



Technical paper

‘Dual-use output’ issues for accounting recycled plastic content

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Summary

The draft Implementing Decision on recycled plastic content in SUP beverage bottles (“amendment to account for additional recycling technologies”, from February 2024, hereinafter referred to as "draft IA on recycled content") includes mass balance accounting methods for “additional types of recycling, including chemical recycling”, and a new concept called ‘dual-use outputs’ (defined as “outputs that can be reprocessed either into fuels or materials other than fuels”). Using a series of questions and answers, this paper assesses the specifics of these proposals and their implications.

Chemical recycling is not like mechanical recycling as it changes plastic chemical structure during processing. Pyrolysis – the most widely promoted chemical ‘recycling’ technology to date – produces an oil so contaminated it must be heavily diluted with virgin crude oil and treated with significant effort before it can enter material processing facilities. This long series of downstream processing steps are not captured by the draft IA on recycled content.

This technical paper shows that **at most only 0.03% recycled content is possible in new plastics when pyrolysis is used**; the rest comes from virgin crude-oil. But the draft IA on recycled content does not account for the resources and energy used in upgrading and necessary additional processing for this 0.03% when introducing the concept of ‘dual-use outputs’. By doing so it betrays the very concept of ‘recycling’. In practice **‘dual-use outputs’ means plastic-to-fuel and more virgin crude oil-derived plastic**.

Attempting to use any single average conversion factor (as envisaged in the draft IA on recycled content, Art. 7 (2)) for “additional types of recycling”, such as pyrolysis, would also be **inappropriate and misleading**, considering the **lack of verifiable data across the whole process line**, the dilution needs specific to the type of pyrolysis used and plastic waste input, and the wide range of contamination issues involved.

By comparing chemical recycling with mechanical recycling, the draft IA is attempting to compare apples with pears. And, unless it is tightened, the European Commission risks being taken in by plastics industry lobbyists and failing to achieve the promotion of high-quality recycling.

Draft IA on recycled content: introduction and background

The European Commission's [draft Implementing Decision](#) on recycled plastic content in beverage bottles for the Single Use Plastics Directive seeks to amend the methodology for calculating recycled content in products (Commission Implementing Decision (EU) [2023/2683](#)). This includes integrating mass balance accounting methods for “additional types of recycling, including chemical recycling”, and introducing a new concept called ‘dual-use’ into the existing ‘fuel-use exempt’ definition.

Despite refusing to accept industry's preference for a permissive free allocation variant of mass balance accounting (nor the more consumer transparent ‘proportional allocation’), the Commission chose fuel-use exempt. This aligns with the Waste Framework Directive, Art 3. 17, which legitimises recycling in the EU to exclude energy recovery and the reprocessing of waste into materials that are used for fuels or backfilling operations. Simply put, portions of waste that get recovered into fuels or used for energy recovery, are not credited as ‘recycled’.

Through a series of questions and answers, this paper assesses the specifics of the ‘dual-use outputs’ concept and its implications. It attempts to unravel whether ‘dual-use outputs’ is in-line with the definition of recycling, fuel-use exempt, and wider EU policy. It also assesses whether it is necessary, accurate, and importantly provides transparency for consumers.



Pyrolysis cannot process PET:

Pyrolysis is by far the most commonly attempted commercial option for unzipping plastics (aka. chemical recycling) both in Europe and globally (Dell, 2024). Other techniques involve solvents. Anomalously, the draft IA on recycled content refers specifically to the recycling of beverage bottles, including those made from polyethylene terephthalate (PET). Yet, pyrolysis cannot function with PET.

This discordant issue has been challenged by the Environment Committee of the European Parliament (European Parliament, 2024) in April 2024. The answer from the Commission is that they want to gather information and see how the process works in a limited sector (PET bottles) before broadening the scope to other types of packaging. The concern is that adoption of the draft IA on recycled content methodology will create a precedent to be followed for other technologies that have far greater environmental impact, and for more difficult waste streams (like multi-layer packaging, or automobile shredder residue, etc.).

Can pyrolysis outputs be reprocessed either into fuels or materials other than fuels?

POSSIBLY: But the operator cannot verify dual-use outputs.

Chemical 'recycling' is not like mechanical recycling in which what comes out of the unit does not get sent for making into new plastic monomers. This is not emphasised sufficiently in the draft IA on recycled content.

