yields reflect the performance of a specific process configuration handling a particular input stream and are influenced by sorting technology, process

control, and input composition (Cimpan et al. 2015). They cannot by themselves distinguish material that is non-recyclable under the applicable reference conditions from technically recyclable material lost through system inefficiencies. This distinction is consistent with recycling approaches that explicitly account for material losses (Ekvall et al. 2020). Normative recyclability criteria, by contrast, provide a transparent and comparatively stable basis for defining the WT–MP boundary (e.g. ZSVR 2025; RecyClass n.d.).

A further complication arises independently of the WT/MP boundary established in Requirement 4: even where material is normatively classified as recyclable, a portion of it is not actually recovered but is lost to residual streams along the recycling path. We refer to such losses as *system inefficiencies*. Residual streams are output streams from a sorting or recycling process that do not serve the MP function and are instead routed to downstream treatment (e.g. WtE or landfill); they typically contain a mix of non-recyclable material (Requirement 4) and recyclable material lost through system inefficiencies. Their causes are heterogeneous, including technical and operational limitations (e.g. suboptimal process settings or detection limits), upstream factors such as insufficient separation of recyclables by consumers prior to collection, plant-specific configuration choices, and deliberate decisions not to recover material where this is not technically or economically viable, or would compromise recyclate quality. In every case, the loss reflects a shortfall relative to the recovery performance technically achievable for the material in question, rather than a change in its normative recyclability status. Requirement 5 attributes the associated burden to MP irrespective of cause, to preserve a consistent incentive structure (Section 4.4). Under standard mass-based allocation, however, the treatment burden of a residual stream is distributed across its mass, without distinguishing between its non-recyclable and its lost-recyclable content. As a result, losses of recyclable material become functionally indistinguishable from the treatment of non-recyclable material: both are absorbed into a single, undifferentiated residual burden. Neither the magnitude of the system inefficiency nor its causal link to the sorting or recycling process that generated it becomes visible in the resulting footprint.

Requirement 5: Losses of technically recyclable material (system inefficiencies) shall be explicitly attributed to the MP footprint and assigned to the materially recycled outputs of the generating process, rather than to the WT footprint, which is causally tied to non-recyclable material only (Requirement 4). The recyclate can only be produced through the complete recycling path, including its unavoidable losses: system inefficiencies are therefore constitutive of the MP function, not incidental to it, and are treated as part of the effective burden of producing the recyclate.

Taken together, Requirements 1–5 narrow the interpretive latitude identified in Section 2.1 and 2.2, where ISO 14044 permits allocation based on physical relationships without specifying which relationship applies or how it should be operationalised. Rather than introducing a new allocation principle outside the ISO hierarchy, the requirements developed here specify a particular, reproducible choice within it.

2.3 Function-based allocation framework

The following four-step procedure operationalises Requirements 1–5 at physically delimited unit-process level. It partitions all observed burdens within the system boundary using composition-based recyclable-material shares for material streams and exergy-based factors for energy outputs. In concise terms, WT bears the burdens associated with non-recyclable material, whereas inefficiencies follow the recyclate outputs of the process that generated them.

2.3.1 Allocation keys

The procedure requires two allocation keys: the *recyclable-material share* for each material stream and the *exergy factor* for energy products.

Recyclable-material share r_k

The recyclable-material share r_k of output stream k is a fraction- and path-specific, composition-based indicator representing the mass share of recyclable material in that stream, given the current state of the art and the applicable recyclability standard. It is a mass-based metric and does not consider quality aspects of the resulting recyclate, as this requires application-specific considerations that lies beyond the scope of this framework (see Section 4.3).

To incorporate design-related recyclability and state-of-the-art constraints for a recycling path, a recyclability factor R_a is assigned to each material type with specific characteristics. Here, a *recycling path* denotes the sequence of processes that a specific fraction follows within the recycling system, from its point of collection to its final fate as either recyclate or treated residue. Consistent with common recyclability classification schemes (e.g. ZSVR 2025 or RecyClass n.d.), we define $R_a = 1$ for fully recyclable configurations (Class A), $R_a = 0$ for non-recyclable configurations (Class C), and $0 < R_a < 1$ for partially recyclable configurations (Class B)[1]. R_a shall capture not only the chemical identity of a material but also its practical recyclability considering the item's design and shape under current sorting and processing technology. Thus, the recyclability factors are assigned at article level, not at material level. Surface adhesions are excluded from this classification, as they represent unavoidable impurities that do not constitute a discrete sortable fraction; they are physically connected to every article and are removed during recycling or upgrading steps (e.g. washing, drying) rather than through dedicated sorting.

The recyclable-material share r_k of output stream k is calculated from the mass of article type a in output stream k with specific recyclability factor R_a assigned to article type and the total mass M_k of output k according to Eq. (1):

$$r_k = \frac{\sum_a m_{a,k} \cdot R_a}{M_k}$$

1

Consistent with Requirement 4, R_a values in Eq. (1) are derived from applicable recyclability standards rather than from observed plant yields, so that the magnitude of the MP share reflects the inherent recyclability of the collected waste rather than site-specific plant performance. This creates direct incentives for design-for-recycling and process improvements: reducing a product's non-recyclable share is the only way to shift its end-of-life burden from WT to MP, whereas improvements in plant yield reduce the recyclate footprint via reduced system inefficiencies (Requirement 5) without altering the WT attribution. An article analysis to obtain the R_a values shall be conducted at sorting level using the predominant recyclability standard. Given the temporal and source-related variability in waste stream composition described in Section 2.2, the analysis shall be based on a representative sample, ideally averaged across multiple sorting campaigns or input batches. Where no codified recyclability standard exists for the waste stream under study, R_a shall be determined based on default technical recyclability under current state-of-the-art conditions (see SI A-2). Based on this analysis, the composition of the collected waste input can be calculated (see SI A-3 for data requirements).

Exergy factor

For WtE processes, the exergy factor $f_{ex,k}$ is used as allocation key to separate the EP footprint from the WT footprint for stream *k*. Where several residual streams are co-treated in one WtE facility and only aggregated data are available, a common facility-level exergy factor shall be calculated. It is defined in Eq. (2) as the ratio of the total useful energy delivered as exergy in all energy products *e* from stream *k* ($Ex_{e,k}$) to the total chemical exergy of the input to WtE treatment unit (Ex_{input})

$$f_{ex,k} = \frac{\sum_e Ex_{e,k}}{Ex_{input}}$$

2

$f_{ex,k}$ is analogous to r_k: both serve as allocation keys to separate the provision footprint (MP or EP respectively) from the WT footprint. $f_{ex,k}$ specifically represents the share of the chemical exergy entering treatment unit that is delivered as useful energy products, and thus reflects the energy-recovery performance of that treatment unit. Exergy provides a physically consistent, price-independent measure of the thermodynamic quality of electricity and heat outputs at different temperature levels (Fruergaard and Astrup 2011). Strictly speaking, the total chemical exergy of the input is not identical to its energy content. However, for heterogeneous waste streams, it can be approximated by the lower heating value (LHV), which is the standard energy metric available from WtE operators. This approximation is consistent with Fruergaard & Astrup (2011) and is generally considered sufficiently accurate for typical mixed waste compositions. It is therefore used here in preference to economic allocation, which does not represent the physical relationship between the WtE process and its energy outputs. The full derivation, default parameters, and the methodological status of the WT attribution are provided in the SI A-4.

