SCRUTINISING SCIENTIFIC STANDARDS

A Scientific Assessment of the JRC Study on European Sustainability Criteria for Plastics Recycling Technologies

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Rethink Plastic, part of the global Break Free From Plastic movement, is an alliance of leading European NGOs working towards ambitious EU policies on plastics. It brings together the Center for International Environmental Law (CIEL), ClientEarth, Environmental Investigation Agency (EIA), European Environmental Bureau (EEB), Environmental Coalition on Standards (ECOS), Greenpeace, Seas At Risk, Surfrider Foundation Europe, and Zero Waste Europe. Together, they represent thousands of active groups, supporters, and citizens in every EU Member State working towards a future free from plastic pollution. www.rethinkplasticalliance.eu

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Zero Waste Europe (ZWE) is the European network of communities, local leaders, experts, and change agents working towards a better use of resources and the elimination of waste in our society. We advocate for sustainable systems; for the redesign of our relationship with resources; and for a global shift towards environmental justice, accelerating a just transition towards zero waste for the benefit of people and the planet. www.zerowasteeurope.eu

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EXECUTIVE SUMMARY

The European Commission's (EC) ambitious plastic waste recycling targets cannot be met by established technologies without upstream interventions to simplify and standardise plastic. New 'back-end' technologies must step forward; but, the only 'new' technologies suggested, are old ones, with no track record of commercial sustainability, and no evidence that they are capable of the task. EC regulations also require that they do the job without having adverse impact on human health and the environment.

This report provides a blueprint for assessing these plastic recycling technologies in terms of their life-cycle environmental footprint. The technologies included in the report are solvent-based and pyrolysis-based depolymerisation, both considered chemical recycling in the context of this report,, and solvent-based stripping also referred to as physical recycling.

Firstly, this report provides a technical critique of a recent study published by the Joint Research Centre of the European Commission (JRC) that uses Life Cycle Assessment (LCA) to compare the environmental impacts of different plastic recycling technologies. Based on this critique, recommendations are provided for decision makers as to the value of the JRC study's findings.

The technologies modelled by the aforementioned JRC study are described in detail, outlining the full extent of processing necessary (in LCA terms, the system boundary) and associated environmental impacts. From this, recommendations are provided for future modelling of the same techniques.

There is a **fundamental hierarchy of plastic recycling technologies in terms of environmental impact**. This is due to the extent with which they decompose plastic waste and the amount of effort (energy and resource use, waste creation) needed to rebuild the output back into plastic. This hierarchy is **Mechanical recycling > Physical Recycling > Chemical Recycling.**[1]

For chemical recycling there is a further sub-hierarchy which is Solvent-based depolymerisation > Pyrolysis-based depolymerisation, based on the plastic type used by each technique. Much would depend however on the metric with which these were assessed (*i.e.* mining of catalysts, embedded carbon of solvents, processing energy), and the extent of upgrading necessary to clean out impurities.

The JRC study is found to have multiple weaknesses in its methodology and lack of transparency in reporting. This has resulted in some improbable results, which largely go un-discussed. The JRC study authors provide a limited discussion on the study's limitations, do not comment on toxicity impact factors, and introduce certain extraneous statements into the text that are not substantiated by the findings or supported by references. All of which combine to show chemical and physical recycling in a favourable light. **As such this report finds that the JRC study should be treated with extreme caution and should not be used as a guide to decision-makers.**

Putting these findings in context, this report draws from wider literature and evidence from real-life case studies. It also provides a deeper analysis of the full processing system boundaries for all chemical recycling techniques modelled by the JRC study along with those for solvent-based stripping/physical recycling.

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[1] ECOS, DUH, ZWE, Chemical Recycling and Recovery – Recommendation to Categorise Thermal Decomposition of Plastic Waste to Molecular Level Feedstock as Chemical Recovery, 2021 https://zerowasteeurope.eu/library/chemical-recycling-and-recovery-recommendation-to-categorise-thermal-decomposition-of-plastic-waste-to-molecular-level-feedstock-as-chemical-recovery/

