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Cite this: DOI: 10.1039/d5su00505a

# Chemical recycling: a new toolbox for materials recycling in industry and the application of the mass balance chain-of-custody approach

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Received 27th June 2025
Accepted 6th February 2026

DOI: 10.1039/d5su00505a

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The chemical sector continues to rely predominantly on fossil-based carbon sources, resulting in substantial waste generation throughout its value chains and contributing notably to greenhouse gas emissions. Increasing circularity in chemical value chains is therefore critical to meet climate and sustainability objectives (SDG 12, SDG 13), but progress is constrained by heterogeneous waste streams, limited recycling infrastructure, and unclear accounting rules for recycled feedstocks. This paper assesses the technical potential, economic implications and governance requirements of chemical recycling and mass balance chain-of-custody (CoC) models to scale the use of waste-derived feedstocks in integrated petrochemical systems. Using a literature review we characterise technology trade-offs and introduce a Cost Multiplier Index (CMI) to quantify how proportional *versus* non-proportional mass balance attribution affects off-taker costs. We also evaluate policy and Monitoring, Reporting, and Verification (MRV) implications considering current EU regulatory developments (*e.g.*, SUPD) and certification schemes (ISCC PLUS, REDcert$^2$). Key findings are: (1) no single recycling technology fits all waste types—mechanical recycling is most effective for clean single streams, while chemical and thermochemical routes are required for mixed or contaminated wastes; (2) mass balance CoC enables rapid scale-up of recycled feedstock use without expensive physical segregation, but attribution rules and credit losses materially affect downstream costs and commercial viability; (3) the CMI demonstrates strong economic sensitivity – strict proportional attribution can substantially increase off-taker costs compared with targeted non-proportional approaches; and (4) robust MRV, third-party verification and clearly specified regulatory rules (including treatment of fuel use) are essential to avoid double counting, limit leakage and mobilise investment. Well-designed mass balance frameworks, combined with technology-open policy and harmonised MRV, can unlock significant volumes of recycled feedstock and accelerate the chemical industry's transition to a more circular, low-carbon future. These outcomes support SDG 12 (responsible consumption and production) and SDG 13 (climate action).

**Sustainability spotlight**

Chemical recycling, an innovative technology, enables achieving high utilization rates of circular feedstock. We provide an evidence-based overview, supported by credible references and up-to-date performance comparisons with existing technologies. Our work follows a life cycle thinking approach, offering side-by-side evaluations of fossil-based and non-fossil-based feedstocks. By promoting the economic exploitation of circular (renewable and recycled) feedstocks, we directly contribute to responsible consumption and production (SDG 12) and climate action (SDG 13) goals. Our work promotes resource efficiency and reduces reliance on fossil feedstocks, aligning with the goals of sustainable industrialization (SDG 9), and fostering responsible consumption patterns. The mass balance approach ensures traceability and integrity in recycled content, enhancing transparency across the supply chain.

## 1 Introduction

The global economy remains largely linear, driving resource depletion, biodiversity loss, and pollution that threaten livelihoods worldwide.[1] Growing waste volumes, GHG emissions, and environmental contamination are among the most urgent consequences. Overexploitation of natural resources, especially reliance on fossil feedstocks, is a primary contributor to these problems. Addressing these challenges advances SDG 12 on sustainable consumption and production and SDG 13 on climate action, while reducing pressures on terrestrial ecosystems (SDG 15).

A systemic shift towards circularity goes beyond measures such as designing products for circularity, using materials more efficiently, and promoting repairing, refurbishing and reuse. It also includes recycling or substituting linear feedstock (*e.g.*,

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fossil-based) with waste-derived inputs. Despite all the use of these measures, waste volumes continue to rise and the share of circular carbon in products remains low. Today only about 9% of the carbon embedded in chemicals and derived materials globally is from circular sources.[2] By contrast, the steel sector has a more advanced recycling model, with 33% of steel production coming from recycled scrap annually.[3] Plastics illustrate both the benefits and the challenges of modern materials. During use, plastics can reduce food waste (through packaging), enable lightweight vehicles, and provide effective thermal insulation in buildings. Improved circularity in plastics contributes to SDG 11 (sustainable cities and communities) by reducing urban pollution. Yet, when mismanaged at end-of-life, plastics become a major environmental problem. Global recycling rates for plastics are alarmingly low (around 9% (ref. 4)), and most plastic waste is landfilled, incinerated, or leaks into the environment. Addressing this requires robust waste management systems to substantially increase the collection and recycling of plastic waste.

By substituting fossil feedstock with waste derived materials, we can not only reduce waste volumes but also increase recycled content in secondary products, which in most cases reduces greenhouse gas emissions *versus* energy recovery.[5]

Chemicals are essential to more than 90% of manufactured goods, underpinning everything from solar panels to pharmaceuticals.[6] For the chemical industry, capturing and reusing carbon is essential, as it serves as a fundamental building block for many compounds necessary for daily life. Carbon's unique ability to form strong bonds with itself and other atoms creates complex structures that are the foundation to products that sustain modern lifestyles.

To produce these products sustainably, we must align our actions with the circular economy principles that emphasize reducing the use of resources, reuse, recycling, and sustainable resource management. By adopting these principles, we can improve resource efficiency, reduce waste, and help secure a more sustainable future for industry and the planet by keeping carbon in the loop (Fig. 1).

For plastics that produce large volumes of clean, homogeneous waste (typically for many packaging applications), mechanical recycling is often the most efficient recycling solution. Mechanical processes are well-suited to such streams because they allow straightforward reprocessing into new plastic products. However, mechanical recycling can cause polymer degradation, which limits the range of applications for recycled material.

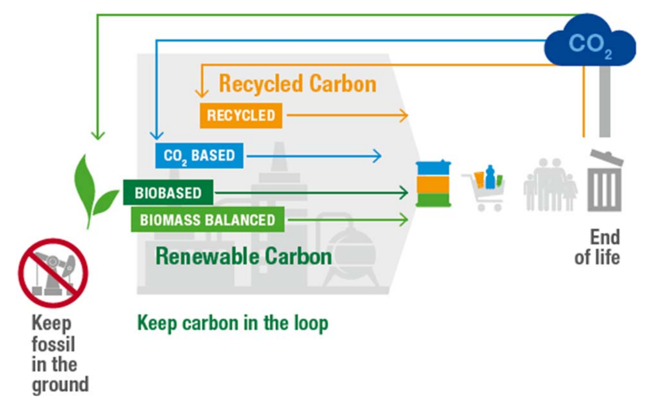

Fig. 1 Keeping carbon in the loop, *e.g.*, by recycled carbon sources, which are replacing fossil resources.

By contrast, chemical recycling is particularly valuable for mixed or contaminated plastic waste where mechanical recycling is often ineffective. Chemical recycling can depolymerize or otherwise convert complex waste streams into secondary raw materials with near-virgin quality, enabling reuse in higher value applications, where traditional mechanical methods fall short.

A strategic combination of mechanical and chemical recycling, using each method where it is most effective, can substantially increase overall recycling rates and support a more sustainable circular economy for plastics.[7]

Mechanical recycling converts waste into secondary raw materials by physically reprocessing the original material without changing its chemical structure. By repurposing waste, mechanical recycling reduces demand for virgin resources, conserves energy, and lowers environmental impact. This approach is particularly applicable to many packaging materials, most notably plastics, where clean, homogeneous waste streams allow efficient reprocessing into new products.[8] For plastics, mechanical recycling transforms plastic waste into secondary raw materials for new applications. The process typically involves several key steps: sorting, shredding/grinding, washing, re-granulation, and compounding. Each step plays an essential role in enabling a second or subsequent life for the material. Proper sorting and washing remove contaminants that would otherwise degrade performance, grinding and re-granulation restore a useable polymer feedstock, and compounding tailors the recycled polymer's properties for specific end-uses. Mechanical recycling is particularly suitable for large quantities of homogeneous plastic waste and is the preferred route when it is environmentally beneficial, technologically feasible, and economically viable. Each stage of the mechanical recycling relies on specific chemistries and technologies to produce safe, high-quality post-consumer recyclate (PCR). A key advantage is that mechanical recycling preserves the polymer's chemical structure and generally does not require highly specialized processing equipment.[9] This makes the approach easier to scale and deploy in many locations, supporting wider adoption of sustainable plastic waste management practices.

