

Plastic recycling stripped naked – from circular product to circular industry with recycling cascade

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This perspective combines various expertise to develop and analyse the concept of technology cascade for recycling waste plastics with the goal of displacing as much fossil crude oil as possible. It thereby presents archetype recycling technologies with their strengths and weaknesses. It then combines them in various cascades to process a representative plastic mix, and determines how much (fossil) naphtha could be displaced and at which energy consumption. The cascades rely on a limited number of parameters that are fully reported in supplementary information and that were used in a simple and transparent spreadsheet model. The calculated results bust several common

myths in plastic recycling, e.g. by prioritizing here recycled volume over recycling efficiency, and prioritizing circular industry over circular products. It unravels the energy cost of solvent-based recycling processes, shows the key role of gasification and the possibility to displace up to 70% of the fossil feedstock with recycled carbon, a recycling rate that compares well with that aluminium, steel or paper. It suggests that deeper naphtha displacement would require exorbitant amount of energy. It therefore argues for the need to complement recycling with the use of renewable carbon, e.g. based on biomass, to fully defossilise the plastic industry.

1. Introduction

Plastics have entered all facets of today's modern life, from housing to health, clothing, sport, transport, food, water, and many more, providing thereby comfort and convenience for a modest price. Their global consumption amounted to some 390 Mt per annum in 2021, with a majority being used in packaging (44%), followed by construction (18%), automotive (8%), electrical/electronic (7%), and many other markets.^[1] Too often, however, these plastics end up in the environment after use. They are found as litter on land and in water, or as CO₂, soot, microplastics and other contaminants in the air, e.g. upon

incineration.^[1,2] This is a waste of resources, for spent plastics can be converted to new plastics and, thereby, reduce the need for fossil resources while avoiding litter, landfill, and incineration.^[3]

Recycling is well supported by European policy. But the concept of recycling is too often associated with or limited to closed-loop recycling, *i.e.* the recycling of one product to its equivalent, *e.g.* recycling bottle to bottle, via washing, re-melting, and re-processing of the used material. Closed-loop mechanical recycling may be the most recognizable form of circularity and might be technically efficient, but the complexity of plastic waste combined with the high technical requirements of end products might present difficulties achieving even a 30% recycled content in products^[4], making thereby deep recycling impossible. Closing the plastic loop requires more than that. It requires a complex array of system changes and technologies that go beyond making individual products circular to making the whole carbon-based chemical industry circular.^[3,5]

We postulate that the most optimal pathway, next to system changes such as consumer engagement that allows increasing collection, is for the recycling system to embrace a cascade of technologies that complement each other to convert the largest possible fraction of end-of-use carbon into high-quality polymers and chemical products to substitute fossil carbon used for their production. Such a recycling cascade focuses on retaining carbon in the economy, which means it does not matter if carbon is recycled in a closed loop (to the same polymer) or reshuffled between polymer types, *e.g.* between polyolefins and aromatic polymers, between addition and condensation polymers, even between thermoplastic and thermoset materials.

Such a recycling cascade builds on a variety of recycling technologies, prioritized according to their own requirements

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regarding feedstock quality and energy use. For instance, the cascade starts with mechanical recycling of specific plastic types that come out of collection and sorting at highest purity. The desired sorted plastics are washed, possibly freed from foreign material by solvent extraction or solvent-based dissolution/precipitation^[6], regranulated optionally with simultaneous degassing/deodorising and blended with virgin plastics and some recycling additives to mitigate the presence of impurities and inevitable chain degradation.^[3,6b,7] This can result in closed-loop recycling, as presently operated with *e.g.* deposit refund schemes for PET beverage bottles or the equally valuable open-loop recycling to other products and applications, *e.g.* by converting 'food-contact' HDPE milk bottles to 'non-food-contact' HDPE shampoo bottles, buckets, *etc.* But recycling can also include recycling to bulky products like plastic lumber, wherein a lower technical performance of the material is compensated by the product's bulk. All these approaches belong to the family of mechanical recycling that uses end-of-use material without chemically changing its polymer chain, *i.e.* without breaking it apart.