A common misunderstanding is that plastic waste is turned directly into new plastic precursor monomers (ethylene or propylene) in the pyrolysis unit. It is not. A long chain of processing must happen in-between and the output from chemical recycling has long way to go. **Unit processes called chemical recycling are just one early step in a 'long-loop'** (Warringa et al., 2023).

Specifically, pyrolysis melts plastics at high temperatures to make a complicated oil mixture. This oil mixture then has to be treated and diluted. To do this it must be shipped off-site to an oil refinery where fractional distillation and other treatments can be applied. Then it must go to a naphtha steam cracker which uses high temperatures to chemically alter the distillate into many fractions, some of which can be used as plastic building blocks (Song, 2024a). This chain of events is simply illustrated in Figure 1. But, even at the end of all this, no recycling has occurred, for the monomers will then need be polymerised and then shaped into products at a different site altogether.

Marked with a star on Figure 1 are the points where, potentially 'dual-use outputs' could be claimed. In reality, only after oil refining might non-fuel use be verified for substances such as lubricants and bitumen. And, only after steam cracking can non-fuel use be claimed for plastic precursor monomers.

It is notable that there can be regressive movement of oil, namely some of the non-monomer output of the steam cracker is sent back to the oil refinery for upgrading. One common example is using fluid catalytic cracking to manufacture marine fuel oil.

Very generally, about 30% of the input to oil refining would become naphtha for steam cracking. And from this, the steam cracker would make about 30% of this naphtha substitute into ethylene and



propylene. So from the 100% plastic, 10% goes into plastic monomers. The 90% could be considered 'dual-use outputs', including that portion sent back to the refinery and subjected to more treatment to be made into transportation fuels. This does not however consider the **contaminated nature of plastic-derived pyrolysis oil** (see next section).

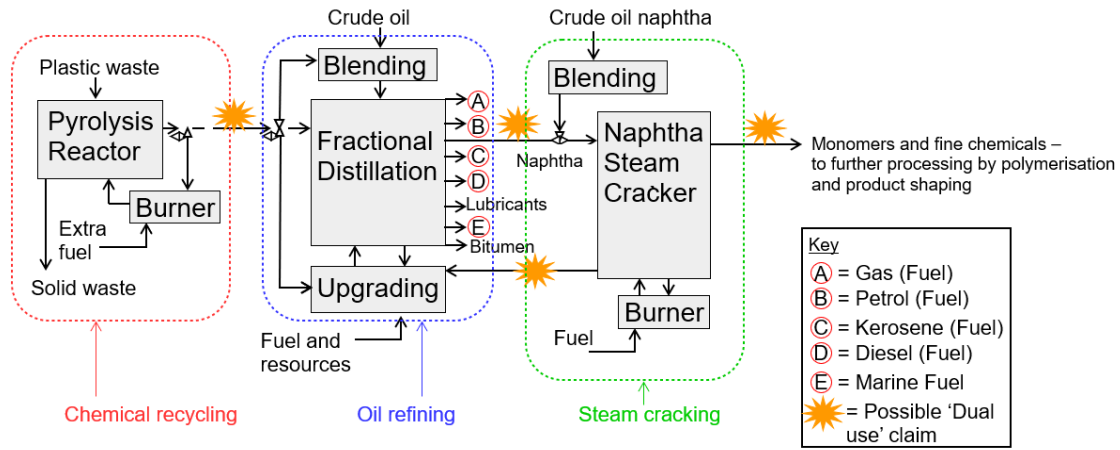


Figure 1 Simplified illustration of the many processing stages involved in converting plastic waste into recycled material.

The draft IA on recycled content, Art 7.6, says that an 'economic operator' will decide on dual-use by providing 'certified evidence' that 'outputs are processed downstream into plastics and other outputs respectively'. But, the definitions of both 'output' and 'economic operator' are ill resolved with respect of the chemical recycling process line. Seemingly contradicting this, and again not capturing the reality of the process line being split over multiple sites, Art 7.7 (draft IA on recycled content), says that "mass balance accounting shall not be transferred between different sites or a company or between different companies". How this issue can be reconciled is unclear.

For plastic precursor material, the only way to accurately and adequately 'verify' is to define the boundary of pyrolysis after the steam cracker, and after any dual-use outputs have previously been through a multi-stage oil refinery processing. Following this, the boundary should even be at a later stage, for only after polymerisation and shaping into products, has recycling occurred. At each stage there should be proportional discounting of losses to fuel along the way.



How much recycled plastic content could come from pyrolysis outputs?

UNKNOWN: Tellingly, information is not available across the supply chain.