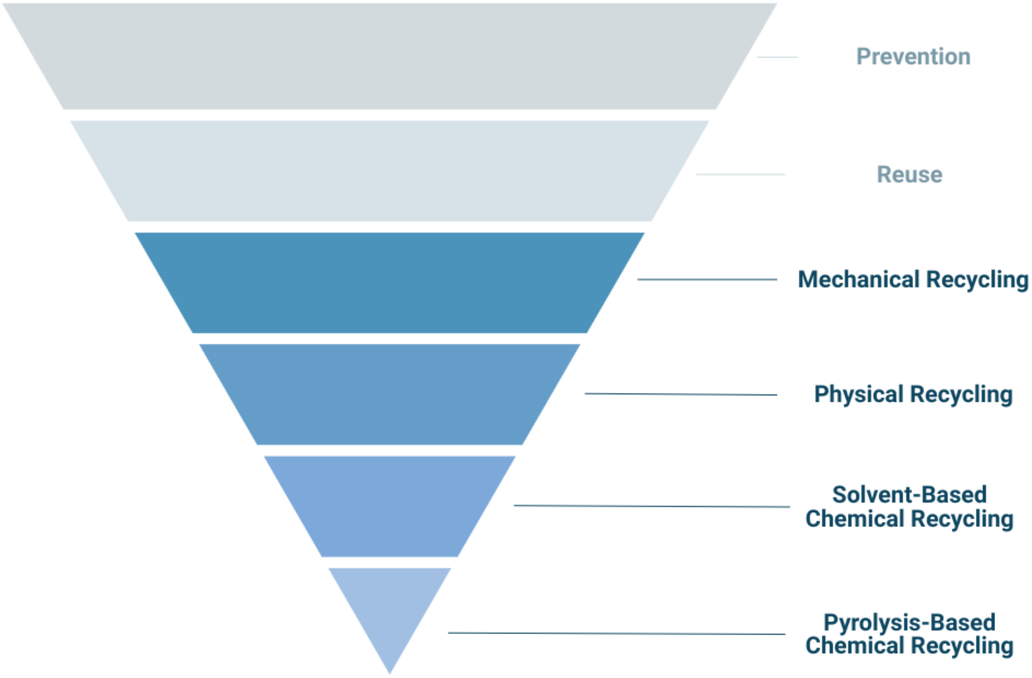

Figure 1: *The hierarchy of plastic recycling technologies in terms of environmental impact*

1. INTRODUCTION

1.1. Background

With the Clean Industrial Deal, the European Commission aims to "*make the EU world leader on circular economy by 2030*", by increasing circularity and recycling capacity in the EU.[2] To start this transition to a 'circular economy', the European Commission has already taken a sectoral approach as outlined by Regulation EU (2025/40) on its Packaging and Packaging Waste Regulation (PPWR) introducing recycled content targets for plastic packaging under article 7 (EC, 2025).

The PPWR adds compulsory requirements to the definition of recycled content that will be resolved at a later stage as part of secondary legislation and not later than 31st December 2026, including sustainability criteria and environmental costs (Article 7, para. 8 and para. 9). A mirroring clause also requires plastic recycling technologies outside the EU to meet equivalent sustainability criteria considering "*the standards of protection of the environment and human health*" as well as "*high quality recycling, such as resource efficiency and quality standards for the recycling sectors*" (Article 7, para. 10).

The problem is that established mechanical recycling cannot achieve these targets in the current conditions; and the only way that they can be met, at the back end (*i.e.* without improving upstream design of plastic) is for chemical recycling techniques to step up to the task. But, **they have yet to show such promise**. Moreover, they must do so without having adverse impact on human health and the environment.

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[2] European Commission, The Clean Industrial Deal: A joint roadmap for competitiveness and decarbonisation, 2025
https://commission.europa.eu/document/download/9db1c5c8-9e82-467b-ab6a-905feeb4b6b0_en?filename=Communication%20-%20Clean%20Industrial%20Deal_en.pdf

1.2. This study

Commissioned by the Rethink Plastic alliance, the aim of this report is to allow for a better understanding of the full environmental impacts of different plastic recycling technologies. It refers to a quote made by Scottish novelist Andrew Lang in 1910, on how analytical tools can be used inappropriately to guide political decision making. Lang chose the analogy that some people use these tools in the way that a drunk uses a lamppost “*for support rather than illumination*”.

In this case, the title refers to Life Cycle Assessments (LCA) of alternative plastic recycling technologies. This is because many LCA studies have been published in recent years that have underestimated the true life cycle impacts of chemical recycling and falsely showing the techniques as favourable, for example by failing to account for essential processing and upgrading stages and system energy use, and comparing with unrealistic counterfactuals (see Pires-Costa et al., 2022; Biessey et al., 2023;, Tabrizi et al., 2020; Rollinson and Tangri, 2020).