However, a significant amount of plastic waste has polymer purities below 90–95%, which disqualifies it for high-quality mechanical recycling (see SI). Complementary recycling then requires breaking the polymer chains down to their constituting monomers, or down to a more versatile hydrocarbon feedstock.^[3a,8] For instance, polyesters and polyamides could be depolymerized back to their constituting monomers, *e.g.* to diols/diamines + diacids, or to hydroxy-/amino-acids, generally using solvent-based depolymerization processes, also called solvolysis. Polyolefins can be pyrolyzed to a blend of hydrocarbons for feeding to a steam cracker^[3,9], whereas mixed polymers, thermoplastics, and thermosets, can be gasified to synthesis gas, a mixture of H₂ and CO for subsequent conversion to methanol and hydrocarbons.^[3b] These approaches, which belong to the family of chemical recycling^[6b], deliver chemical building blocks of virgin quality that can be repolymerized into polymers of the highest quality and the highest standards. Chemical recycling to feedstock, such as pyrolysis and gasification, facilitates a reshuffling of carbon between the various polymer chains. In this way, polyolefins can be converted to aromatic polymers via pyrolysis and their aromatic gasoline fraction, or via syngas, methanol, and aromatic gasoline. Chemical conversion also allows to produce building blocks for thermoset polymers and non-polymeric



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chemicals, such as detergents, solvents, additives, and lubricants.

This paper combines expertise in the various recycling technologies to argue that a well-composed cascade of technologies enables to process waste streams of increasing contamination using processes of increasing severity, thereby mitigating the use of fossil carbon at the system level rather than focusing recycling policies and thinking at products level. We will first present the individual recycling technologies mentioned above and report some critical characteristics such as feed specification, yield and energy demand. We will then place them in archetype cascades according to plastic type and quality, and then discuss their energy demand and crude displacement potential. We will finally discuss some of the premises used here and the need for improvements.

This perspective has approached plastic recycling at systemic level and from the angle of technological feasibility. To maintain its focus, we intentionally left other aspects such as economic affordability and greenhouse gas emissions out of scope. Such aspects would indeed require detailed analyses on their own and warrant dedicated papers.

2. Recycling Technologies

We considered here a few archetype technologies for mechanical recycling (conventional and solvent-based) and chemical recycling (solvent-based depolymerization, pyrolysis and gasification). All of them require a degree of sorting and some also require washing beforehand. The technologies themselves are described in more detail in SI (sections S4-S9), with mention of the various performances and their related references.

These various recycling technologies show clear differences in output and input, *i.e.* in yield and quality of recycled plastics, and in feedstock and energy requirements, which are detailed in SI (table S2, and sections S4-S9 with appropriate references) and illustrated in Figure 1. We define yield as the carbon fraction of the plastic products entering the recycling technology that effectively ends up in a new plastic product, called hereafter yield in recyclate. As detailed in SI (table S2), we assumed the yield in recycled plastic drops from ~95% for conventional and solvent-based mechanical recycling, to 90% for depolymerization, and ~50% for pyrolysis and gasification. The blending ceiling of recyclate into final products shows the opposite trend: it increases from 40% for mechanical recycling (see SI, table S2) to 75% for solvent-based mechanical recycling to ~100% for all chemical recycling options (depolymerization, pyrolysis and gasification). However, the technologies also differ in their input requirements (see in SI, table S2). The expected required feedstock purity is decreasing from ~95% for mechanical recycling to ~85% for solvent-based recycling, depolymerization and pyrolysis to ~10% for gasification (a gasifier feedstock qualifies largely on heating value, *i.e.* on C:H:O content). The energy demand follows a different and more complex trend, being high (> 30 MJ/kg) for the solvent-based processes for mechanical recycling and depolymerization, and low (~10 MJ/kg) for 'dry' processes such as conventional mechanical