Industry does not admit how much pyrolysis oil is created and how much gets sent off-site for further processing (Song, 2024a). Evidence suggests that it is just burned (Patel, 2020 NRDC, 2022). Similarly, industry is reticent as to the yields from subsequent stages (refinery and steam cracking). This lack of disclosure may suggest that the yields are very low or that this necessary processing line to the steam cracker stage is not occurring at all. The latter is supported by independent research, particularly that which identifies the **highly contaminated and off-specification nature of plastic-derived pyrolysis oil** (Cook et al, 2023; Erkmen et al., 2023; Kusenberget al., 2022; Kusenberget al., 2024; Rollinson 2023).

This section presents new research to quantify how much recycle, or as the draft IA on recycled content term it “material stemming from post-consumer plastic waste” (Recital 5), makes it past each of the processing stages, which could be considered as ‘dual-use outputs’. Ultimately, it quantifies the maximum possible recycled content in new plastics using pyrolysis.

Method

Data on pyrolysis oil yield was obtained from ten independent studies (Rollinson, 2023). This was supplemented by data from a new study jointly authored by academia and chemical recyclers Neste (Kusenberget al. 2024). All samples were of washed and well sorted commercial polyolefins, these being the ‘right’ feedstock for pyrolysis.

Plastic contaminant and single conversion factor issues

Table 1 (Appendix) shows that **even with the ‘right sort’ of polyolefin plastic waste, the maximum achievable recycled plastic waste content in new plastic is 0.02%**. This is however dependent on the very maximum 89% pyrolysis oil yield. It also assumes the maximum ethylene and propylene yield from the steam cracker. Taking the minimum pyrolysis oil quantity, steam cracking cannot produce plastic with more than 0.001% recycled content.

These limitations are due in part to the carryover of plastic additives that put even the distilled oil over contaminant thresholds for steam crackers (Kusenberget al., 2022). The source used, as shown in Table 1, only considered one of the many contaminants in plastic waste – oxygen (Kusenberget al., 2024). Diluting the pyrolysis oils in a ratio of 1:4 with new hydrocarbons after fractional distillation did not de-contaminate the oil. To achieve the steam cracker oxygen limit value of 100ppm oxygen, the pyrolysis oil would need diluting in the overall ratio of 1:340 (for PE) and 1: 644 (for PP) with crude oil naphtha.

These results are still an underestimate, because there are many other downstream process contaminants in plastic-derived pyrolysis oil. These include arsenic, aluminium, antimony, bromine, chlorine, lead, silicon, etc., and for some no amount of dilution would bring the oil under the steam cracker threshold (Kusenberget al., 2022; Rollinson, 2023).

The second limiting factor is that the unwanted hydrocarbon molecules, created by pyrolysis, also make the oil unsuitable. In Kusenberget al. (2024) the distilled oil had very high concentrations (up to 64%) of unsaturated olefins and aromatics, in comparison to naphtha which had zero. These molecules cause operational problems and lower the ethylene and propylene yield (Gholami et al., 2021; Kopinke et al., 1993). Though the authors speculated that this might be due to contamination by



PS, there was no evidence. In fact, it has been known for over one hundred years that pyrolysis is not selective and makes unwanted hydrocarbons (Rollinson, 2023). Many authors have evidenced that olefins and aromatics are formed during pyrolysis of PE and PP (Erkmen et al., 2023; Font et al., 2003; Hájeková et al., 2007; Zhou et al., 2015).

What these results, and the cited findings of other recent studies, show, is that **attempting to use any single average conversion factor** (cf. draft IA on recycled content, Art. 7.2) **for chemical recycling would be misleading**. This is considering the lack of verifiable data across the whole process line, the dilution needs specific to the type of pyrolysis used – or to the ‘additional types of recycling’ – the plastic waste input, and the wide range of contamination issues involved.

Would ‘dual-use outputs’ “maximise the potential for a circular economy” (Recital 14)?

NO: ‘Dual-use outputs’ make no technical sense

The fundamental concept of ‘dual-use outputs’ is actually absurd because any mixed hydrocarbon oil could be upgraded with sufficient effort. To upgrade it will need more resources and energy for processing, thus putting the method at odds with both technical common sense and the broader ethos of EU policy to minimise environmental impact and preserve resources. This holistic aspect is not at all captured by the current draft IA on recycled content.

Recycling is not, per se, an indisputably good thing. Its value depends on the amount of material recycled, the quality of the recycled product, and most importantly the amount of new resources, including energy from burning, and in-turn the extra emissions and other waste (pollution) generated.