Where a WtE plant produces multiple energy products (e.g. electricity and heat), a second exergy-based key ($\alpha_{e,k}$) allocates burdens between those products. In Eq. (3), $\alpha_{e,k}$ is the exergy share of energy product *e* in input stream *k* and the sum of $Ex_{e,k}$ is the total exergy of all energy products generated from that input stream:

$$\alpha_{e,k} = \frac{Ex_{e,k}}{\sum_{e} Ex_{e,k}}$$

3

Eq. (2) serves the allocation factor to attribute between the total EP and WT, while Eq. (3) distributes the EP share among the individual energy products.

2.3.2 Four-step allocation procedure at unit-process level

The four-step procedure is applied sequentially to each unit process of the recycling path (collection, sorting, mechanical or chemical recycling, and downstream treatment) and equally to WtE as a standalone unit process receiving waste streams without prior sorting or recycling. Steps 1–3 address the allocation of process-internal burdens; Step 4 attributes burdens from downstream treatment facilities (WtE, landfill, incineration without energy recovery) back to the generating processes, where they are subjected to the same Steps 2 and 3. All four steps constitute allocation based on the introduced physical relationships in Section 2.3.1 that are in the sense of ISO 14044, using mass, composition and exergy as allocation keys derived from measurable properties of the system.

Step 1: Allocation between output streams: When a unit process generates two or more material output streams (recyclates, sorted fractions, residual streams directed to downstream treatment), total process burdens B_P are allocated to each output stream k by mass. In Eq. (4), B_k is the burden allocated to output stream *k*, m_k is its mass and M is the total mass of the process's material output streams:

$$B_k = B_P \cdot \frac{m_k}{M}$$

4

Mass allocation is applied here as a pragmatic key, assuming each kilogram of output requires the same marginal process effort for handling, routing and physical separation (examined further in Section 4.3). Treated residues (ash, slag, landfill deposits) are excluded, as they carry no burden. Step 1 is skipped when only a single output stream exists; the full burden passes directly to Step 2. Where a residual stream is routed to downstream treatment, any additional attributed treatment burden is partitioned separately in Step 4c.

Step 2: Functional split between life cycles: The burden B_k allocated to each output stream in Step 1 is split between the waste-producing and resource consuming life cycle using the recyclable-material share

r_k (Eq. 1). The MP share that is assigned to the resource consuming life cycle is calculated via Eq. (5). The disposal share D_k represents the share of B_k causally attributable to the waste-producing life cycle and is assigned directly to WT via Eq. (6).

$$MP_k = r_k \cdot B_k$$

5

$$D_k = (1 - r_k) \cdot B_k$$

6

Step 2 applies, when a unit process in a recycling system is intrinsically multifunctional. This is always the case if recyclable and non-recyclable material are both present in its input. The subsequent treatment of MP_k depends on the role of stream k. For the material provision share MP_k:

- If k is a material output stream (whether an intermediate fraction routed to a subsequent sorting or recycling step, or a final recyclate): MP_k constitutes the burden assigned to that stream for the MP footprint at this process step. The complete cradle-to-gate MP footprint of a recyclate is the sum of MP_k contributions from all process steps along the recycling chain.
- If k is a residual stream: MP_k is redistributed to the materially recycled product outputs of the same process in Step 3, provided that $r_j > 0$ and at least one materially recycled product output exists (see Step 3 conditions); otherwise $MP_k = 0$

When a recycler co-processes non-recyclable material into a marketable recyclate without generating a separate residual stream, the logic remains unchanged: r_k is calculated from the normative R_a values of all article types present in the product output, yielding $r_k < 1$. Material normatively classified as non-recyclable retains its WT function regardless of whether a particular recycler processes it. Step 2 thereby attributes the share of the burden causally caused by non-recyclable content to $D_k = WT_k$, consistently applying the polluter-pays principle at unit-process level.

Step 3: Redistribution of MP shares from residual streams: Step 3 applies when (i) at least one output stream k is a residual stream with $r_k > 0$, and (ii) at least one materially recycled product output exists. For each residual stream k, the MP share MP_k determined in Step 2 is redistributed to the materially recycled product outputs j of the same process in proportion to their recyclable masses. Product outputs with $r_j = 0$ receive no redistribution. If multiple residual streams exist, the total redistribution is summed across all residual streams. Eq. (7), $\mathcal{R}$ denotes the set of residual streams with $r_k > 0$. $\mathcal{P}$ is the set of materially recycled outputs, and $m_j r_j$ the recyclable mass of product output j.

$$\Delta \mathrm{MP}_j = \sum_{k \in \mathcal{R}} \mathrm{MP}_k \cdot \frac{m_j r_j}{\sum_{j' \in \mathcal{P}} m_{j'} r_{j'}}$$

7

The WT share of each residual stream ($WT_j = D_j = B_j \cdot (1 - r_j)$) remains attributed to the WT footprint. After redistribution in Step 3, the residual stream's burden is fully partitioned: its MP share accrues to the materially recycled products, and its WT share accrues to WT. This redistribution operationalises Requirement 5 (Section 2.2), attributing losses of recyclable material to the recyclate rather than to WT.

Process-internal attribution

Redistribution is always directed at the outputs of the same process that generated the residual stream, ensuring each process bears responsibility for its own recovery performance. Upstream sorting imperfections that route foreign recyclable material into a downstream input are already partially reflected in the upstream process's allocation via the composition-dependent r_k values; at the downstream process, the operator holds the last actionable opportunity to recover this material. The rationale for this rule and its implications relative to material-specific cross-process attribution are illustrated using the case-study data in Section 4.3 and discussed in the SI A-5.

Application to standalone WtE

For a WtE system receiving a single waste input, Step 3 does not apply, as no materially recycled product output exists to which an MP share could be redistributed; the resulting disposal share is attributed to WT directly via Step 2 and, where applicable, further attributed across multiple generating processes in Step 4.

Step 4: *Attribution of downstream treatment burdens from recycling residuals*: Residual streams from sorting or recycling processes are typically routed to downstream treatment, most commonly WtE or landfill. The burdens arising from this downstream treatment represent the environmental cost of the residual stream that the generating process could not avoid; Steps 4a–4c attribute this burden back to the generating process (numerical illustration in Section 2.4 and Annex B-1.5).

Step 4a: Partitioning of downstream facility burdens depends on the type of downstream facility:

Application to WtE

Where a WtE treatment unit receives residual streams from multiple generating processes, the exergy-based procedure of Section 2.3.1 partitions the observed burden between EP and a facility-level disposal share; the EP share is assigned to the recovered energy products, while the disposal share represents the burden attributable to WT rather than EP and is subsequently attributed to the residual-stream-generating processes in Step 4b. Stream-specific LHV values are not used to allocate the total WtE burden to residual input streams; they are used only in Step 4b to attribute the facility-level disposal share.