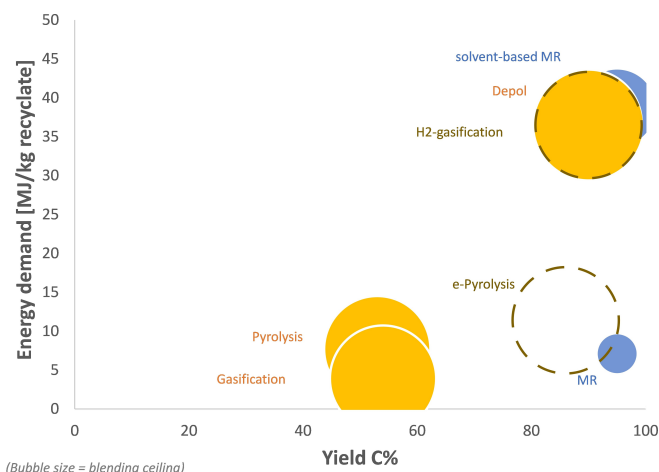


Figure 1. Characteristics of recycling technologies: conventional mechanical recycling MR and solvent-based mechanical recycling sMR (closed blue symbols), chemical recycling (closed orange symbols), and future 'electrified' chemical recycling (open brown symbols). More details and used sources are provided in SI.

recycling, pyrolysis and gasification. Energy is expressed here as MJ per kg of plastic produced by recycling, called hereafter MJ/kg recyclate. It corresponds to the energy demand that can be directly supplied by electricity; it does not account for eventual inefficiency of indirect energy supply. The high energy demand of the solvent-based process is related to the recovery and purification of the solvent. Mechanical recycling owes its low energy demand to its simple processing. The low energy demand of pyrolysis and gasification may be surprising at first sight but in fact results from their low yield and from the fact that these they are consuming a portion of their feedstock or by-product as process energy.

In the future, however, the pyrolysis and gasification processes could be operated at higher yield by running them on renewable electricity and diverting their by-products from energy source to carbon source. For example, the pyrolysis could be run in an e-furnace and the by-products directed to a gasifier (see SI, section S8 for more details) or, respectively, a gasifier could be provided with renewable H₂ to valorise the CO₂ produced during gasification (see SI, section S9 for more details). These operations could raise the product yield to ~80 or 90%, respectively, but also raise energy consumption to 11 and 36 MJ/kg, respectively, as illustrated by the open symbols in Figure 1 and detailed in in SI (table S2). Note that this analysis uses best-estimate numbers based on literature and expert judgement, taken at the time of writing this paper. These numbers may vary per technology type and may change with time, e.g. due to new developments. However, the improvements need to be very large to significantly affect the technology ranking illustrated in Figure 1 and the benefit of the technology discussed below.

3. Recycling Cascades

3.1. Plastic waste

The proposed technology cascade is built to process a mixed plastic waste stream, which consists of 56 C% polyolefins, 14 C% PS + PVC and 13 C% PET + PU (in SI, section S1 and table S1) and based on the global production of plastics.^[10] These polymers were sorted in streams of varying quality to be fed to the various recycling technologies, while the residual fraction that could not be sorted was sent for incineration and/or for gasification. The collection and sorting yields are reported in in SI (table S1), based on existing data^[5b,11], as well as expert judgment for a realistic (~2030) and a futuristic (~2050) scenario for western Europe. The various recycling schemes were developed for the individual polymer families (see SI) but are reported below in fully lumped form for the sake of simplicity. We assumed that PET and PU (a 13% minority of the polymer) could be depolymerized back to their monomer, polyolefins and PS (a majority of ~60%) could be recycled to feedstock by pyrolysis, but all polymers could be recycled by gasification, irrespective of their quality, and only by mechanical recycling if the feed quality is high (see SI, table S1).