This paper reviews current chemical recycling technologies, summarizes their commercial development status, and evaluates their technical advantages and limitations. Integrating recycled intermediates into existing chemical production chains at scale requires a robust mass balance chain-of-custody (CoC) system; therefore, we analyse alternative mass balance approaches and assess their economic implications for multi-output petrochemical facilities.

Specifically, the paper pursues three objectives:

(1) Comparing recycling technologies—mechanical recycling, depolymerization/solvolysis, pyrolysis and gasification—across key criteria, including required feedstock quality,

primary energy demand, waste-to-plastics yield, and quality of the recycled products.

(2) Analysing CoC models (Identity-Preserved, Segregated, Controlled Blending, Mass balance, and Book & Claim), evaluating their traceability, verification needs, and practical applicability in integrated chemical value chains.

(3) Quantifying the economic impact of different mass balance attribution variants (*e.g.*, proportional *vs.* non-proportional) in multi-output production systems by developing a Cost Multiplier Index (CMI).

The paper concludes with policy recommendations and a roadmap to align mass balance accounting, MRV standards and certification schemes with EU regulatory developments to support cost-effective scaling of circular feedstocks.

## 2 Comparing different chemical recycling technologies

Chemical recycling technologies can help realise SDG 12 (sustainable production and consumption) and SDG 9 (build resilient infrastructure, promote sustainable industrialization, and foster innovation) by transforming waste into valuable inputs using new innovative technologies and installed infrastructure. While mechanical recycling is effective for many waste streams, chemical recycling complements it by treating mixed or contaminated plastic wastes that mechanical routes cannot process efficiently. Chemical recycling comprises diverse processes that convert plastic waste into secondary raw materials *via* chemical conversions.[8] Table 1 summarizes the main technology routes and examples of commercial players. Short-loop chemical-recycling methods include depolymerization and solvolysis. Industrial research and scale-up in this area are rapidly advancing.

Notable recent developments include BASF who announced commercialization of polyamide 6 (PA6) depolymerization (amide-bond cleavage to produce caprolactam monomer) targeting 2025, with a pilot plant recently launched in China.[10] Ineos and Agilyx are independently advancing polystyrene (PS) depolymerization and scaling up production.[11,12] Eastman is advancing the methanolysis of polyethylene terephthalate (PET), breaking ester bonds by a transesterification reaction with methanol. They have recently commissioned a commercial plant in Kingsport, US.[13] Over the past year several companies have increased R&D activity on solvolysis of polyurethane (PU) derived from mattresses and automotive components[14–16]

Thermochemical recycling breaks chemical bonds at elevated temperatures (typically >400 °C). The two main thermochemical routes, pyrolysis and gasification, are progressing towards commercial deployment. Pyrolysis, the currently most industry-driven chemical recycling method, heats plastic waste in the absence of oxygen to decompose polymers into smaller molecules, yielding products such as pyrolysis oil. It is particularly effective for waste streams dominated by polyolefins and can tolerate limited shares of other polymer types (*e.g.*, PS, PET, PA6). Pyrolysis oil can be co-processed in steam crackers to produce a broad range of carbon-based chemicals. However, because steam crackers require strict feedstock specifications, crude pyrolysis oil typically needs upgrading, often by hydrogenation, before it can be used as a steam-cracker feed. Heavier pyrolysis fractions are generally unsuitable for steam cracking and require alternative upgrading routes or processing.

For several years, BASF has been pioneering the use of pyrolysis oil derived from plastic waste, feedstock for which

Table 1 Recycling technologies (mechanical, depolymerization/solvolysis, pyrolysis, gasification) grouped against common polymer feedstocks (polyolefins, PET, PS, PA6, PU), with concise status/comments and representative references

| Recycling technology/ common plastic waste type | Mechanical | Depolymerization/ solvolysis | Pyrolysis | Gasification |
|---|---|---|---|---|
| PE, PP (polyolefines) (*e.g.*, sorted, relatively clean packaging waste (possible shape: films, containers)) | Common practice for single-stream, homogeneous waste (sorted packaging)[36] | Not typically applicable for polyolefins (no defined monomer product) | Applicable—yields oils for further processing[21] | Applicable, *e.g.*, municipal solid waste (MSW) to syngas/methanol pathways currently commercialized,[20] PE and PP are often part of MSW |
| PET (polyethylene terephthalate) (*e.g.*, bottles and other sorted PET streams) | Common practice for single-stream PET (bottle-to-bottle recycling)[21] | Applicable and commercial (recovery of monomers)[13] | Possible *via* MSW routes but PET is often minor in mixed inputs[22] | MSW to methanol currently commercialized,[20] PET is often part of MSW |
| PS (polystyrene) (*e.g.*, foam and rigid PS from fast-food packaging, insulation) | Possible for specific clean PS streams, though less common[23] | Feasible and being scaled[11,12] | Only in minor amounts in input streams[20] or use of a rubber waste[20] | MSW to methanol currently commercialized,[20] PS is often part of MSW |
| PA6 (polyamide 6/Nylon) (*e.g.*, selected waste streams (textiles, carpets, fishing nets, automotive)) | Possible for relatively clean, single-type streams[24] | Technically feasible and being commercialised[10] | Only in minor amounts in input streams[22] | MSW to methanol currently commercialized,[20] PA6 can be part of MSW |
| PU (polyurethane) (*e.g.*, mattresses, automotive interiors, insulation) | Partial practice[25] limited applicability due to mixed construction; rebonding/ reuse in insulation possible | Active R&D and some commercialization for PU solvolysis[14–16] | Only in minor amounts in input streams[22] | MSW to methanol currently commercialized,[20] PU can be part of MSW |

high-value processing options are still limited.[17] This initiative enables the production of virgin-grade chemical products from recycled feedstocks, including mixed plastic waste (*e.g.*, processed by Quantafuel[18]) and end-of-life tires (*e.g.*, *via* Pyrum[19]). ChemCycling® targets plastic waste that cannot be mechanically recycled for technological, economic, or environmental reasons. Examples include heavily contaminated plastics, mixed fractions that will not be sorted further, and scrap tires that currently lack viable recycling options.

Gasification provides an alternative route, converting nearly unsorted, and contaminated chemically complex mixed waste into syngas (a mixture of hydrogen and carbon monoxide). Syngas can be converted into platform chemicals such as methanol by hydrogenation.

Recently, Repsol passed its Final Investment Decision (FID) to build a new methanol plant in Tarragona, Spain.[20] Repsol intends to use methanol for sustainable maritime fuel and to support the production of recycled plastics.

For the technical differentiation of recycling technologies following criteria were selected (based on ref. 26):

- Required feedstock quality: specifies the characteristics of suitable waste feedstock, target polymer composition, tolerance to contaminants, and sensitivity to non-target polymers.

- Primary energy demand: the net primary energy required by the process, *i.e.*, energy extracted or captured from natural resources (crude oil, natural gas, coal, biomass) to run the recycling pathway.

- Waste-to-plastic yield: the fraction of input waste that is converted into useable plastic products, losses from non-eligible fractions or process inefficiencies reduce yield and typically increase associated greenhouse gas emissions.

- Quality of recycled products: the performance and specification of output materials (mechanical properties, purity, suitability for food/contact applications, *etc.*) compared against virgin equivalents and technical specification for the application.