Application to landfill or incineration without energy recovery

No EP exists. The full facility burden constitutes the disposal share, which is attributed entirely to the generating processes in Step 4b.

Step 4b: Attribution of the disposal share to generating processes: When a downstream treatment facility receives residual streams from multiple generating processes i, the disposal burden attributed to each process, D_i, is calculated in proportion to the LHV-weighted mass of its residual input relative to that of all other generating processes i'. Here, D_{total} is the total disposal share of the downstream treatment facility determined in Step 4a, and $m_{k(i),res}$ and $LHV_{k(i)}$ denote the mass and LHV, respectively, of the residual stream generated by process i via Eq. (8):

$$D_i = D_{Total} \cdot \frac{m_{k(i),\mathrm{res}} \cdot LHV_{k(i)}}{\sum_{i'} m_{k(i'),\mathrm{res}} \cdot LHV_{k(i')}}$$

8

Step 4c: *Application of Steps 2 and 3 to the attributed disposal share*: Once attributed to the generating process, D_i is treated as an additional process burden on that process's residual stream. It is split into an MP component ($MP_{D,i}$) and a WT component ($WT_{D,i}$) based on the composition of that residual stream, using r_k (the recyclable-material share of residual stream k, generated by process i) via Eqs. (9) and (10):

$$MP_{D,i} = r_j * D_i$$

9

$$WT_{D,i} = (1 - r_j) * D_i$$

10

$MP_{D,i}$ is then redistributed to the materially recycled outputs of the generating process according to Step 3. $WT_{D,i}$ is attributed to the WT footprint. Since the ambition of the allocation framework is to allocate at unit-process level, this is not cross-process allocation in the sense of transferring burdens between products of different processes. It is the standard LCA practice of attributing downstream waste-management burdens to the process that generates the waste: the generating process bears the consequences of its residual stream's existence, including downstream treatment costs, which is consistent with the polluter-pays principle.

A formal notation for the complete allocation of any generic unit process is provided in the SI A-6.1. The summation rule holds by construction for every unit process, ensuring that no burden is lost or double-counted (the formal proof is provided in the SI A-6.2).

Note on collection burdens

Collection remains a physically distinct unit process. However, where it transfers a single mixed material stream without separating or materially transforming it, its burdens may be carried forward and jointly allocated at the first downstream process generating multiple material outputs. In the numerical example, collection burdens are therefore combined with sorting burdens and allocated to the sorting fractions using their fraction-specific $r_k$values (Requirement 3). This avoids applying an aggregate r_k to the mixed collection stream.

The allocation framework is modular

Recycling-only applications without WtE require only Steps 1–3. WtE applications require an analogous procedure for energy products, but without step 3. The full four-step procedure applies when both functions are combined in a recycling chain with downstream WtE treatment. By construction, the four-step procedure exhaustively partitions the total burden within the defined system boundary across MP, WT, and EP; a formal proof of the summation rule is provided in the SI A-6. In line with the interpretation of the polluter-pays principle adopted here, fully recyclable material carries no WT burden associated with non-recyclable content, whereas fully non-recyclable material is assigned entirely to WT. Partially recyclable material is partitioned according to its recyclable-material share, while burdens associated with losses of recyclable material are assigned to MP.

2.4 Numerical example

We illustrate the function-based allocation approach on a simplified two-stage recycling chain. The system processes a fictitious waste stream containing two recyclable materials (material A and material B), as well as co-collected non-recyclable material. For simplicity, all recyclable items of materials A and B are treated as homogeneous Class A articles ($R_a = 1$), and all non-recyclable items as fully non-recyclable Class C articles ($R_a = 0$). Real-world applications would differentiate further within each material class, capturing the recyclability of Class B articles.

Environmental impacts are expressed in a single generic indicator "Points" (Pt). The absolute values are arbitrary. Only relative differences and the internal consistency of the allocation are relevant. Practical applications shall use established life cycle impact assessment methods. The example is intentionally stylised to isolate the structural properties of the allocation framework from empirical uncertainty and reduce complexity of recycling systems and impact assessment. The relevant validation criterion is preservation of the summation rule and correct attribution across all paths and process stages. Sensitivity analyses covering three parametric scenarios (S1: WtE exergy factor; S2: article-level recyclability classification; and S3: assumed recyclable-material shares of residual streams) and two methodological scenarios (S4: normative residual-loss attribution versus a zero-recovery allocation variant; and S5: mass-proportional versus intensity-weighted Step 1 allocation) are provided in the SI C.

The system boundary covers (i) collection and sorting of 1 000 kg of mixed waste into three fractions in a sorting plant, (ii) mechanical recycling of two recyclable fractions at separate recyclers, and (iii) WtE treatment of all residual streams. Figure 2 shows the system boundary diagram.

The starting point is the collection of 1,000 kg mixed waste with the composition shown in Table 1 that is sorted into the three exemplary fractions: an A-rich F1 fraction, a B-rich F2 fraction, and a residue fraction F3 that also contains materials A and B that could not be sorted into F1 and F2 due to system inefficiencies.

Table 1
Output fractions from the sorting plant

Fraction	Total mass (kg)	A (kg)	B (kg)	Non-recyclable (kg)	Destination
Total (Input)	1,000	350	330	320	-
F1 (A-rich)	300	280	10	10	Recycler A
F2 (B-rich)	400	20	310	70	Recycler B
F3 (residual)	300	50	10	240	WtE

Collection burdens are carried forward and jointly allocated at the sorting stage, consistent with the general treatment of single-stream upstream operations (Section 2.3.2). In line with common recycled-content conventions for waste inputs in attributional LCA, burdens from the previous product life cycle (e.g. production and use) are cut off at the point of collection and are not included within the system boundary (Wernet et al. 2016, Ekvall et al. 2020). The 'Non-recyclables' category comprises macro-scale foreign items as well as items made of the same base polymers as materials A and B but assigned a Class C recyclability factor (Section 2.3.1) due to their design.

The downstream processing of fractions F1, F2 and F3 is as follows: Fraction F1 (A-rich) is mechanically recycled without further cleaning/separation via grinding and regranulation at recycler A. The recycling of fraction F1 yields a single output of 300 kg, named *Recyclate A*, containing 280 kg of material A but also co-processed 10 kg of material B and 10 kg non-recyclable material. No residual stream is generated. This represents the special case of incorporating material beyond the target material A, as minor shares of material B and non-recyclable material are incorporated into the product. Fraction F2 (B-rich) undergoes a cleaning and separation step followed by granulation at recycler B. The process yields two output streams: 300 kg, named *Recyclate B* (290 kg of material B plus 10 kg of material A) and 100 kg residual stream R1 (10 kg of material A, 20 kg of material B and 70 kg non-recyclables).