3.2. Full technology cascade

The various recycling technologies were combined into the cascade shown in Figure 2 to process the various sorted fractions according to their purity. Limiting the discussion to the futuristic scenario for the sake of simplicity, the plastic waste would be collected and sorted for 73 C%, with about half being directed to mechanical recycling and half to depolymerization and pyrolysis. The unsorted fraction would be directed to gasification and incineration in equal amounts (meaning 50% of the ~30% not collected and sorted for recycling is sent to gasification), which results in 87 C% of the waste C being sent for recycling. Noteworthy, the futuristic scenario redirects the by-products of chemical and mechanical recycling (*i.e.* 15 C%, coming mainly from pyrolysis) to the gasifier, an option that was not considered for the realistic scenario. The plastic stream would formally comprise 33 C% of mechanically recycled carbon, 10 C% depolymerized/repolymerized carbon and 26 C% feedstock-recycled carbon (via 0.7*14 C% pyrolysis and 16 C% via gasification). The remaining 31 C% (0.7*44 C%) needs to come from virgin carbon, e.g. from naphtha (a fraction of crude oil) in today's fossil economy and from biomass in a circular economy, as discussed later. But a minor fraction of the recycled carbon will also be diverted to non-polymeric chemicals such as detergents, solvents, plasticizers, and intermediates for fine chemicals. While this allows to feed recycled carbon to the rest of the chemicals, it also requires compensation with additional virgin input.

Overall, such plastic loop requires only 44 C% of naphtha, a fraction of crude used as feedstock for chemicals (based on 100 C% polymer flow). This represents a reduction of 69% of the crude required in absence of any recycling, since the steam

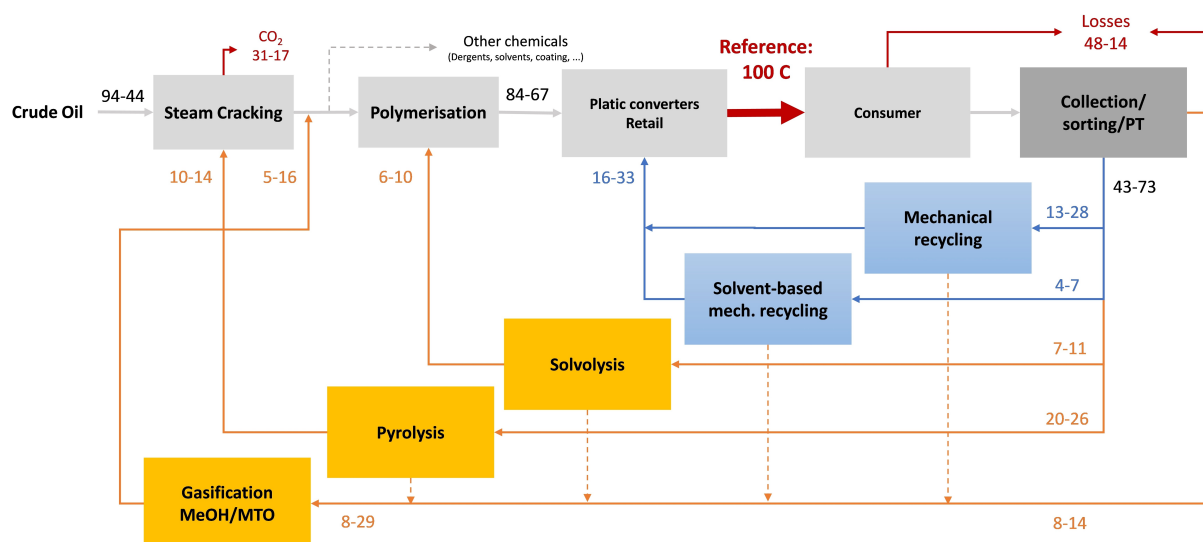


Figure 2. Normalized carbon flow of a cascade of recycling technologies based on mechanical recycling (blue) and chemical recycling (Orange) technologies. The numbers represent normalized C-flows, based on a realistic (2030) -futuristic (2050) sorting scenario. (The naphtha intake is scaled to deliver 100 unit of C plastics on the market, excl. the additional non-plastics chemicals).

cracker requires 142 C% of crude to produce 100 C% of valuable product and consumes the rest as process fuel. For comparison, the realistic 2030 scenario would already displace 35 C% of the crude needed otherwise. Interestingly, however, (nearly) none of the recycling technologies could displace that much naphtha alone or in pairs, as discussed in the next section.

3.3. Alternative technology cascades

We also evaluate alternative recycling cascades and calculated how much naphtha could be displaced and how much energy it would cost. Only external energy was counted, *i.e.* combustion of by-products to run the process was excluded from the energy cost but considered as yield loss and, thereby, as reduced naphtha displacement. The alternative scenarios were calculated using the same mixed plastic waste as used above (SI, table S1) but with sorting schemes adjusted to feed single recycling technologies, feed various combinations of two recycling technologies or feed the full cascades (see SI and table S1 for further discussion).