Table 2 summarizes the most relevant technical criteria for several recycling technologies. In general, chemical recycling offers greater tolerance to contaminated feedstocks than mechanical recycling. Gasification is the most tolerant of highly impure waste streams, while mechanical recycling is preferred where clean, homogeneous waste is available. Mechanical recycling is superior concerning operational energy demand. For pyrolysis and gasification, a substantial share of the process energy can be supplied by energy recovery from the waste feedstock, which lowers the net primary energy demand in practice. Depolymerization processes typically require more external energy, but energy intensity varies widely across different depolymerization technologies. Higher yields are observed in mechanical recycling and in depolymerization/solvolysis methods when applied to appropriately sorted feedstocks. Chemical recycling processes can rebuild polymer chains or recover monomers, enabling the production of virgin-grade materials. Outputs from chemical recycling can therefore meet strict product specifications and, with proper certification and mass balance accounting, may be indistinguishable from products made from fossil feedstocks. By contrast, mechanical recycling often causes polymer degradation; mechanically

Table 2 Recycling technology comparison based on key technical criteria, including waste impurity tolerance, primary energy demand, waste-to-plastic yield, quality of recycled products

| Recycling technology | Mechanical | Depolymerization/ solvolysis | Pyrolysis | Gasification |
|---|---|---|---|---|
| Required feedstock quality | High: ≥90–98% target polymer (highly sorted streams)[27] | Moderate: ∼70–85% target polymer; benefits from sorted streams[27] | Moderate: ∼60–85% target/mixed polymers (polyolefins preferred)[27] | Low: accepts individual and complex mixed polymers and organic waste; highest impurity tolerance[27] |
| Primary energy demand | Low: ∼10 MJ $kg^{-1}$ (process energy only)[7] | Higher: >30 MJ $kg^{-1}$ (technology-dependent; solvent recovery energy significant)[7] | Moderate: ∼10 MJ $kg^{-1}$ effective (a portion supplied by feedstock energy recovery); electrified furnaces increase external energy needs if not using green electricity)[7,28] | Moderate: ∼10 MJ $kg^{-1}$ effective (energy partly provided by feedstock); depends on process electrification and conditioning[7] |
| Waste-to-plastic yield | High: up to 90–95% for well-sorted streams;[27] significant rejects for contaminated streams[28] | High: up to 90–97% for well-sorted input; yields vary with process and feedstock[27] | Variable: 49–53% for mixed plastic waste[27] | Variable: depends on waste composition and gasification technology; 34–54% for mixed plastic waste[27] |
| Quality of recycled products | Reprocessed polymer; degradation limits some applications; food-contact compliance not achievable for polyolefins[27] | Can rebuild polymer chains or recover monomers → virgin quality possible after purification[27] | Produces pyrolysis oil/intermediates; after upgrading feedstocks are suitable for chemical production to make virgin-grade products[27] | Produces syngas ($H_2$ + CO); after synthesis (*e.g.*, to methanol) can yield platform chemicals used to make virgin-grade products[27] |

recycled plastics are frequently blended with virgin material to meet performance and quality requirements. For example, closed-loop PET bottle recycling commonly requires the use of 25% virgin PET to ensure consistent product quality.[26]

There is no "one-size-fits-all" recycling technology, each route has distinct advantages and limitations (see Tables 1 and 2).

Mechanical recycling is the most established and besides depolymerization typically the most efficient option and should be preferred when clean, single plastic waste streams are available and the recycled material meets the required product quality. For example, mechanically recycled polyolefins cannot reliably meet food-contact standards and are therefore typically used in non-food applications – an outcome often described as downcycling. Downcycling can, in some cases, lead to higher greenhouse gas emissions than high-quality recycling that keeps plastics within the same application.[29]

Thermochemical recycling methods such as pyrolysis and gasification are particularly valuable for processing mixed or contaminated waste streams, as they are more tolerant of impurities and can handle a broader range of plastic types including mixed plastics. Among these, gasification is especially robust, tolerating even higher levels of impurities than pyrolysis. However, because both thermochemical processes break down plastics into smaller chemical building blocks compared to mechanical or depolymerization recycling, their overall waste-to-product yield is significantly lower, especially when the respective waste stream is incinerated as state of the art.

Depolymerization technologies, such as PET methanolysis and PA6 remonomerization typically require cleaner, more homogeneous feedstocks than gasification and are often tailored to specific polymer types. While these processes demand specialized methods depending on the plastic type, they can achieve high waste-to-plastic yields.

The future landscape will likely combine multiple recycling technologies to address the heterogeneous nature of plastic waste and to maximise overall circularity. Policy design, for example, mandates directing specific waste streams to particular recycling loops, and will influence which technologies scale commercially. Besides open loop solutions closed loops are also discussed like the use of automotive waste for the generation of secondary plastics for the use in automotive applications. In the future most likely a combination of different recycling technologies and the link to open and closed loop options will be applied to effectively address the complex challenges associated with carbon waste. Recent research suggests that combining mechanical and chemical recycling could achieve substantially higher overall recycling rates (in the order of ∼60%) while accounting for constrained energy resources, particularly in Europe.[7]

## 3 Understanding the different chain-of-custody models for a transparent and traceable supply chain

### 3.1 Basic chain-of-custody models and the use of chemical pathways

Chemically recycled feedstocks can be integrated into the chemical value chain using several Chain-of-Custody (CoC) models. These models provide frameworks for linking the sustainability attributes of recycled feedstocks to specific customer products. The appropriate CoC approach depends on the plant configuration and process integration, ranging from dedicated production lines to highly integrated, multi-output facilities, and on traceability requirements.

Selecting the right CoC model enables companies to balance operational efficiency, transparency and verification needs while allowing chemically recycled materials to be used across diverse product portfolios.

The different CoC models offer distinct levels of traceability and transparency regarding the flow of raw materials

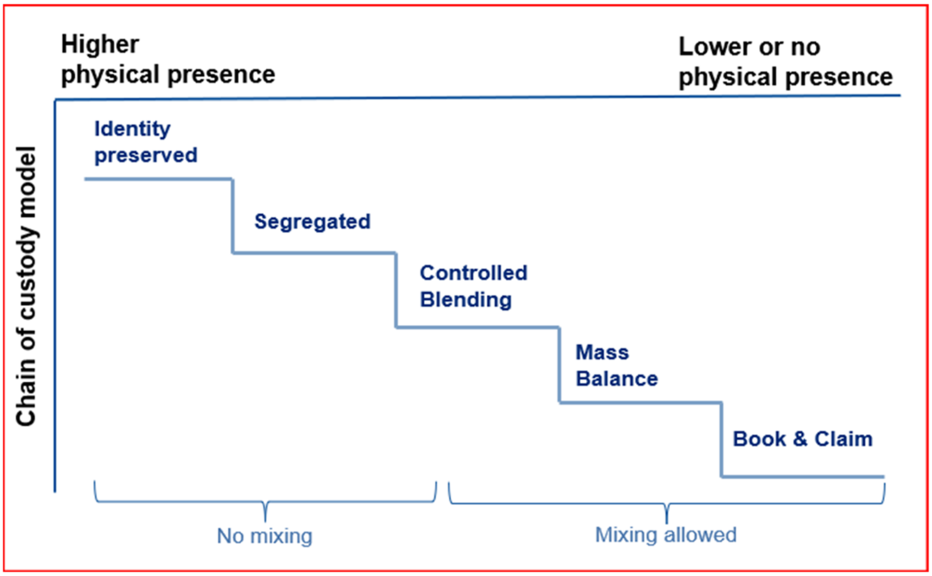

Fig. 2 Different Chain-of-Custody (CoC) methods, differentiated by physical presence in the target product, based on ISO 22095:2020.[30]

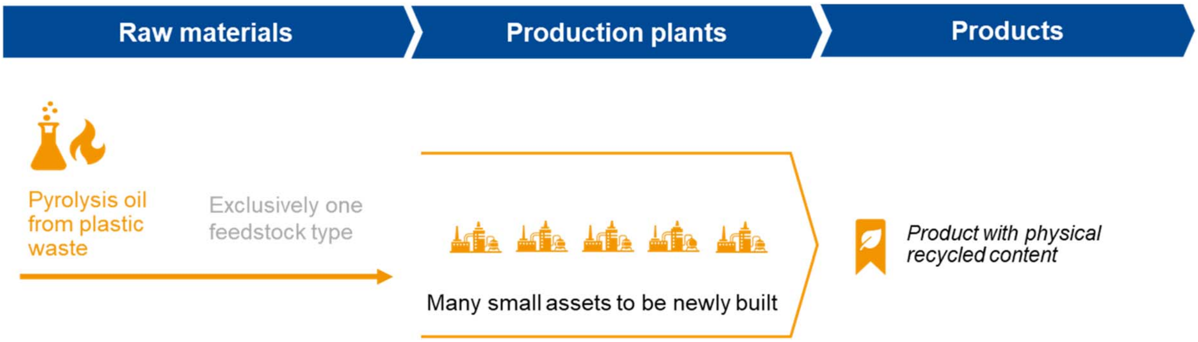

Fig. 3 Illustration of a separated value chain, where a recycled feedstock is processed by applying the identity preserved or segregated chain-of-custody model.

throughout the supply chain. ISO 22095:2020 (ref. 30) is a global standard that defines all CoC models and outlines the basic requirements for their implementation. The CoC models are differentiated by the physical presence of characteristics in the final product, as illustrated in Fig. 2. Each model is tailored to specific supply chain and production contexts, enabling companies to select the most appropriate framework for their needs.