The sorting residual F3 (300 kg) and the recycling residual R1 (100 kg) are both routed to a WtE plant. In practice, residual streams separated along the recycling path, such as F3 and R1, can be treated in separate WtE facilities or co-treated in a common facility. Where stream-specific treatment inventories and energy-output data are available, the WtE allocation can be applied separately to the respective treatment units. For simplicity, F3 and R1 are assumed here to be co-treated in one WtE facility with an average total burden of 1.75 Pt/kg residual input. The WtE facility burden includes treatment of solid combustion residues; dedicated metal recovery from bottom ash is not modelled (Section 4.3). The resulting disposal share is attributed to F3 and R1 in proportion to their LHV-weighted masses. The WtE plant produces electricity and heat with an overall exergy factor $f_{\mathrm{ex}} = 0.28$ and an exergy ratio of

$\alpha_{\text{elec}}/\alpha_{\text{heat}} = 71.4/28.6$ between the two energy products. The LHV of the two residual streams are LHV_{F3} = 15 MJ/kg and LHV_{R1} = 25 MJ/kg, reflecting the higher polymer concentration in R1. All process burdens (fictitious but plausible values) are shown in Table 2.

Table 2
Process burdens [Pt] for the example

Process stage	Burden [Pt]	[Pt/kg_{input}]
Collection and sorting of 1,000 kg mixed waste	150	0.15
Recycling A: Grinding + regranulation	300	1.00
Recycling B: Cleaning + separation + granulation	340	0.85
WtE (400 kg total residuals - F3: 300 + R1: 100)	700	1.75
Total	1,490	

2.5 Validation of the function-based approach

To validate our approach, we compare it against two widely used recycled-content (RC) approaches. As in the function-based approach (Section 2.4), upstream burdens from the previous life cycle are cut off at the point of collection; the three approaches differ exclusively in how burdens arising within the recycling system are allocated.

In both RC approaches, allocation is applied between the marketable fractions (co-products) only (ISO 2006b, 4.3.4.2). Here, the sorting residual F3 and the recycling residual R1 are waste flows and hence not allocation recipients. The collection and sorting burden, including the downstream WtE treatment of F3, is therefore allocated by mass to the marketable outputs F1 and F2, and thus, to the recyclates; the burden of Recycler B, including the downstream treatment of R1, is assigned in full to Recyclate B. This implementation reflects one common way of applying the RC convention, under which burdens of the previous life cycle are cut off at collection and accrue to marketable outputs; an alternative implementation is discussed in SI B-2.6. In contrast to our function-based approach, neither RC approach as implemented here yields a WT footprint (WT = 0). The two RC approaches differ in the handling of multifunctionality in WtE units:

- RC/cut-off: All WtE burdens are attributed by mass to the recyclates A and B; recovered energy is provided burden-free (no EP footprint is generated; the cut-off is set after the residual streams are treated).
- RC/sub: As RC/cut-off, but substitution credits are applied for recovered energy (electricity and heat) from F3 and R1. The credits are attributed by mass to the marketable outputs of the previous unit process and are calculated as the energy generated from that stream via its LHV-weighted share of the WtE input and multiplied by the footprint of the market electricity and heat production (SI B-3.4).

The intention is not to provide a full product life cycle comparison, but to illustrate how allocation within the recycling chain affect the cradle-to-gate (CtG) footprints of recyclates and the visibility of the WT and EP footprints. Methods to allocation impacts between product life cycles, such as the 50/50 approach or the CFF, are not included in the numerical example, as they require system-boundary extension to include virgin production and final disposal impacts of the material after several life cycles (Ekvall et al. 2020). The resulting structural incomparability at the recycling-module boundary is discussed in Section 4.2.

3 Results

Applying the three approaches to the numerical example yields CtG recyclate footprints ranging from 1.23 to 3.00 Pt/kg, with the divergence driven by whether WT and EP are made explicit and whether system inefficiencies are distinguished from the treatment of non-recyclable material. Results are presented below; the complete step-by-step calculations, including all intermediate results, are documented in the SI B-1, B-2 and B-3.

Function-based allocation

Slightly more than half of the total system burden is assigned to the MP footprint (Table 3), and split unevenly between Recyclate A (1.23 Pt/kg) and Recyclate B (1.41 Pt/kg) due to compositional and efficiency differences between the two paths, both providing 300 kg of marketable recyclate. The footprint of Recyclate B is higher compared to A, especially as Recyclate B carries the burdens from the treatment of residue R1, which still consists of lost recyclable material (10 kg of A, 20 kg of B). Both recyclable materials are sorted into recycled B-rich fraction F2, but not preserved at Recycler B. Thus, the treatment burdens of the remaining recyclable material shares are referred to as system inefficiencies at recycler B and attributed to Recyclate B. The framework assigns approximately one third of the burdens to WT and explicitly provides a footprint for the recovered electricity and heat. After partitioning, WT receives a footprint of 0.50 Pt/kg of treated waste input, and EP is split into footprints for electricity (0.10 Pt/MJ) and heat (0.02 Pt/MJ). No burden is lost or double-counted; total allocated burdens equal the system total of 1,490.0 Pt. Table 3 summarizes the obtained results for the function-based approach.

Table 3
Results of the numerical illustration: Total burdens and footprints of the system under study for the recyclates A and B, the WT service as well as the EP heat and electricity

Process step	Recyclate A [Pt]	Recyclate B [Pt]	WT [Pt]	Electricity [Pt]	Heat [Pt]
Collection & sorting (internal process burden)	47.7	54.3	48.0	—	—
Collection & sorting (attributed WtE burden for sorting residual F3)	30.3	34.5	259.2	—	—
Recycler A (internal process burden from grinding and regranulation)	290.0	—	10.0	—	—
Recycler B (internal process burden from cleaning, separation, and granulation and redistributed impacts from step 3)	—	280.5	59.5	—	—
Recycler B (attributed WtE burden for recycling residual R1)	—	54.0	126.0	—	—
Energy product burdens from WtE plant	—	—	—	140.0	56.0
Total burdens per kg input waste [Pt]	**368.0**	**423.3**	**502.7**	**140.0**	**56.0**
Recyclate output (for MP) / waste input (for WT) [kg] / generated energy (for EP) [MJ]	300	300	1000	1400	2800
Footprint [Pt/kg] / [Pt / MJ]	**1.23**	**1.41**	**0.50**	**0.10**	**0.02**

Mass allocation at sorting and cut-off for recovered energy: Consistent with the RC/cut-off logic defined in Section 2.5, the combined collection and sorting burden and the downstream WtE treatment of the sorting residual F3 (525.0 Pt) are allocated by mass to the marketable sorting outputs F1 and F2, while the burden of Recycler B (340.0 Pt) as well as the downstream WtE treatment of the recycling residual R1 (175.0 Pt) are assigned in full to Recyclate B. Recovered energy is provided burden-free. The complete step-by-step calculations are documented in the SI B-2. The approach yields higher CtG footprint of 1.96 Pt/kg for Recyclate A and 3.00 Pt/kg for Recyclate B compared to the footprints of the function-based approach. The reason for this is that, in this case, the recycled materials bear the full burden of the non-recyclable materials collected alongside them. No WT and no EP footprints are generated (WT = 0; EP = 0): the entire system burden of 1,490 Pt is carried by 600 kg of recyclate.