As described earlier, the full cascade would displace ~35 to 69% of the naphtha for the realistic 2030 and optimistic 2050 scenarios and do it at a moderate energy penalty of 13 to 15 MJ/kg of recyclate (see Figure 3, closed green diamond). A full cascade appears more effective than smaller cascades. Applying single recycling technologies to the optimistic scenario (see Figure 3, closed blue triangles) delivers significantly lower naphtha displacement than the full cascade, generally <35%, with high energy demand (>30 MJ/kg) for the solvent-based technologies and low energy demand (<10 MJ/kg) for the 'dry' technologies. Combinations of conventional mechanical recycling with another recycling technology displace nearly 40% of naphtha (closed orange circles), which is still lower than the full

cascade. This shows the value of multiple recycling technologies in cascade.

A few additional observations are worth stressing, however.

Firstly, gasification represents a notorious outlier by displacing 46% of naphtha when used alone, while consuming no more than 4 MJ/kg of recyclate. Its low yield of 54 C% is clearly compensated by its ability to process the full mixed waste stream. The low yield allows it to also run exothermally, with limited external energy input. Gasification should therefore form a corner stone in any recycling cascade. When combined with mechanical recycling, for instance, it allows to displace 59% of the naphtha with no additional energy demand. Intriguingly, adding pyrolysis to MR+gasification does not change the overall yield of recyclate (~59 C% in both cases) but lowers the naphtha displacement by 5 C% as part of the recycled carbon is getting burned in the steam cracker.

Secondly, depolymerisation and solvent-based recycling stand out by demanding much energy to recover their solvent while not displacing much naphtha because they process a minor fraction of waste in the mix. Of course, some of these technologies are still under development and significant energy improvements might still be made. One could nevertheless challenge their strategic role in a recycling cascade.

Thirdly, the 'electrification' of pyrolysis and gasification technologies increases their naphtha displacement, when used alone or in a cascade, but also increases their energy demand (open symbols with e-pyro and H₂-gasif in Figure 3). The shift is moderate for the e-pyrolysis (accompanied by gasification of the by-products) because we here assumed to only electrify the pyrolysis but not the steam cracker. However, the shift is much more pronounced, nearing 80% naphtha displacement, for a prohibitive energy demand of 37 MJ/kg for H₂-gasification that requires a very large amount of renewable H₂ to push the process yields to 90 C%.