The Identity Preserved (IP) CoC model is employed in systems where the identity and integrity of a specific product or material are maintained throughout the supply chain. This model is particularly relevant in industries such as food, agriculture, and specialty products. For example, in food value chains, the material flow is tracked from the farm or forest where raw materials are grown or harvested – through processing and manufacturing stages, all the way to the final product.

The segregated CoC model refers to a system in which materials or products from diverse sources or certified origins are kept separate throughout the supply chain. This separation maintains their distinct identity and ensures traceability. For renewable and fossil raw materials, the segregated CoC model requires complete separation along the linear value chain. For instance, a claim of 100% physical recycled content can be made if the recycled material is not mixed with fossil content at any point in the process (Fig. 3).

Controlled blending CoC model[26] ensures the traceability and integrity of materials that are blended in a controlled manner. This approach is commonly used in industries such as plastics, forestry, agriculture, and manufacturing, where multiple materials or components are combined to create a final product. Typical examples include bio-based products, where the biogenic component is chemically mixed with a non-biogenic component.

In complex production environments characterized by multi-input and multi-output set-ups, the most relevant attributional CoC model is the Mass Balance (MB) model, as shown in Fig. 4. The MB model allows users to simultaneously utilize a mix of recycled and conventional feedstocks within an interconnected system of production plants. The models allow attributing the sustainability characteristic from the recycled feedstock to specific outputs of the production system, following the attribution principles laid out in the standard. This flexibility enables the rapid and effective scaling of recycled carbon use without necessitating costly adaptations of production processes and value chains and focusing the investments on innovation for the feedstock itself.

The Book and Claim (B&C) CoC model offers a way to share sustainability attributes between companies without the need for the physical transport of energy or materials. This model is commonly applied in the energy sector, particularly for tracking energy through Energy Attribute Certificates (EAC).†[30] EAC such as Guarantees of Origin (GOs),‡ can be transferred and traded independently of the use of physical energy produced.[31] These certificates document specific characteristics of the energy generated, including its source (*e.g.*, wind, solar, coal), the location of generation, and the date when the production facility first came online.

By issuing EACs to producers, these sustainability attributes can be traded or transferred to consumers, allowing for a flexible and transparent market. Given the informational and economic value associated with EACs, it is crucial that they are accurate and securely managed to prevent issues such as double counting.

When comparing CoC models, an important distinction emerges: Identity Preserved (IP), segregated, and controlled blending CoC models deliver products with physical content of the specified plastic waste in the final product, enabling direct quantification of the material's attributes throughout the

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† Energy Attribute Certificates (EACs) are the vehicle used to carry energy attributes certified *via* an attribute tracking system. In Europe, the primary certificate used by attribute tracking systems is the Guarantee of Origin or "GO". In other locations, like the United States, the certificate used is the REC (Renewable Energy Certificate). An EAC is often bought, sold, and cancelled with prices determined by a supply and demand market.

‡ The Guarantee of Origin (GO or GoO) is the tracking certificate regulated by the EU Renewable Energy Directive 2023/2413.[32] The GoO is the carrier of energy attributes. The trade, cancelation, and use of GoOs are further governed by the European Standard CEN EN 16325,[33] as referenced in the RED III. In addition, the European Energy Certificate System (EECS) rules, maintained and enforced by the Association of Issuing Bodies (AIB), provide further rules that serve to harmonize and standardize GoO markets. GoO prices are determined by a voluntary supply and demand market.

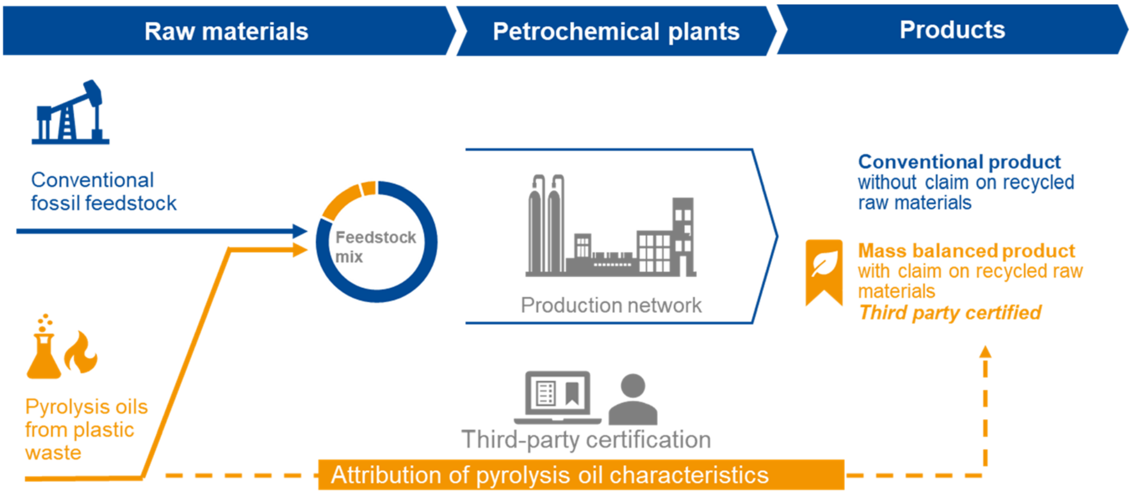

Fig. 4 The mass balance approach in chemical production. Coprocessing of pyrolysis oil with conventional fossil feedstock and attribution of characteristics (*e.g.*, chemically recycled carbon) to a product.

supply chain. In contrast, attributional models such as Mass Balance (MB) and Book and Claim (B&C) provide products with attributed content regarding the specified plastic waste. Therefore, these models rely on accounting methods and robust auditing and verification schemes to assign sustainability attributes to materials based on their use, rather than by following the physical flow of materials.[30]

The CoC models are implementation options for using recycled feedstocks in the chemical industry. Their value lies in enabling access to different feedstock streams and integrating those streams into production and supply chains, However, the sustainability performance of the final product is ultimately determined by the characteristics of the underlying feedstock and the conversion processes used, not by the choice of CoC model.

### 3.2 Mass balance approach: concepts and implementation in petrochemical value chains

For the petrochemical industry, the mass balance CoC is particularly relevant to scale up the use of waste derived feedstocks with large, integrated production chains that supply diverse end markets. Mass balance enables the gradual introduction of recycled intermediates into existing processes while allowing producers to attribute the sustainability characteristics of those inputs to specific customer products. Mass balance approaches therefore align with SDG 12 (responsible production) and SDG 9 (industry innovation), by enabling industrial-scale circularity to generate recycled content. This involves combining the growing adoption of innovative waste-derived feedstocks—such as pyrolysis oil and depolymerized monomers—while leveraging existing infrastructure. The approach supports the manufacture of a wide range of goods—from plastics and coatings to crop-protection agents and vitamins[34]—without requiring complete physical segregation of streams.