Mass allocation and substitution credit for recovered energy: The RC/sub approach follows the same logic as RC/cut-off but applies substitution credits for the electricity and heat recovered from both residual streams (F3: 900 MJ electricity, 1,800 MJ heat; R1: 500 MJ and 1,000 MJ), using illustrative footprints of the displaced reference technologies (grid electricity: 0.12 Pt/MJ; natural-gas heat: 0.04 Pt/MJ). The

complete step-by-step calculation is documented in the SI B-3. Credits of − 180.0 Pt (resulting from F3) and − 100.0 Pt (resulting from R1) offset part of the WtE burdens assigned to the fractions F1/F2 and to Recyclate B, yielding CtG footprints of 1.71 Pt/kg for Recyclate A and 2.33 Pt/kg for Recyclate B. For the summation rule to hold, the credits are compensated by an assigning the credited burdens to the substituted energy: The total EP footprint is 280.0 Pt (0.12 Pt/MJ electricity, 0.04 Pt/MJ heat), representing the footprint of the displaced reference technologies rather than the causal WtE process footprint (0.10 and 0.02 Pt/MJ under function-based allocation). As in RC/cut-off, no waste-treatment footprint is generated (WT = 0).

Summary

Figure 3 displays a contribution analysis across the three approaches, providing the numerical basis for the discussion in Section 4.1. The structural reasons for the divergences are discussed in Section 4.1.

4 Discussion

By construction, the proposed allocation framework exhaustively partitions burdens across MP, WT and EP while preserving the summation rule, yielding attributional recyclate CtG footprints that are comparable to virgin-material footprints on a consistent system-boundary basis (subject to the substitutability caveat in Section 4.3), alongside explicit, comparable WT service and EP footprints.

4.1 Comparison of allocation approaches

The three approaches obtain substantially different CtG recyclate footprints despite identical underlying process burdens (Fig. 3 in Section 3), revealing how allocation assumptions drive results. Both established RC approaches produce systematically higher recyclate footprints (by 60% and 113% under RC/cut-off and by 39% and 65% under RC/sub, relative to the function-based results) because they treat the recyclates as the only allocation recipients within the recycling system, and thus, neglecting the WT function of the recycling system. The burden of separating and incinerating 310 kg of co-collected non-recyclable material, which the system removes from the waste stream as a service to the waste holder rather than to produce material, is thereby loaded onto 600 kg of recyclate. The resulting footprints are functionally non-equivalent to virgin-material footprints, mixing MP with the WT service that has no counterpart in primary production, and are therefore systematically unfavourable to secondary materials.

Substitution reduces but does not remove this effect here (RC/sub), because the credits offset only the burden associated with the energy actually recovered, not the burden associated with the 90 kg of recyclable material lost to the residual streams, which remains conflated with the burden of their non-recyclable content. Incinerating fossil-based material typically generates a larger burden in some impact categories than the credit obtainable from the recovered energy, so that substitution cannot offset the effect (Astrup et al. 2009), but the actual effect is indicator-specific. Preserving the summation rule under these credits further requires an equal, explicit burden shifted to the recovered energy (EP = 280.0

Pt); this compensating step, correctly applied in the illustration above but discussed in Section 4.2, is not always implemented in common practice.

Under the RC implementation applied here, neither RC approach reports a WT footprint. The WT service is not merely allocated incorrectly, it remains structurally invisible in this convention: the same burden that the function-based framework reports as 0.50 Pt/kg of collected waste is redistributed across the recyclates, where it can neither be attributed to the waste producer nor compared across recovery systems. This undermines the use of recyclate footprints as a stable basis for procurement decisions, recyclate certification and policy design, and it removes any footprint-based signal for design for recycling (Section 4.4).

4.2 Methodological consistency and positioning

The four-step procedure is proposed here as allocation based on physical relationships in the sense of ISO 14044 (ISO 2006b). It further satisfies its requirement that, where an output is partly co-product and partly waste, burdens be allocated to the co-product part only (ISO 2006b, 4.3.4.2): thus, the residual flows F3 and R1 are not allocation recipients, since the burden apportioned to them in Step 1 is fully re-partitioned in Steps 2 and 3, leaving no burden attached to a waste flow. WT is thus neither modelled as a waste output carrying burdens, nor are its burdens absorbed into the recyclate footprints. Instead, it is treated as a co-function of the process, with the collected waste input as its reference flow, which is an established construct in waste management LCAs (Weidema et al. 2013). Recognising this WT function alongside the material and energy products is structurally precluded under common RC implementation, which restricts allocation to marketable outputs and therefore leaves the recyclates as the only allocation recipients (Section 2.5; SI B-2.6).

All allocation keys are derived from measurable properties of the system under study: the recyclable material share r_k is calculated from measured stream composition and article-level recyclability factors (Section 2.3.1), providing a composition- and standard-based, rather than market-based, allocation key, although the classification thresholds themselves remain normative. The exergy factor $f_{ex,k}$ is derived from measured energy outputs and the chemical exergy of the WtE input and therefore provides a physical measure of energy-recovery performance. Exergy accounts for the different thermodynamic quality of electricity and heat, unlike LHV; the use of fex to demarcate the EP footprint from the WT footprint, however, is a measurement-based convention rather than a strict causal identity (Fruergaard and Astrup 2011; SI A-4.2.4). Economic allocation was not used because the resulting allocation would depend on market conditions rather than on the physical characteristics of the WtE process.

By assigning the recovered energy its own causal, exergy-derived footprint, the function-based procedure upholds the summation rule at the recycling-system level without relying on a compensating substitution mechanism or on assumptions about displaced technologies. This does not imply that substitution credits are inherently incompatible with the summation rule, also termed the *additivity criterion* by Majeau-Bettez et al. (2018), which Provost-Savard and Majeau-Bettez (2024, their Eq. 9) show to be preserved if the credited recyclates' footprints are offset by an equal, explicit burden on the recovered

energy. In the RC/sub scenario reported in Section 3, this condition causes a total EP footprint of 280.0 Pt. This value equals the footprint of the displaced reference technologies rather than a process-based footprint, so that identical physical energy flows carry a footprint that differs depending on the assumed counterfactual. Notably, computing these credits correctly requires additional external, region- and time-specific data (grid-mix and heat-market footprints) that introduces further uncertainty and reduce comparability across sites, echoing the market-dependence critique levelled against economic allocation in Section 2.1.

In common implementations of RC/sub, this compensating burden is typically omitted altogether: the WtE module receives a negative burden for avoided energy while the next product system using the recovered electricity and heat simultaneously report it as burden-free (Brander and Wylie 2011). This is precisely the combination that Provost-Savard and Majeau-Bettez (2024) identify as the source of double counting when substitution is applied without a compensating burden. A second, distinct practice problem persists even where the compensating burden is correctly assigned: consistent accounting requires that the credit is carried through the entire downstream value chain, including an equivalent adjustment at the displaced technology, so that the avoided burden is not claimed independently by more than one actor. In practice, responsibility for reporting the credit is frequently contested between the WtE operator, the energy off-taker, and downstream users of the recyclate, and the corresponding adjustment is rarely made consistently across all parties (Vadenbo et al. 2017). This is a question of stakeholder governance and cross-value-chain bookkeeping, not a structural flaw of substitution modelling. Other ISO-compatible implementations continue to prefer system expansion and substitution without necessarily reporting this compensating burden. The function-based approach avoids this dependency structurally, by deriving EP directly from the WtE process itself. The present paper does not claim to provide the uniquely ISO-compliant solution, but argues for one internally consistent option that prioritises full transparency of the underlying process burden.