These metrics are a function of universal laws (the laws of thermodynamics), meaning there will always be the need for resources and energy in the shaping of materials, and there will always be waste (Cullen, 2017; Rigamonti et al., 2018). The harder one has to work to recycle a material, the more resource use and/or wastage there will be. As previously shown, with pyrolysis of plastics, one has to work very hard indeed to bring any ‘dual-use outputs’ back into useful circulation.

This can be done by various methods in oil refining. For example, using, steam, or hydrogen, coking of the bitumen (a form of pyrolysis), alkylation – a catalytic process using sulphuric acid or hydrofluoric acid. Then there are possible options to cleanse the pyrolysis oil of downstream contaminants that originate from the many additives in post-consumer plastic, all of which will also need energy and resources.

Hydrogen is mostly made by steam reforming of natural gas. Sulphuric acid is also mostly obtained from natural gas or crude oil, while some is a by-product of metallurgy, but this also involves burning at high temperature (1030 °C). Hydrochloric acid is partly made from chlorine taken from sea-water by electrolysis, a tremendously energy intensive process (as it burns natural gas) and one which has wider adverse impacts on marine ecology (Dawoud and Mulla, 2012). The chlorine is then combined with hydrogen, made from, again, the steam reforming of natural gas.

The outputs from solvent-based chemical recycling would perhaps require greater use of resources. Reactors need heating, but they require large quantities of solvent, then even larger amounts of anti-solvent to strip the target molecule out from the first (Bell, 2023).

The draft formulae (i.e. 8 and 9 in Annex 1) of the draft IA on recycled content do not factor in the many resources used in dual-use output processing. They only capture ‘residue and input consumed



as a fuel in the process'. As previously mentioned, **the boundaries of 'the process' are not defined, which is very important because the process is over many steps.**

Without considering all these resources and upgrading stages, the European Commission will give **a grossly unfair advantage to the chemical recycling industry**, misrepresent the concept in the eyes of the consumer, and be mis-aligned with overarching EU's climate and resource use strategy. Not accounting for the resources and energy used in upgrading and necessary additional processing **betrays the very concept of 'recycling'**. In practice 'dual-use outputs' means plastic-to-fuel. And, it would also betray the very concept of mass balance, for essentially it is selective and permissive boundary allocation, something that is most **like a book and claim credit method.**

Does pyrolysis reduce greenhouse gas emissions?

NO: It increases them.

It is important to acknowledge that pyrolysis puts the recyclate back many steps earlier in the plastic production line than mechanical recycling – before the steam cracking and oil refining stages. It thereby has all the emissions associated with these processes.

A single full-scale naphtha cracker will emit between 2 to 3 million tonnes of CO₂ per year. Globally, and in total, steam cracking is estimated to result in over 190 million tonnes of CO₂ annually by 2030, a value equivalent to the GHG emissions from 42 five-hundred mega-watt coal power plants running round the clock for a full year (Harrison et al., 2019)¹.

Oil refining results in slightly less GHG emissions, but still appreciable, at 61% of those associated with naphtha steam cracking (Karali et al., 2024). This however is for crude oil feedstock, and **does not account for the additional upgrading necessary to strip out additives from plastic-derived pyrolysis oil**, of which there is no information.

On top of this, there are the GHG emissions associated by the high temperature operation of the first step – pyrolysis. The former Agilyx (pyrolysis) plant emitted over 3 t of CO₂ for every tonne of plastic waste processed in 2019, and a huge 47 t of CO₂ per tonne of plastic waste processed the year before; this came from burning over 250,000 m³ of natural gas per year to heat pyrolysis along with burning some of the plastic waste itself (Patel et al., 2020). For the same reason, permits for U.S pyrolysis facilities allow GHG emissions of between 16,000 and 316,000 t/y (Bell, 2023).

As with resource use (discussed in the last section), **the additional energy use from burning fuel for multi-step processing is not factored in to the draft IA formulae on recycled content** (i.e. 8 and 9 in Annex 1 of the draft IA on recycled content). This should be revised accordingly, with 'the process' (currently not defined by the draft IA on recycled content, but referred to in formula 9 of Annex I) made to include all oil refinery and steam cracking stages, i.e. the additional fuel used by these processes in treating the intermediate output (both that which comes from burning plastic waste intermediate and burning additional fuel such as diesel or natural gas) should be incorporated into the formulae.