In other markets like the biofuel sector the mass balance approach is already well established. Both green methane (biomethane from renewable sources) and grey methane (natural gas from conventional sources) can coexist within the same network or pipeline grid. This approach allows for the mixing and blending of diverse sources of methane using a shared infrastructure. Consumers receive gas from this common network without differentiation between the various sources.

The mass balance model ensures that the total amount of renewable or green gas injected into the network matches the respective amount consumed by users, even though the specific molecules from renewable sources cannot be physically traced to the end consumer.

In the petrochemical industry, the mass balance model enables substitution of hydrocarbons from virgin fossil sources with hydrocarbons from non-fossil or recycled sources at the beginning of petrochemical value chain (input) and are attributed to the product (output) in such a manner that the input and the output match, *i.e.*, the overall balance of raw material attributes is maintained considering all process losses. Using actual production data for a product's process chain, the hydrocarbon feedstock demand can be calculated back to primary carbon sources – such as naphtha or natural gas – and then substituted by an adequate volume of alternative feedstock within petrochemical production systems.

Because petrochemical production is most efficient at large scale, parallel coprocessing of conventional and alternative feedstocks is essential. This paper focuses on alternative feedstocks from plastic waste (*e.g.*, pyrolysis oil from post- or pre-consumer waste streams). Other circular feedstocks, such as biogas or bio-naphtha can also be suitable within mass balance schemes.

For a proper mass balance accounting system, the following prerequisites must be fulfilled:

(1) Accurate calculation of all raw material inputs used in the actual production system.

(2) Accounting must explicitly include all process losses and gains (for example, fossil fuels, mainly natural gas, used for steam and electricity generation, fuel production, and general yield losses in chemical transformations).

(3) Equally important is the selection of a suitable alternative feedstock (*e.g.*, pyrolysis oil), which meets the required sustainability criteria and is suitable for attribution to the targeted sales product.

(4) Maintaining the overall balance or proportion of raw materials, ensuring input equals output, *via* predefined rules or calculations.

(5) The mathematical attribution of certified content of raw materials (input) to specific products (output).

Management of the credit balance to ensure that the alternative-feedstock account remains non-negative (zero or positive) throughout each balancing period.

The traceability§ along the value chain can be ensured by internal audits, according to a set of transparent rules and the third-party certification approach. The most common certification schemes in the chemical sector are the REDcert$^2$ scheme[35] and the ISCC PLUS.[36] These schemes are aligned to horizontal standards like ISO 22095:2020 and cover the use of renewable and recycled feedstocks, as well as renewable electricity instead of their fossil comparatives. Mass balance calculations are subject to regular third-party verification. Robust MRV and governance frameworks support SDG 12 and SDG 16 (peace, justice, and strong institutions) by ensuring transparency, accountability, and accuracy. The availability of transparent and accurate product claims, based on certificates, empowers consumers to make choices that align with their sustainability preferences. The following guidelines are outlined in the ISO 22095:2020:[30]

(1) Documentation and record-keeping: the standard emphasizes the importance of maintaining accurate and comprehensive documentation throughout considered system boundaries of different CoC models, including the production networks. This includes recording the origin, quantity, and characteristics of the input materials, with characteristics mixed with conventional inputs (blended process), the processes to produce an output, and the flow of characteristics, as well as any relevant information about sustainability or quality standards.

(2) Material identification: a clear identification of different raw materials is needed to maintain their traceability.

(3) Verification and certification: the standard encourages companies to obtain third-party certifications or execute audits, and to provide independent verification of their CoC systems.

(4) Training and competence: the personnel involved in the application of the different CoC models must have a solid understanding of the CoC requirements, proper handling, and storage of materials, and adhere to relevant procedures and documentation.

(5) Internal audits and management review: the standard recommends conducting regular internal audits to identify any non-conformities, implement corrective actions, and continuously improve the certification process.

### 3.3 Rolling average

In principle, there are two different mass balance accounting methods according to ISO 22095:2020.[30] The rolling average mass balance method is a specific approach to account for the mixture of inputs with and without specific characteristics when average claims are sufficient to fulfill the market and regulatory expectation. This method involves considering the average characteristics of inputs over a defined period, typically one year. In the context of recycled raw materials, the rolling average method allows for the co-processing of waste derived and virgin fossil raw materials. The average of waste derived inputs is determined over the defined booking period, and this average is then assigned to all outputs in the same output ratio, meaning all outputs from the production system receive the same average claim.

### 3.4 Credit mass balance method: non-proportional and proportional attribution

The mass balance method considers the flow of characteristics within the defined boundaries and ensures that the total quantity or value of the characteristics entering the system is balanced with the quantity or value of those leaving the system. Within the system boundaries, the sum of the physical input and the output mass flows must be identical.

The credit method mass balance, Fig. 5 and 6, is a specific approach that involves generating credits based on specific input characteristics, such as the recycled attribute of a feedstock. The credit method is applied when a link for a waste derived feedstock with a specific product in the production network is requested by the market or regulation. The credits are stored in a credit account. The credits stored in the credit account can be used to attribute the associated input characteristics to an output of the production process following the attribution rules from the standards. By utilizing the credit method mass balance companies can demonstrate that, *e.g.*, waste derived feedstocks have replaced conventional ones and are used in the production system for specific products. For chemical companies, the credit mass balance method is the key method that can help to enable the raw material transformation and reduce dependencies on virgin fossil feedstocks since the replacement can be tailored to specific products and markets and hence use the tailwind from market with early adopters or from regulated markets.

The use of credit mass balance models to determine attributed recycled content is still relatively recent. The European Commission has proposed a "fuel-use excluded" approach for future regulation of single-used plastics in beverage bottles other than PET.[37] ISCC PLUS has issued guidance on mass balance rules in its latest publication.[36]

ISO/DIS 13662:2025¶[38] provides important guidance on applying credit mass balance to multi-output processes. This

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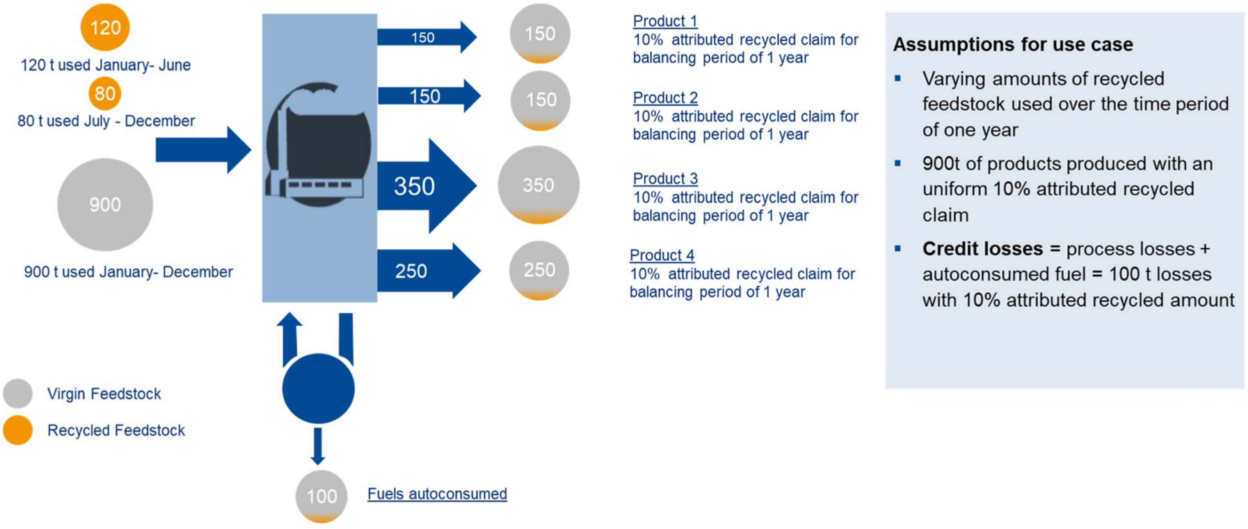
§ Traceability is defined according to ISO 22095:2020: ability to trace the history, application, location or source(s) of a material or product throughout the supply chain.[30]

¶ The ISO/FDIS 13662:2025 (ref. 38) is under development. A draft is being reviewed by the technical committee ISO TC 308. The final version of the public draft ISO/FDIS 13662:2025 is expected by the end of 2025 and may contain further editorial updates.