The critique of mass allocation developed in Sections 1 and 2.1 targets its use as the sole allocation mechanism: mass alone cannot distinguish recyclable from non-recyclable content and therefore cannot make system inefficiencies visible, as demonstrated quantitatively in Sections 4.1 and 4.3 (e.g. the 153.3 Pt inefficiency burden that undifferentiated attribution would otherwise absorb into WT or leave with the recyclate indiscriminately). In Step 1, by contrast, mass is applied only to split a process's own burden across its own output streams of the same type (e.g. F1, F2, F3 at sorting) before any MP/WT split is made in Step 2; it plays no role in determining recyclability shares and is therefore not subject to this critique, for the reasons set out in Section 2.3.2.

Methods with fixed or rule-based parameters, such as the CFF, operate at a different level than the unit process level (life cycle split) and require system-boundary extension to external virgin-production and disposal data from other life cycles. They can therefore neither report WT/EP footprints nor produce recyclate footprints comparable at the recycling-module boundary. A meaningful numerical comparison within the recycling-module boundary is structurally impossible, which is itself an argument for function-based allocation to be used, especially for benchmarking C2G footprints.

4.3 Framework properties and limitations

The structural results presented in Section 3 emerge directly from the framework's design. Building on the concept of functional separation and exergy-based WtE allocation, it integrates these elements consistently at unit-process level and adds two complementary mechanisms that render system inefficiencies explicitly visible: the process-internal redistribution of MP shares from residual outputs (Step 3), and the attribution of downstream WtE treatment burdens back to the generating process (Step 4), to which the Step 3 redistribution logic is subsequently applied. The procedure preserves the summation rule: every burden is allocated exactly once to MP, WT or EP, with no burden lost or double-counted across functions or process stages. The numerical results illustrate this concretely: the 60 kg of recyclable material lost at the sorting stage and the 30 kg lost at Recycler B generate a combined MP burden of 153.3 Pt, of which 118.8 Pt (77%) originates from downstream WtE treatment attributed via Step 4 and 34.5 Pt (23%) from the internal Step 3 redistribution, that is transparently assigned to the respective recyclates rather than distributed across WT and EP.

The process-internal attribution rule (Step 3) deliberately avoids cross-process tracing of foreign material. In the case of Recycler B, rather than attributing R1's foreign material-A content back to the sorting stage, the burden accrues to Recyclate B, as Recycler B held the final technically meaningful opportunity to recover it. Cross-process attribution would require system-wide compositional data that individual operators neither hold nor can reasonably obtain. The process-internal rule is methodologically consistent and practically implementable (see also SI A-5). The co-processing case at Recycler A illustrates a related benefit: because no residual stream is generated, the co-processed non-recyclable content triggers no downstream WtE treatment burden, unlike R1's residual at Recycler B.

Step 1 uses mass as allocation key (Section 4.2), reflecting the assumption that each kilogram of output requires the same marginal process effort for handling, routing and physical separation. This holds well where process burdens are dominated by shared infrastructure steps such as conveyor systems and container routing. It may understate fraction-specific effort in processes with intensive optical sorting, for example dedicated near-infrared detection and ejection passes per fraction, where per-kilogram effort differs systematically between output streams. The sensitivity of recyclate footprints to this assumption is tested in the SI C (S5). Step 4b's use of LHV-weighted mass is likewise a pragmatic proxy: it reflects differences in chemical energy content but not other properties relevant to disposal burden, such as moisture or contaminant content (SI A-3.4.1).

The relative ranking of Recyclate A and B is sensitive to two normative choices examined in the SI: the recyclability classification of ambiguous (Class B) articles (S2) and the residual-loss attribution principle (S4), either of which can reverse the base-case ranking (SI C, Finding 5). The WtE exergy factor (S1) and the Step-1 allocation key (S5) instead affect mainly the EP/WT split and footprint magnitude, without reversing this ranking (Findings 2, 6). This sensitivity is distinct from, and considerably smaller than, the structural divergence between approaches in Section 4.1. Cross-recyclate comparisons should therefore

be interpreted with reference to the underlying classification and attribution choices, particularly where the observed difference is small.

The framework allocates burdens based on the mass share of recyclable material (r_k) and is designed to yield recyclate footprints comparable to virgin-material footprints at consistent system boundaries. Whether this comparison is meaningful in a given application, however, depends on the recyclate's actual substitutability, which the framework does not address: recyclates may differ from virgin material in mechanical performance, purity or processing behaviour, and comparability of footprints is a necessary but not sufficient condition for substitutability. Whether a recyclate qualifies as a functional equivalent to virgin material is therefore an application-specific judgement, based on the product's or process's specific quality requirements, that lies beyond the methodological scope of this framework.

The numerical example covers mechanical recycling and WtE as the two most prevalent process types in post-consumer recycling. Chemical recycling, including pyrolysis, solvolysis and dissolution processes, is not illustrated despite growing industrial relevance (Vollmer et al. 2020). The four-step procedure applies in principle: Steps 1 and 2 remain unchanged, and Step 3 can be applied once a process-specific r_k is defined for the feedstock output. Extending and validating the framework for chemical recycling pathways is identified as a priority for future work.

4.4 Implications for practice, policy and existing frameworks

For operators of sorting and recycling facilities, the approach offers a differentiated way to benchmark technologies, products and sites. Plants that handle more heterogeneous or contaminated inputs can demonstrate that part of their burden stems from providing additional WT service rather than from inefficiency in material recovery. This distinction is unavailable under RC approaches, where this burden is silently transferred to the recyclate and the waste-producing life cycle carries a zero end-of-life footprint irrespective of the recyclability. At the same time, attributing system inefficiencies to MP rather than to WT maintains an incentive to improve recovery performance. Scenario S4 illustrates the methodological consequence of suppressing this attribution (see SI C): the recyclate footprints decrease even though physical mass flows, residual-stream compositions and plant performance remain unchanged. S4 therefore represents an allocation counterfactual rather than a physical plant-yield scenario. The framework can support Extended Producer Responsibility (EPR) schemes, which define who has to finance or organise waste collection and treatment: while it does not prescribe a specific legal allocation of responsibilities, it operationalises the polluter-pays principle at unit-process level and can therefore serve as a physically grounded basis for such schemes.

For product manufacturers and procurers, recyclate footprints become more interpretable, as they predominantly represent MP and are therefore more meaningfully comparable to virgin-material footprints, supporting procurement decisions, eco-design and the setting of recyclability or recycled-content targets (subject to the classification- and attribution-sensitivity discussed in Section 4.3). For

regulators and standard setters, this improved comparability, together with the explicit WT footprint, provides building blocks for more coherent rules in PEF, EPD and sector-specific standards. Function-based CtG outputs can supply physically grounded inputs to existing frameworks such as the CFF, in particular for the recycling-process burden terms (Section 4.2; conceptual outline in SI D).