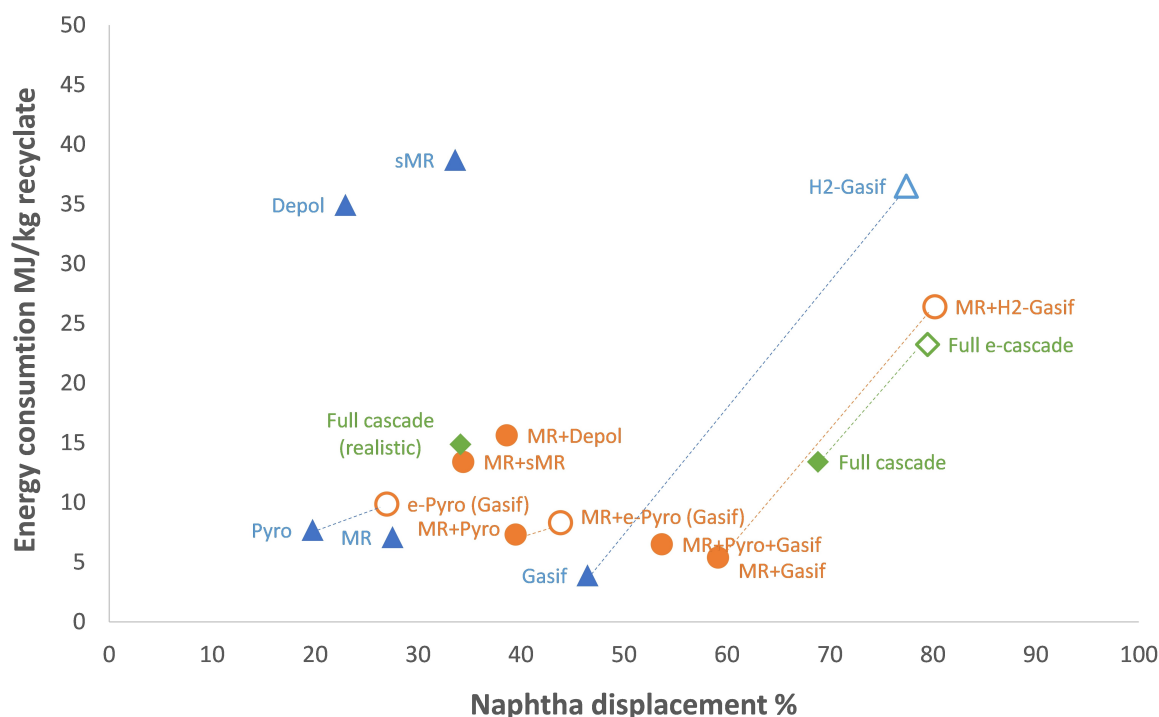


Figure 3. Energy consumption and naphtha displacement for single-technology recycling (blue triangles), double/triple-technology cascades (orange circles) and full cascade (green diamonds). The open symbols contain 'electrified' technologies. (MR / sMR: conventional / solvent-based mech. recycling; Depol: solvent-based depolymerisation; Pyro: pyrolysis + steam cracking; e-pyro (gasif): e-pyrolysis + steam cracking + gasification of pyro by-products; Gasif: gasification; H₂-gasif: H₂-fed gasification).

4. Discussion

4.1. Critical premises

A few premises of this analysis warrant a bit of explanation that is summarized here and discussed in more length in the SI.

Firstly, mechanical recycling often requires blending with virgin resin and the use of additives to mitigate the effect of chain degradation that develop during use and mechanical recycling itself, and to stabilize contaminants that result from imperfect sorting and treating of the plastic waste. These additives are expected to build up upon multiple recycling and, thereby, to deteriorate the long-term quality of the recyclate. Our simplified model developed in SI, estimates the build-up of additives to raise significantly at blending rate beyond 40–50% recyclate in virgin resins. Hence, we propose to allow a blending ceiling of 40%, vs. the 30% target often used in legislation or pledges^[2,12], and we ensured that our recycling cascade did not exceed this ceiling for each individual polymer.

Secondly, the solvent-based mechanical recycling processes are yet in the early stage of their development. We have assumed that further process optimization will reduce their energy consumption of the extraction/dissolution step to ~35 MJ/kg, about half the overall energy demand reported by Uekert *et al.*^[8b]

Thirdly, pyrolysis of polyolefins is estimated to operate with a polymer yield of ~53 C%, by cumulating the yield of the pyrolysis step (~75 C%) and the yield of 'high value chemical' (~70 C% of olefins and aromatics) that is achieved in the

subsequent steam cracking. Many of the unavoidable by-products of pyrolysis and steam cracking are then used for powering the processes.

Fourthly, the gasification route is assumed to process the sorting residue, a mixture of unsortable plastics, textiles, paper/cardboard and other biobased components that is often called Residue Derived Fuel (RDF). We have here estimated a methanol yield of ~60 C% for its plastic fraction that is rich in hydrogen ($H/C_{\text{eff}} \sim 2$, see SI, section S9 and figure S3–) and a subsequent methanol-to-olefin yield of 90 C%. We intentionally excluded the biowaste fraction to keep the focus on plastic recycling and ignored, thereby, its contribution to circularity by co-producing biobased chemicals. An important factor in the analysis is how much of the waste that is not sorted for recycling is actually still valorised by gasification. In our analyses this factor varied from 15–50%.