**Assumptions for use case**

- Varying amounts of recycled feedstock used over the time period of one year
- 900t of products produced with an uniform 10% attributed recycled claim
- **Credit losses** = process losses + autoconsumed fuel = 100 t losses with 10% attributed recycled amount

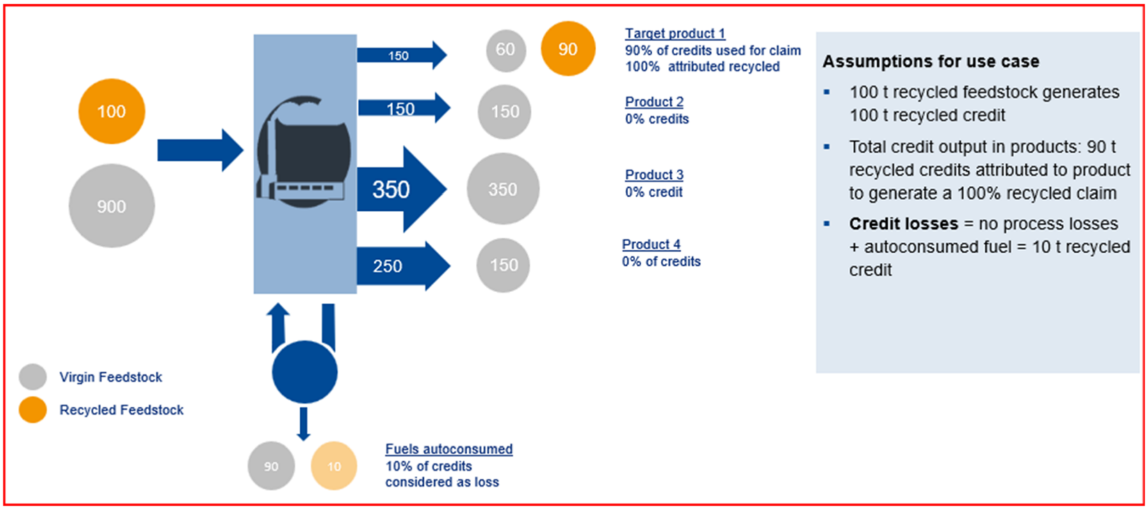
Fig. 5 Illustration of the rolling average mass balance CoC method with exemplary multi-output processes including resulting attributed recycled claims.

standard outlines two distinct methods for attributing recycled content: non-proportional attribution and proportional attribution. Below, we describe both attribution models as use cases for applying mass balance for introducing waste derived feedstocks in production chains. Both use cases will be explained and compared. Fig. 5 and 6 illustrate a production system in which part of the conventional virgin feedstock has been replaced by recycled feedstock. The recycled feedstock is attributed to one of the output products applying a credit mass balance chain-of-custody.

In the non-proportional attribution method, illustrated in Fig. 6, credits generated from specific input characteristics, such as recycled content, are attributed to specific products. For instance, Fig. 6 demonstrates how recycled credits are directly attributed to product 1, showcasing the benefits of this method in highlighting that recycled feedstocks have been fed into the production system based on demand for attributed recycled content for specific target products.

In contrast, the proportional attribution method, shown in Fig. 7, distributes the recycled characteristics according to the output yield of each product following the yields in the conventional production system. In this concept the tailored use of a recycled feedstock for a specific market is usually not possible, since the credits shall be used in all outputs typically reflecting products for diverse markets. In Fig. 7, you can see how recycled credits are proportionally distributed among all outputs based on their respective yields.

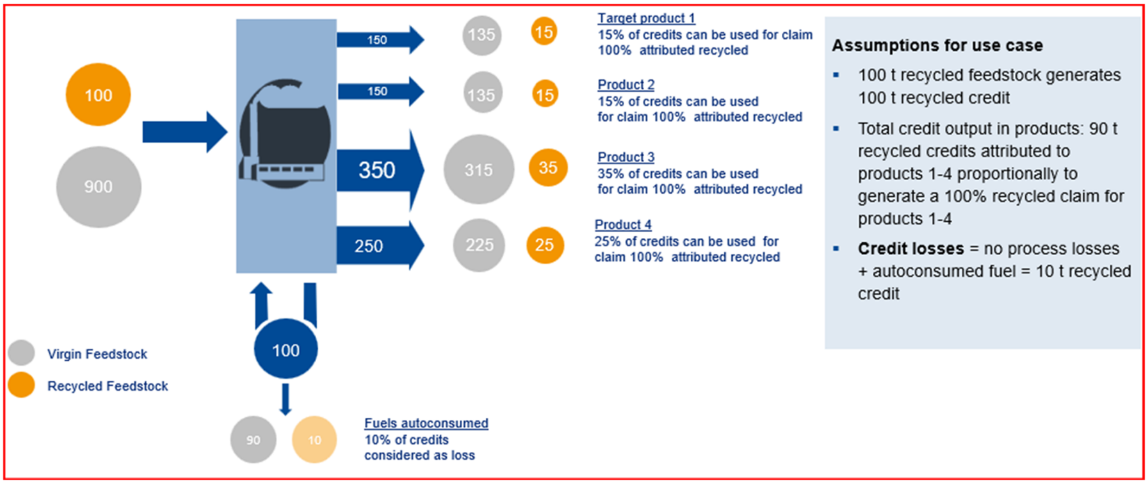
The non-proportional attribution model is currently prevalent in voluntary markets for materials. Given the existing market dynamics and the cost differentials between renewable



**Assumptions for use case**

- 100 t recycled feedstock generates 100 t recycled credit
- Total credit output in products: 90 t recycled credits attributed to product to generate a 100% recycled claim
- **Credit losses** = no process losses + autoconsumed fuel = 10 t recycled credit

Fig. 6 Illustration of the non-proportional attribution of the recycled characteristics of credit MB CoC for exemplary multi-output processes within a system boundary including the description of credit losses.



**Assumptions for use case**

- 100 t recycled feedstock generates 100 t recycled credit
- Total credit output in products: 90 t recycled credits attributed to products 1-4 proportionally to generate a 100% recycled claim for products 1-4
- **Credit losses** = no process losses + autoconsumed fuel = 10 t recycled credit

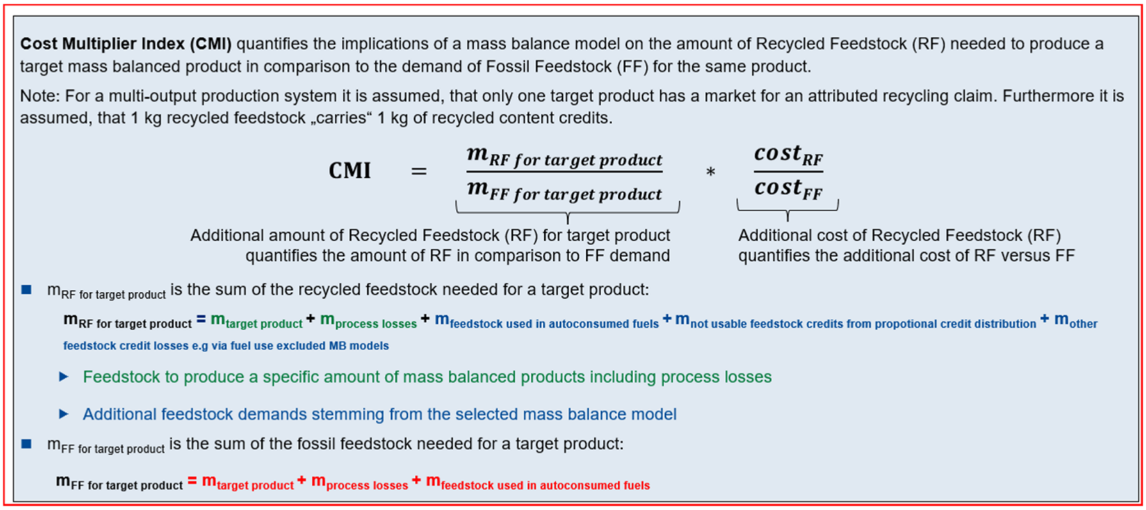
Fig. 7 Illustration of the proportional attribution of the recycled characteristics of credit MB CoC for exemplary multi-output processes within a system boundary incl. the description of credit losses.

feedstocks and their fossil counterparts, this model helps mitigate price disparities. Conversely, some regulated markets[32] require proportional attribution.