For LCA practitioners, the framework offers a narrower, more consistent modelling guideline than approaches relying on generic or market-based coefficients (Section 2.1), fostering comparability across studies. Its four steps require only data already available at unit-process level in current recycling practice (SI A-3), supporting practical implementability alongside methodological consistency.

5 Conclusion

This paper proposes a function-based allocation framework for attributional LCA of multifunctional recovery systems. By operationalising the polluter-pays principle at unit-process level, the four-step procedure exhaustively partitions all system burdens into material provision (MP), waste treatment (WT) and energy provision (EP) using physically grounded allocation keys derived from measurable properties of each process stage.

The numerical example demonstrates that the framework yields cradle-to-gate recyclate footprints that are functionally comparable to virgin-material footprints, as they predominantly reflect MP while burdens of treating non-recyclable material are transparently attributed to the WT service (see Section 4.3 on limitations for substitutability). System inefficiencies, such as losses of recyclable material at sorting and recycling stages, are made quantitatively visible through the redistribution mechanism in Step 3 and the attribution of downstream treatment burdens, creating a direct incentive to improve recovery yields and design for recyclability. The summation rule is preserved by construction across all process stages and functions, eliminating hidden double counting and rendering results independent of substitution assumptions. Compared to common practice combining mass allocation with substitution credits, the function-based approach avoids the summation-rule violations and cross-stakeholder bookkeeping problems associated with omitted or inconsistently applied compensating burdens (Section 4.2), and produces recyclate footprints that do not conflate MP and WT burdens.

The framework is compatible with ISO 14040/44 and can be integrated into existing frameworks without prescribing a specific legal allocation of responsibilities. It provides regulators, procurers and operators with a formally consistent, reproducible basis for benchmarking recycling technologies, setting recycled-content thresholds and designing footprint-based policy instruments.

Future work should validate the framework using real-world case studies with operational plant data as well as extend the framework to chemical recycling pathways, where output characterisation and yield variability require process-specific adaptations. Quality differences between recyclates and virgin materials could be integrated through quality-adjusted factors, particularly where downcycling effects are significant. Harmonised default data for recyclability factors and exergy parameters across major

waste streams and recycling technologies would further facilitate consistent implementation in LCA databases and industrial practice.

Declarations

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Competing Interests

Financial interests: Andreas Vogt is the Chief Executive Officer (CEO) of Vogt-Plastic GmbH, the company that commissioned and funded this study. No author received additional compensation specifically for this publication. Anna Kerps and Christina Galafton declare that they have no financial interests related to this work.

Non-financial interests: This work originated from a collaboration between Fraunhofer UMSICHT and Vogt-Plastic GmbH, in which Vogt-Plastic GmbH defined the general research objective based on practical challenges observed in the application of existing allocation methods for modelling recycling in LCA. Vogt-Plastic GmbH was given the opportunity to review the final version of the manuscript prior to submission. The final formulation of the methodological framework, the formal analysis and investigation of the numerical example as well as the interpretation of results were conducted independently by the authors at Fraunhofer UMSICHT and were not influenced by the interests of Vogt-Plastic GmbH. The authors declare no further competing interests.

Ethics approval / Consent

This article does not involve any studies with human participants or animals performed by any of the authors. Not applicable.

Consent to participate / Consent for publication: Not applicable.

Data availability statement

The numerical example presented in this study is fictitious and was constructed to illustrate the structural properties of the proposed allocation framework; it does not rely on externally collected or restricted research data. All input values, intermediate results, and step-by-step calculations underlying the numerical example are fully disclosed within the manuscript and its Supplementary Information (SI A–C), which are provided alongside this article.

Author contribution statement

Conceptualization: Anna Kerps, Andreas Vogt; *Methodology:* Anna Kerps, Christina Galafton; *Formal analysis and investigation:* Anna Kerps; *Writing – original draft preparation:* Anna Kerps; *Writing – review and editing:* Christina Galafton, Andreas Vogt; *Funding acquisition:* Anna Kerps; *Resources:* Andreas Vogt (provision of practice-based expertise on recycling-system configurations); *Supervision:* Anna Kerps.

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Footnotes

1. The determination of R_a values for Class B articles involves practitioner judgment and is subject to inter-standard variation. Requirements for the responsible party, documentation obligations and handling of conflicting standards are set out in the SI A-2.4; mandatory sensitivity testing for Class B values is specified in the SI A-2.5 and implemented in SI C, Scenario S2.

Figures

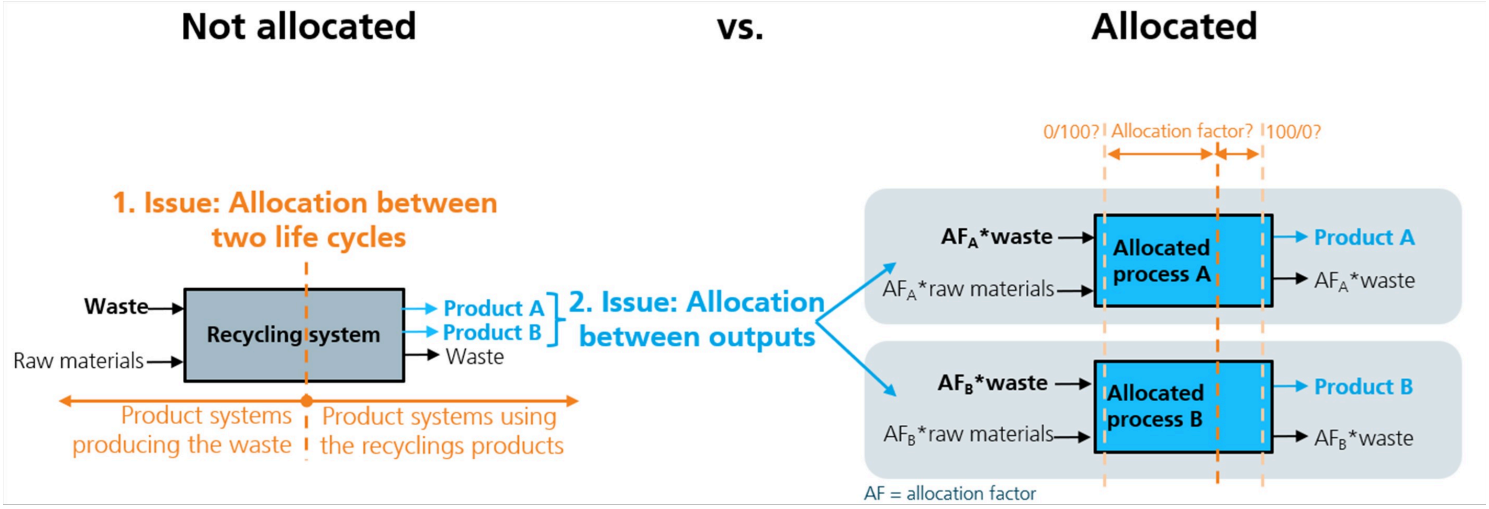


Figure 1

Two-dimensional allocation issues for recycling and recovery systems at two distinct levels: Between two life cycles (orange) and between several output flows (blue)