¹ Based on 193.35 Mt/a, and source data of 92.4 Mt/a equivalent to 20 coal power plants.



Would 'dual-use outputs' encourage a complementary approach?

NO: It would give an unfair advantage to an unsound competitor.

Most plastic waste is unsuitable for chemical recycling. Multilayer packaging used in food cartons and bags is unacceptable, along with things like computer casings and vehicle interiors. These are too heterogeneous with the wrong chemical composition (Bell, 2023).

Even common homogeneous plastic wastes cannot be treated: pyrolysis cannot handle polyethylene terephthalate (PET) and polyester - disposable bottles and textiles. Nor does it accept polyamide (nylon). Polyurethane - foam used in packaging and construction must also be excluded, along with polyvinyl chloride (PVC). These either don't decompose as required, or contains oxygen and other molecules such as chlorine that impair the process or cause chronic issues such as corrosion (Kusenberget al., 2022; Rollinson, 2023).

This leaves only polyethylene (PE) and polypropylene (PP), known collectively as polyolefins, along with polystyrene (PS). But PS cannot be mixed in the same process as the polyolefins. The flagship Agilyx pyrolysis plant that treated PS only closed in 2024 (Seal, 2024).

Importantly, both the polyolefins for pyrolysis and PET for solvent-based chemical recycling must be very clean, well sorted, and washed. These are, in fact, exactly the same feedstock required for mechanical recycling thus putting the two in direct competition.

If all the pyrolysis plants currently constructed in Europe could operate at capacity (which they don't), **they could only process a tiny fraction (0.3%) of the EU's plastic waste** (Dell, 2024)², and they would be **competing with mechanical recycling**.

Although this value of 0.3% might be considered better than nothing, it is not so when accepted that **the 0.3% can only be recycled by high dilution with 99.7% petroleum**. So, far from being 'circular' **pyrolysis locks in to more fossil-derived plastic**, more use of resources, and more GHG emissions (ZWE, 2024).

In summary, the proposed mass balance method offers up an unfair competitive advantage for a group of technologies that are not as mature nor as environmentally sound as mechanical recycling; even though the same methods (re-branded as 'chemical recycling') have been 'in development' (in other words, technically stagnant) for half a century. This is exacerbated by the 'dual-use outputs' concept. It could be considered as a breaking of the 'technological neutrality' concept (i.e. treating technologies with equal environmental performance equally). And if this is to be so then the European Commission should favour technologies that are better for the environment and move away from those which ensure fossil lock-in, in line with Member States' duty of due diligence concerning climate change³.

² Based on data from OECD for plastic waste generated in Europe in 2024 (57.4Mt/y), and chemical recycling capacity in Europe of 178.5kt/y.

³ Judgment Verein KlimaSeniorinnen Schweiz and Others v. Switzerland - Violations of the Convention for failing to implement sufficient measures to combat climate change, 09/04/2024.



Conclusion: Plastics industry's push for 'dual use outputs' will defeat EU's targets for high-quality recycling

The USA EPA, this year rejected the use of 'fuzzy' mass balance accounting methods for calculating recycled content with its Safer Choice programme (Song, 2024b). Instead, recycled content must be determined 'by weight', effectively forbidding what is perceived as a mathematical sleight of hand. By doing so the EPA resisted heavy plastics industry lobbying.

Similar pressure is being applied in the EU by the plastics industry, where the very principle of 'dual-use outputs' and mass balance accounting seem to be accepted by the European Commission. What remains unresolved is how exactly this concept is to be implemented. The plastics industry will be pushing hard to manoeuvre the methodology in the free allocation direction, using dual-use outputs as a lever for greater flexibility. One option they may propose is for verifying all dual-use outputs as recycled and then discounting non-fuel use at the end based on transferrable volume credits. With the many players in the long supply chain this might be akin to a very complex multi-stage book and claim method.

But, there is no precedent for the use of such mass balance accounting methods with plastics or chemical processing. Indeed, it is not necessary. And, unless the European Commission tightens the current draft IA on recycled content, it risks being taken in by the plastics industry pushing for 'dual use outputs', hereby **defeating EU's targets for high-quality recycling**.

The processing units involved are all chemical reactors, for which the balancing of mass is basic engineering, conventionally done using established industry calculations. It is based on simple conservation of mass equations, since the inputs and outputs to each reactor are known. To give an example, if pyrolysis oil forms 1% of an input mixture to steam cracking with 99% naphtha, and the output yield of monomers is 40% then the recycled content that goes on to make new plastic is 0.4%. This is both accurate and simple for the consumer to understand.