## 4 Economic comparisons of different mass balance variants with a fossil comparative

The mass balance chain-of-custody model is a crucial tool for implementing chemical recycling technologies within existing chemical value chains, allowing companies to leverage their cost-intensive infrastructure while increasing the share of waste derived feedstocks. This model facilitates the simultaneous use of recycled and fossil feedstock in the same processes, addressing market demands for circularity and helping to meet legislative quotas.

The economic impact of the use of different mass balance variants in multi-output systems as described in Fig. 6 and 7 can be extremely high. In the refinery and the petrochemical industry multi-output systems play a vital role, where several products are produced at the same time by a process. Examples in the refinery industry are fluidized catalytic cracking processes that ultimately furnish hydrocarbons for the chemical industry as well as products for the transportation fuel market. Examples in the petrochemical industry are steam crackers, where different hydrocarbons are produced using feedstocks such as naphtha. For comparing the economic impact of the application of different mass balance variants to multi-output systems we have developed the definition of a Cost Multiplier Index (CMI), which compares the costs *versus* 100% fossil production for the user of a specific mass balance approach. The CMI depends on the additional feedstock needed due to the higher costs of the recycled feedstock and the credit losses along the



**Cost Multiplier Index (CMI)** quantifies the implications of a mass balance model on the amount of Recycled Feedstock (RF) needed to produce a target mass balanced product in comparison to the demand of Fossil Feedstock (FF) for the same product.

Note: For a multi-output production system it is assumed, that only one target product has a market for an attributed recycling claim. Furthermore it is assumed, that 1 kg recycled feedstock „carries“ 1 kg of recycled content credits.

$$\mathrm{CMI} = \underbrace{\frac{m_{RF\ for\ target\ product}}{m_{FF\ for\ target\ product}}}_{\text{Additional amount of Recycled Feedstock (RF) for target product quantifies the amount of RF in comparison to FF demand}} * \underbrace{\frac{cost_{RF}}{cost_{FF}}}_{\text{Additional cost of Recycled Feedstock (RF) quantifies the additional cost of RF versus FF}}$$

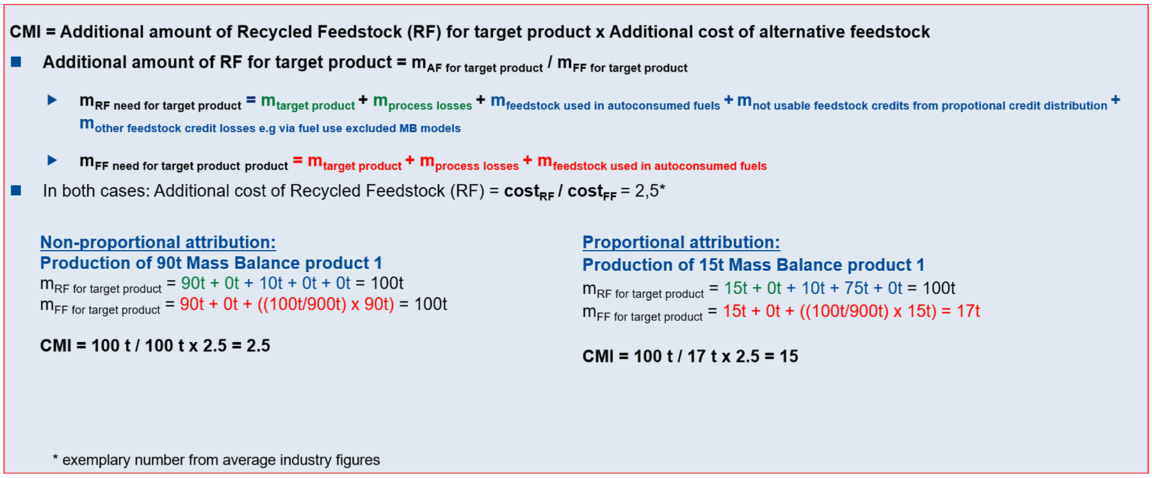
- $m_{\text{RF for target product}}$ is the sum of the recycled feedstock needed for a target product:

  $m_{\text{RF for target product}} = m_{\text{target product}} + m_{\text{process losses}} + m_{\text{feedstock used in autoconsumed fuels}} + m_{\text{not usable feedstock credits from propotional credit distribution}} + m_{\text{other feedstock credit losses e.g via fuel use excluded MB models}}$

  - Feedstock to produce a specific amount of mass balanced products including process losses
  - Additional feedstock demands stemming from the selected mass balance model
- $m_{\text{FF for target product}}$ is the sum of the fossil feedstock needed for a target product:

  $m_{\text{FF for target product}} = m_{\text{target product}} + m_{\text{process losses}} + m_{\text{feedstock used in autoconsumed fuels}}$

Fig. 8 CMI definition for the comparison of the costs for the use of recycled feedstocks in multi-output systems considering auto-consumption of fuel. The methodology and key variables used in the calculation are detailed, demonstrating how the CMI reflects the economic implications of utilizing recycled feedstocks alongside fossil feedstocks in a multi-output process.



**CMI = Additional amount of Recycled Feedstock (RF) for target product x Additional cost of alternative feedstock**

- **Additional amount of RF for target product =** $\mathbf{m_{\text{AF for target product}} / m_{\text{FF for target product}}}$
  - $m_{\text{RF need for target product}} = m_{\text{target product}} + m_{\text{process losses}} + m_{\text{feedstock used in autoconsumed fuels}} + m_{\text{not usable feedstock credits from propotional credit distribution}} + m_{\text{other feedstock credit losses e.g via fuel use excluded MB models}}$
  - $m_{\text{FF need for target product product}} = m_{\text{target product}} + m_{\text{process losses}} + m_{\text{feedstock used in autoconsumed fuels}}$
- In both cases: Additional cost of Recycled Feedstock (RF) = $\mathbf{cost_{RF} / cost_{FF}}$ = 2,5*

**Non-proportional attribution:**
**Production of 90t Mass Balance product 1**
$m_{\text{RF for target product}}$ = 90t + 0t + 10t + 0t + 0t = 100t
$m_{\text{FF for target product}}$ = 90t + 0t + ((100t/900t) x 90t) = 100t

**CMI = 100 t / 100 t x 2.5 = 2.5**

**Proportional attribution:**
**Production of 15t Mass Balance product 1**
$m_{\text{RF for target product}}$ = 15t + 0t + 10t + 75t + 0t = 100t
$m_{\text{FF for target product}}$ = 15t + 0t + ((100t/900t) x 15t) = 17t

**CMI = 100 t / 17 t x 2.5 = 15**

* exemplary number from average industry figures

Fig. 9 CMI calculation for non-proportional and proportional attribution considering auto-consumption fuel as described in Fig. 6 and 7.