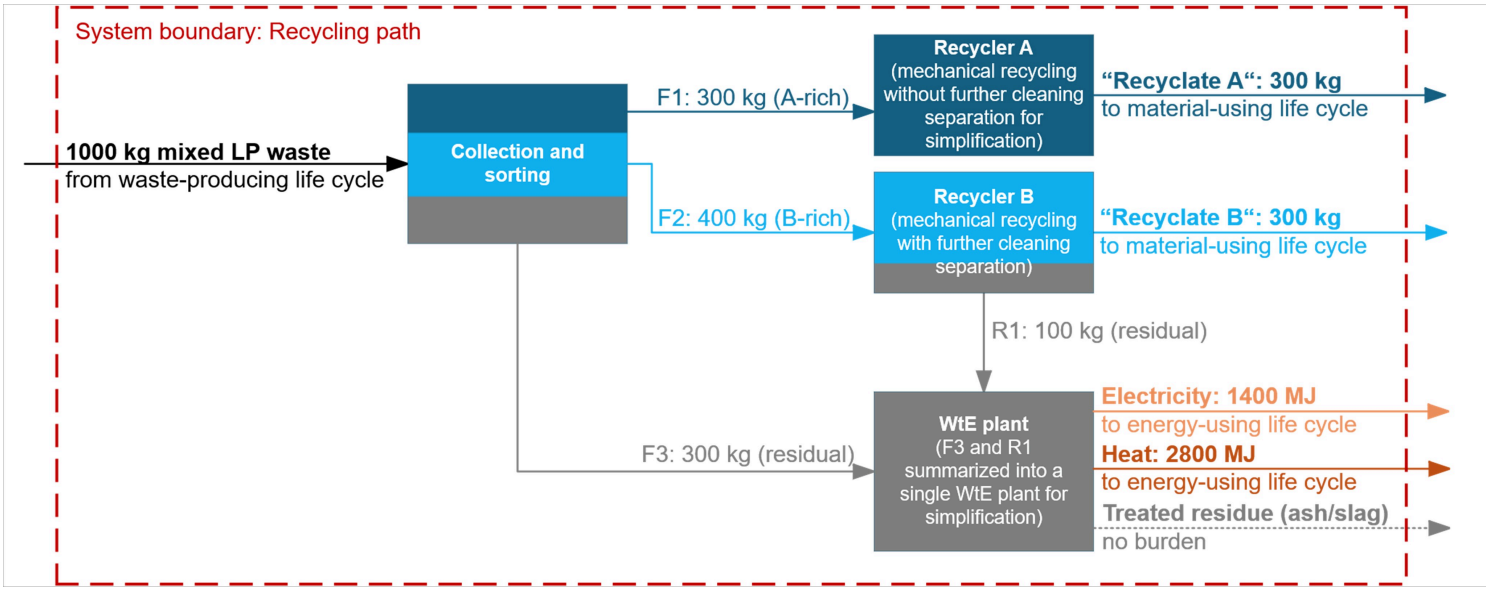


Figure 2

System boundary and mass flows of the case-study recycling system (input: 1,000 kg mixed lightweight-packaging waste); solid arrows indicate mass flows in kg or energy flows in MJ, box segments indicate allocated unit processes with colored material composition (dark blue material A, light blue material B, grey non-recyclable material), dashed grey arrow indicates the treated residue (no burden), dashed border indicates the system boundary

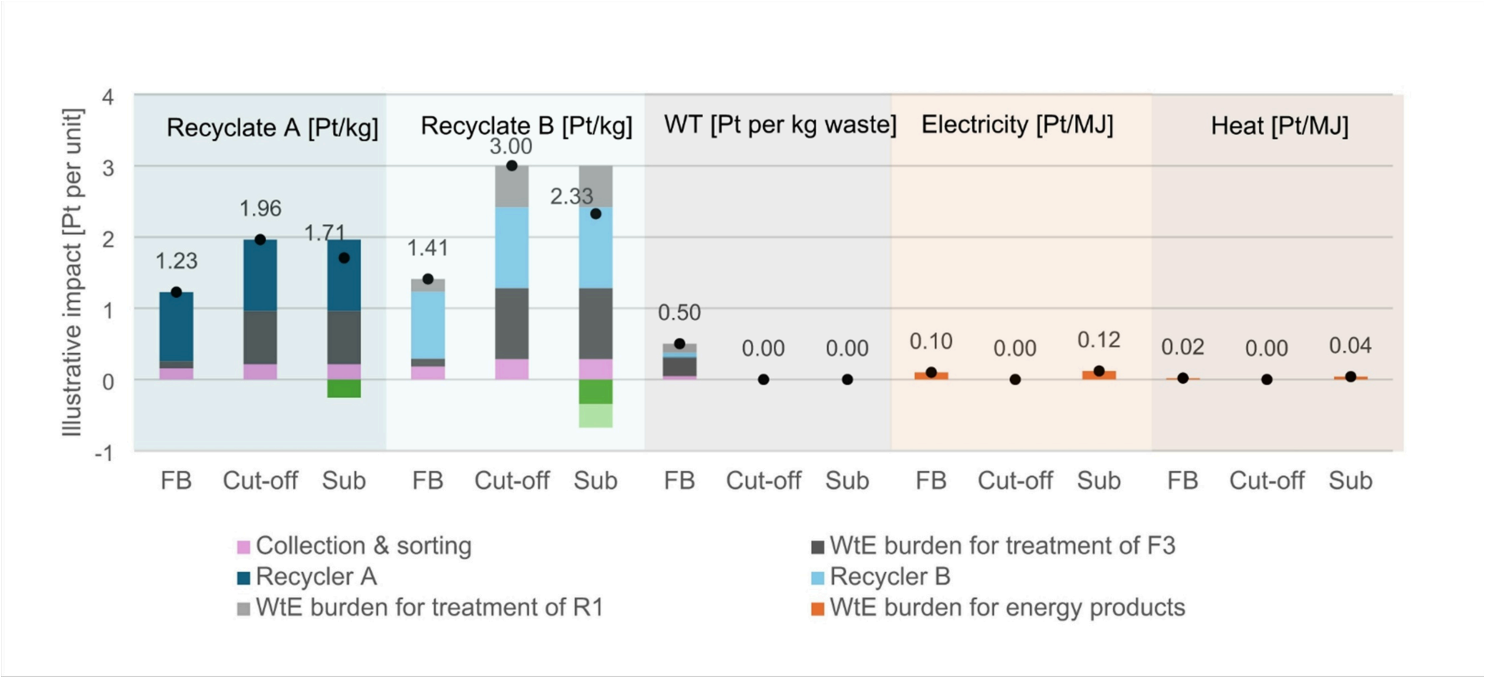


Figure 3

Contribution analysis of the three allocation approaches – function-based approach (FB), mass allocation at sorting and cut-off for recovered energy (Cut-off) and mass allocation at sorting and substitution for recovered energy (Sub) - for the case-study system

Supplementary Files

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