Finally, the sorting schemes used for alternative cascades reported in Figure 3 were derived from the full cascade of the optimistic scenario. Namely, recycling technologies with higher rank in the cascade (*i.e.* those that require high-quality feed and are placed higher in Figure 2 or more to the left in Table S1 in SI), could be omitted by passing their feed to a lower-ranking technology. For instance, mechanical recycling of polyolefins could be omitted by adding its high-quality feed to lower-quality polyolefins fractions for processing by solvent-based mechanical recycling or by pyrolysis. The effect this would have on overall footprint of the cascade is outside the scope of this paper. All the alternative schemes are reported for HDPE in SI (table S3) for illustration purpose.

Overall, slight changes in sorting yield as well as in yield and energy demand of individual recycling technologies don't destroy the advantage of the cascade over any individual technology, in terms of naphtha displacement and energy demand. This has been confirmed by a short sensitivity analysis that set the energy demand to 110% and the sorting or recycling yields to 90% of what was estimated for the optimistic scenario (SI, table S4). The resulting impact was moderate, being proportional for the energy demand and less-than-proportional for the naphtha displacement. Yield drop appeared to be partially compensated by diverting more unsorted waste or recycling by-products to gasification.

4.2. Potential improvements of the technology cascade

We have so far limited the option of depolymerization back to monomer to solvolysis of condensation polymers; we did not consider the solvent-free depolymerization by pyrolysis, which can proceed in good yields for PS, PA6 and PMMA.^[3a] Such depolymerization is expected to proceed with modest energy demand because it does not require solvent evaporation and recycling, and it proceeds with a low weight-base heat of depolymerization (e.g. 0.7 MJ/kg for PS and 0.1 MJ/kg for PA6 vs. 3.8 MJ/kg for PE). Such efficient chemical recyclability could confer these polymers a strong position in a circular economy and, therefore, allow them to take a larger role in the plastic economy than they do presently.

According to the proposed cascade, the recycling yield for carbon in polymers can reach ~70%, *i.e.* the fraction of naphtha it can displace. This is of similar magnitude to existing studies: the 2022 evaluation performed by Systemiq^[5b] predicted 78% circularity but included systemic solutions such as reduce and substitute, which are not considered here. Their predicted share of recycling solutions would cover 60%. Lase *et al.*^[13] calculated that a complementary system between mechanical and chemical recycling could deliver a recycling rate of near 80%. However, this is plastics going to different recycling technologies rather than overall circularity and more residue was sent to gasification.

Finally, a recycling rate of ~70% would bring plastics on par with other materials, which already have mature recycling systems: European recycling rates are around 70% for aluminium^[14], 54% for steel^[14b], and 52% for paper^[15], for example. But carbon material (including paper) may still become more circular than metals after all: the inevitable material losses that result from unrecyclable products or from incomplete collection, sorting and recycling can eventually be compensated by using renewable carbon coming from either biomass or from chemical capture and reduction of atmospheric CO₂.^[5a]

5. Conclusions and outlook

Overall, the present analysis is delivering some sobering and other hopeful learnings:

The popular closed-loop recycling alone cannot deliver the high circularity society aspires to. Barring any paradigm-shifting development in technology, overall mechanical recycling rates will unlikely be able to move far beyond the proposed 40%, if only from a cautionary point-of-view. Hence, we need complementary pathways such as chemical recycling to produce the other 60% of virgin-like material needed for a fully performing product based on 100% non-fossil carbon.

Solvent-based mechanical recycling may contribute to raising the blending content beyond 40%, but at the cost of high energy consumption, at least based on current status in these technologies. The same applies to solvent-based depolymerization, also called solvolysis, which is presently under development. It will likely consume large amounts of energy to purify and recycle the solvent.

Solvent-free depolymerisation based on pyrolysis (e.g. for PS, PMMA, and PA6) is more energy-efficient and, thereby, more promising. To be impactful, however, the industry would need to significantly increase the fraction of these polymers in the plastic mix to make collection and recycling affordable.

Chemical recycling by means of pyrolysis and gasification can deliver high contributions to plastic recycling. By diverting large fraction of the waste from landfill or incineration, namely mixed polyolefins for pyrolysis and the whole mix of plastic residual waste for gasification, these processes could displace much crude oil, more accurately its naphtha fraction, even after correcting for their modest yield of ~50 C%. Pyrolysis may be favoured in the short term by making good use of existing steam cracking plants and requiring only gradual complementary investment. However, gasification may eventually take over the largest role in recycling at later stage by accommodating the whole mixed plastic waste and displace up to 45% of the naphtha with moderate energy demand. Hence, gasification may become the true corner stone of a circular carbochemical industry.