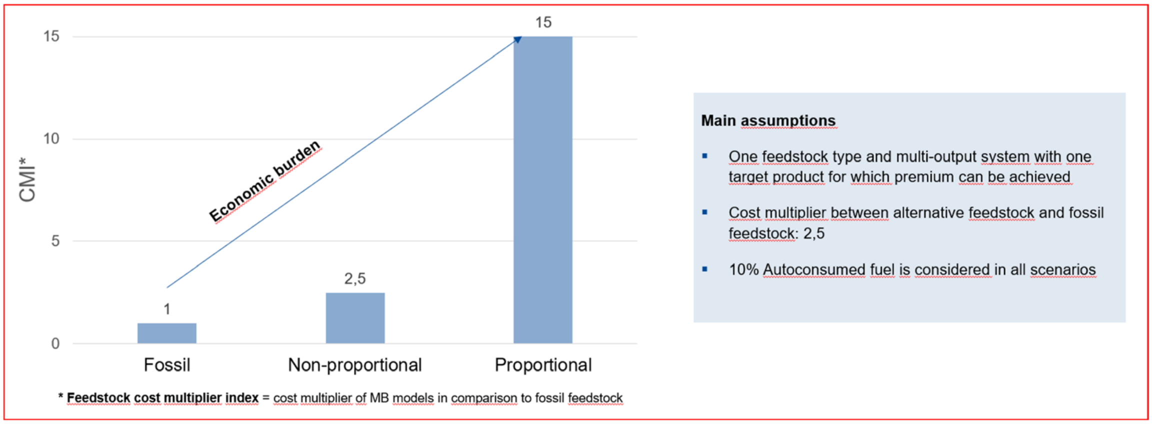
recycling pathway applying a mass balance variant. The loss calculation is focusing on the extra cost being opposed by the mass balance model, this means it goes beyond the perspective of process losses being described by the conversion factor of a mass balance product. For 100% fossil feedstock use, the CMI is equivalent to 1 as a baseline. In Fig. 8 the formula and general assumptions for the CMI calculation are summarized.

We have calculated the CMI for the use cases described in Fig. 6 and 7. The eligible recycled feedstocks for steam crackers are usually much more cost-intensive, and therefore we assumed an additional cost factor of 2.5 for Recycled Feedstock (RF, *e.g.*, pyrolysis oil) compared to Fossil Feedstock (FF, *e.g.*, naphtha).

Today the petrochemical industry relies on more than 95% fossil feedstock. As an assumption for the purpose of demonstrating the calculation we assumed that there is a market request for one output in a multi-output system. Consequently, we assumed as a simplified scenario that in the cases described in Fig. 6 and 7 only product 1 has a market value, driven by factors such as recycled content quotas or market demand. The calculation for both use cases is illustrated in Fig. 9.

In Fig. 10, the results of the CMI calculation for non-proportional attribution and proportional attribution as described in Fig. 6 and 7 are compared with 100% virgin fossil production. The analysis reveals that, compared to the fossil pathway, companies face 15 times higher costs to produce product 1 with proportional attribution, while non-proportional attribution, considering auto-consumptive fuel has 2.5 higher costs. This reflects the high sensitivity of the application of different mass balance variants to multi-output systems.

The EU Commission is currently developing Fuel Use Excluded (FUE) mass balance rules for calculating recycled content in relation to the Single-Use Plastic Directive Implementing Act (SUPD ID). The intention to establish clear rules has gained widespread support by industry stakeholders who recognize the necessity of clear guidelines.[39] As the SUPD ID is still under discussion, the economic impact can only be estimated. The FUE rules are specific to the recycling legislation since they are intended to reflect a definition in the waste framework direction that excludes the processing into energy and fuel from the recycling definition. It is not clear today how the EU COM will address recycled content credit losses. The



* **Feedstock cost multiplier index** = cost multiplier of MB models in comparison to fossil feedstock

**Main assumptions**

- One feedstock type and multi-output system with one target product for which premium can be achieved
- Cost multiplier between alternative feedstock and fossil feedstock: 2,5
- 10% Autoconsumed fuel is considered in all scenarios

Fig. 10 Illustration of the economic impact of non-proportional and proportional attribution considering auto-consumption fuel as described in Fig. 6 and 7.

authors anticipated that the CMI could range from 2.5 to 15 for an FUE model developed by the EU COM. Our case studies described in Fig. 6 and 7 are illustrative and represent extreme situations that highlight the complexities of accounting for recycled content in various applications. It demonstrates the significant economic implications and challenges for implementing a meaningful and acceptable circularity model for the value chain with a mass balance model calling for high credit deductions.

## 5 The impact of policy in accelerating the transition to a sustainable future

Chemistry continues to be indispensable for modern life, and the successful transition of the chemical industry towards full circularity requires clear, predictable steps that can instill confidence among investors. The European Union is actively advancing a circular economy through new and forthcoming legislation that promotes recycled content, particularly in the context of chemical recycling. Clear regulatory signals help realize SDG 12 (responsible production and consumption) and can stimulate green jobs and economic growth consistent with SDG 8 (decent work and economic growth).

One significant piece of legislation is the recently published Packaging and Packaging Waste Regulation (PPWR), which establishes a 10% recycled content target for contact-sensitive non-PET applications for 2030. This target is particularly appealing for the recycled polyolefin packaging intended with food contact, which currently relies on chemical recycling. Among these methods, pyrolysis stands out as an effective technology, as it allows for the recycling of waste streams predominantly made up of polyolefins into new polyolefins. To calculate the recycled content accurately, a mass balance approach is essential since recycled pyrolysis oil is often blended with fossil feedstock. The specific mass balance rules in materials' legislation, however, are still under development by the EU Commission and are expected to be finalized by the end of 2026. However, only the specific rules implied will decide whether this model will truly be effective in creating an impactful tool for our circular economy.

The European Commission's proposed revision of the End-of-Life Vehicles Regulation (ELVR) foresees a recycled-plastic content target of about 20–25%, including partially closed-loop approaches. Such a requirement could create demand for chemical recycling routes for common automotive plastics (polyolefins, PA6 and PU). Automotive shredder residue (ASR) contains a broad mix of polymer types, making it a promising feedstock for gasification, which can handle highly mixed waste streams. Where sorting is technically and economically feasible, mechanical recycling and pyrolysis are attractive for the polyolefin fraction; remonomerisation is a potential route for PA6; and solvolysis offers a route for PU. These pathways remain under active R&D, and we expect notable progress in the near future.

## 6 Conclusion

The chemical industry is a pivotal force in driving innovation across various sectors. The transformation of the chemical industry towards defossilization and circularity requires a shift beyond the limitations of mechanical recycling, particularly when dealing with complex waste streams. In this context, chemical recycling emerges as a vital solution, offering new opportunities to recycle waste streams that are technically and economically unfeasible for mechanical recycling. The outputs from chemical recycling processes are of virgin-grade quality, ensuring that performance standards are met without compromise.

The implementation of a mass balance approach for recycled feedstock presents a promising strategy for fast and efficient uptake of the innovative waste derived feedstocks. This method leverages existing infrastructure, enabling the delivery of affordable products while maintaining high performance. To realize the full potential of circularity, it is crucial to utilize waste-based feedstock from chemical recycling effectively.

The various mass balance models can significantly influence the costs for off takers of recycled feedstock. This aspect is vital for lawmakers, such as the EU Commission, who are in the process of developing metrics for calculating recycled content. A technology-open approach that leverages mechanical, chemical, and thermochemical recycling, supported by transparent CoC and attribution rules, offers a pragmatic pathway to increase circular carbon in the chemical sector and advance SDG-relevant outcomes.

In summary, the acceptance of chemical recycling in regulation is crucial for the development of this highly innovative technology. Acknowledging the credit mass balance method is essential for scaling up chemical recycling initiatives. Adopting technology-open policies and harmonised mass balance accounting can accelerate progress on SDG 12, SDG 13 and SDG 9, delivering climate, industrial and resource-efficiency benefits. By integrating these approaches, the chemical industry can play a key role in advancing circular production processes, ultimately conserving fossil resources.

## Conflicts of interest

The authors are all employed by BASF. There are no conflicts to be declared.

## Data availability

This study was carried out using publicly available data as summarized in the chapter "References". The data supporting the calculations described in this article have been included in the article.

## Acknowledgements

Many thanks to all the experts inside and outside of BASF for the discussions and the learnings around this exciting topic. We explicitly want to acknowledge the valuable feedback from our anonymous reviewers. We thank the editors for their excellent management of the submission process, and the opportunity to share our industry view. We hope, that this article will contribute to develop the topic further from different perspectives.

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