Adopting a volume-based free allocation dual-use methodology would be bringing in extra and unnecessary layers of complexity to magnify an already troublesome concept. **The output of pyrolysis is not a 'virgin-like' plastic: it is a highly contaminated resource that must be heavily diluted with virgin crude oil and treated with significant effort before it can enter material processing facilities.** Therefore, flexible mass balance accounting is used to fudge over the reality. It will only lead to **greater public confusion over recycled plastic content in materials, provide greater industry greenwashing potential, and give an unfair advantage over preferential mechanical recycling.**

As shown in this technical paper, attempting to compare chemical 'recycling' with mechanical recycling is like attempting to compare apples with pears. Their full and necessary process line boundaries are totally different. **Currently, the draft IA on recycled content is lacking in comprehensive text and calculation methodology to adequately account for the resources used and energy usage in the multiple stages of managing the outputs from "additional types of recycling"**. For plastics, the sensible methodology would be to verify recycled content after the steam cracking stage, where plastic precursor monomers are finally made; or more precisely, after the steam cracking monomers have been subject to both polymerisation and product shaping, for only then has recycling occurred. This can be done by **proportionally discounting the mass lost as fuels at each and every prior stage.** A similar methodology would correctly apply to those streams designated as non-fuel intermediates (such as lubricants) following oil refining.



Table 1 Unless stated otherwise, data in the Reported yield column is from Kusenberget al., 2024. * = Running loss factor min and max values in stages 2 to 4 are based on the range of oil yields shown in Row 1 (min and max oil yield). PE = polyethylene waste, PP = polypropylene waste.

Stage	Name	Explanation	Reported yield	Loss factor (yield)	Running loss factor*	
					PE	PP
1	Pyrolysis	It is not possible to turn all the waste plastic into oil. The oil quantity depends on plastic type, reactor design and operating conditions, and oil capture method. Some oil will clog pipelines and be lost.	From ten independent studies ⁴	0.05 to 0.89	0.05 to 0.89	
2	Distillation	The pyrolysis oil is too viscous and complicated to be fed directly into a steam cracker. Fractional distillation improves the quality of the oil, but still does not make it suitable.	Naphtha range distillation	0.24 (PE) 0.38 (PP)	0.01 (min) 0.21 (max)	0.02 (min) 0.34 (max)
3	Blending	The distillate is still too contaminated to be fed to a steam cracker. It must be treated further and/or heavily diluted. Kusenberget al. (2024) tried a 1:4 dilution with petroleum naphtha, but the oil still had oxygen concentrations of 85 (PE) and 161 (PP) times greater than the steam cracker threshold value.	Values are obtained by multiplying a 1:4 dilution with 1:85 (for PE) and 1:161 (for PP) to bring the oil under the threshold value.	0.003 (PE) 0.002 (PP)	4x10 ⁻⁵ (min) 6x10 ⁻⁴ (max)	3x10 ⁻⁵ (min) 5x10 ⁻⁴ (max)
4	Steam cracking	Less than half the distilled plastic-derived pyrolysis oil is converted into ethylene and propylene (monomers). This is however similar to petroleum naphtha, but the pyrolysis oil by-products have other negative impacts on the steam cracker (see main text).	26-32% ethylene 8-17% propylene Combined total = 34 – 49% ⁵	0.34 – 0.49	1x10 ⁻⁵ (min) 3x10 ⁻⁴ (max)	1x10 ⁻⁵ (min) 3x10 ⁻⁴ (max)

⁴ Rollinson, 2023.

⁵ Combined data from Kusenberget al. (2024) and Kusenberget al. (2022).

5	Polymerisation	Here the monomers are made into polymers. Methods vary dependant on polymer type.	Unknown. But assumed to be high.	> 0.95	Negligible relative to prior losses in stages 1 – 4.	
6	Product shaping	Plastic type specific.	This stage is excluded from the calculation as it is common also to mechanical recycling		N/A	
<p>Calculated minima and maxima percentage values of the recycled plastic waste content in new plastic products, practically achievable based on treatment necessary to overcome just one contaminant (oxygen). These values exclude losses associated with polymerisation, and are simply the values after steam cracking (stage 4) multiplied by 100.</p>					<p>0.001 % (min)</p> <p>0.03 % (max)</p>	<p>0.001 % (min)</p> <p>0.03 % (max)</p>

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