Combining chemical recycling with mechanical recycling in a cascade could displace even more naphtha, up to ~60–70% in the futuristic scenario developed here, at a modest energy cost of 5–8 MJ/kg recycle. But it also requires important improvements in collection and sorting to allow ~70% of the plastic to be sorted for recycling.

Deeper naphtha displacement (>70%) may consume disproportionate amounts of renewable electricity, ~100 MJ/kg of additional recycle, to convert recycling by-products instead of burning them as process fuel.

But one should also consider the alternative approaches to deep naphtha displacements, namely a switch to renewable carbon as ultimate feedstock, *i.e.* carbon derived from biomass or CO₂, water and renewable electricity.^[5b] Deep recycling should be more efficient than the latter, the so-called e-chemicals, for it does not need to capture CO₂ from the atmosphere and it nicely builds on the recycling infrastructure that should then be in place. Deep recycling may, however, remain disadvantaged over biomass which is available in large volume and at a price that is competitive with today's naphtha. Biomass could be converted to existing or new plastics, e.g. bio-PE or polylactic acid (PLA). But it can also deliver alternative

materials such as paper, cardboard and wood that are already capturing some of today's plastic markets. One should however ensure that the deployment of novel biobased plastics and other biobased materials does not jeopardize the recycling of existing plastics and materials. Preferably, these novel materials are selected to enable deeper recycling, e.g. providing new options for depolymerisation at high yield and modest energy demand. Note that gasification of unsorted municipal solid waste offers a route to accommodate biowaste in the carbon cycle, for municipal solid waste indeed contains about as much biogenic carbon (e.g. unsortable paper, cardboard, wood and natural textiles) than end-of-life plastic carbon. This further consolidates the essential role of gasification in the plastic circularity.

Overall, a systemic recycling yield of ~60% could be feasible by 2050, a level that compares well with that of other materials such as aluminium, steel and paper (52–70% in Europe). However, such deep recycling will not develop without proper legislation that allows sorters and recyclers to make decent margins. Legislation should focus on the goals of recycling rather on its means. It should aim at maximizing the displacement of fossil resources and support all forms of recycling.

It should be noted, however, that the resulting displacement of fossil carbon may be offset by an increase in demand for plastic materials, which is expected to have doubled by then. Unless society significantly reduces the demand for plastic and materials, or drastically ramps up the valorisation of renewable carbon, the carbochemical industry may keep consuming as much naphtha by 2050 as it does today.^[5b]

5.1. Credit roles

Jean-Paul Lange: Conceptualization, methodology, writing – original draft, review & editing. Sascha Kersten, Steven De Meester, Marcel van Eijk, Kim Ragaert: Methodology, writing – review & editing.

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Conflict of Interests

The authors declare no competing interest beyond the affiliations reported. JPL is employed by Shell that is commercializing chemical recycling technologies.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords: Plastic recycling · cascade · gasification · pyrolysis · energy

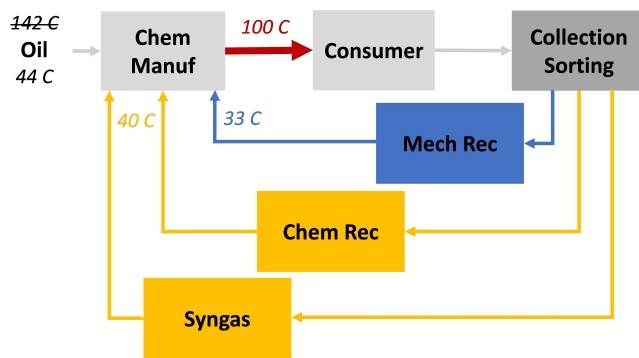
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PERSPECTIVE



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Plastic recycling stripped naked – from circular product to circular industry with recycling cascade



Plastic recycling stripped naked :
Combining mechanical and chemical
recycling in cascade can largely defos-

silise the plastic economy at modest
energy cost.