This report provides a technical critique of a recent LCA study published by the Joint Research Centre of the European Commission (JRC); hereafter called the ‘JRC Study’[3]. The JRC study uses LCA to compare the environmental impacts of different plastic recycling technologies, with its stated aim “*to close the knowledge gap and advise policymaking*”[4].

After this critique, recommendations are made for supporting robust sustainability criteria on plastic recycling technologies, followed by technical recommendations for future LCA models of the same. Its findings will be applicable to work on the PPWR, but also for other areas such as the Ecodesign for Sustainable Products Regulation (ESPR) (EC, 2022) and its secondary legislation development along with other sectoral legislations about plastic. The target audience is EU Member State policymakers, but this report should be relevant to other interested citizens seeking to better understand the environmental footprint of alternative plastic recycling techniques, not least future LCA modellers.

2. NOTES ON THE TEXT

Because there is no standard nomenclature for chemical recycling techniques, some explanation is necessary as to how this report addressed the problem. The matter is particularly relevant to the JRC study’s choice of categorisation. The reader is also advised to refer later sections of this report (Section 3 and Section 8) where the techniques are discussed in greater detail.

- For *chemical recycling*, the JRC study’s nomenclature includes both *pyrolysis-based* and *solvent-based* depolymerisation. The latter is also called “solvolysis” but this term is not used by the JRC authors.

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[3] García-Gutíerrez, P., Amedei, A.M., Klenert, D., Nessi, S., Tonini, D., Tosches, D., Ardente, F., Saveyn, H.G.M. 2025. Environmental and economic assessment of plastic waste recycling and energy recovery pathways in the EU, *Resources, Conservation & Recycling*, **215**, 108099.

[4] Section 1, page 2.

    - In the JRC study, the solvent-based depolymerisation category is split into sub-categories of *glycolysis*, *alkaline hydrolysis*, and a two-step *hydrolysis-methanolysis*. There are other methods, but not in the JRC study.
- *Physical recycling* is the name used by JRC study to describe what is elsewhere called *solvent-based stripping*. The term 'physical recycling' is avoided unless referring to its use in the JRC study, because:
    - The JRC study has got into a muddle: Text says that "*physical recycling is a variant of mechanical recycling*", while Figure 1 shows it, instead, grouped with chemical recycling[5] (Further discussion on apparent confusion here in the JRC study is provided in Section 4.2 of this report).
    - The use of the term *physical recycling* and its relation with mechanical recycling/chemical recycling has political origins, due to advantages that may be gained in countries which demand mechanical processes in their legislation for meeting recycling quotas (Quicker, 2023). See also a position paper by one technology provider (Altnau et al., 2021).
    - It is considered by many authors to be a sub-set of solvent-based chemical recycling. This is due to its use of chemicals to break apart the plastic material followed by purification stages using more chemicals, rather than physically grinding up the plastic as with mechanical recycling.

2.1. Abbreviations

CO_2 eq. = Carbon dioxide equivalent

CR = Chemical recycling

HNO_3 = Nitric acid

H_2SO_4 = Sulphuric acid

H_3PO_4 = Phosphoric acid

LCA = Life cycle assessment

MPO = Mixed polyolefins

MR = Mechanical recycling

NaOH = Sodium hydroxide

PE = Polyethylene

PET = Polyethylene terephthalate

PP = Polypropylene

PR = Physical recycling (aka. Solvent-based stripping)

PS = Polystyrene

TPA = Terephthalic acid (TPA)

VOC = Volatile organic compounds

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[5] Section 2.4.

3. PLASTICS RECYCLING HIERARCHY

Engineering obstacles block the realization of a circular economy in plastics. These are due to the laws of thermodynamics[6], and are the foundation of a plastic recycling hierarchy (Figure 1).

Specifically, unless information is built into the plastic to make it easily recyclable, **the deeper one decomposes a plastic, the more effort - energy and resources - will be needed to re-build it, while the more processing stages there are the more losses in efficiency there will be.** Consequently, this creates a fundamental hierarchy of plastic recycling technologies, which is **Mechanical recycling (MR) > Physical Recycling (PR) > Chemical Recycling (CR)**.

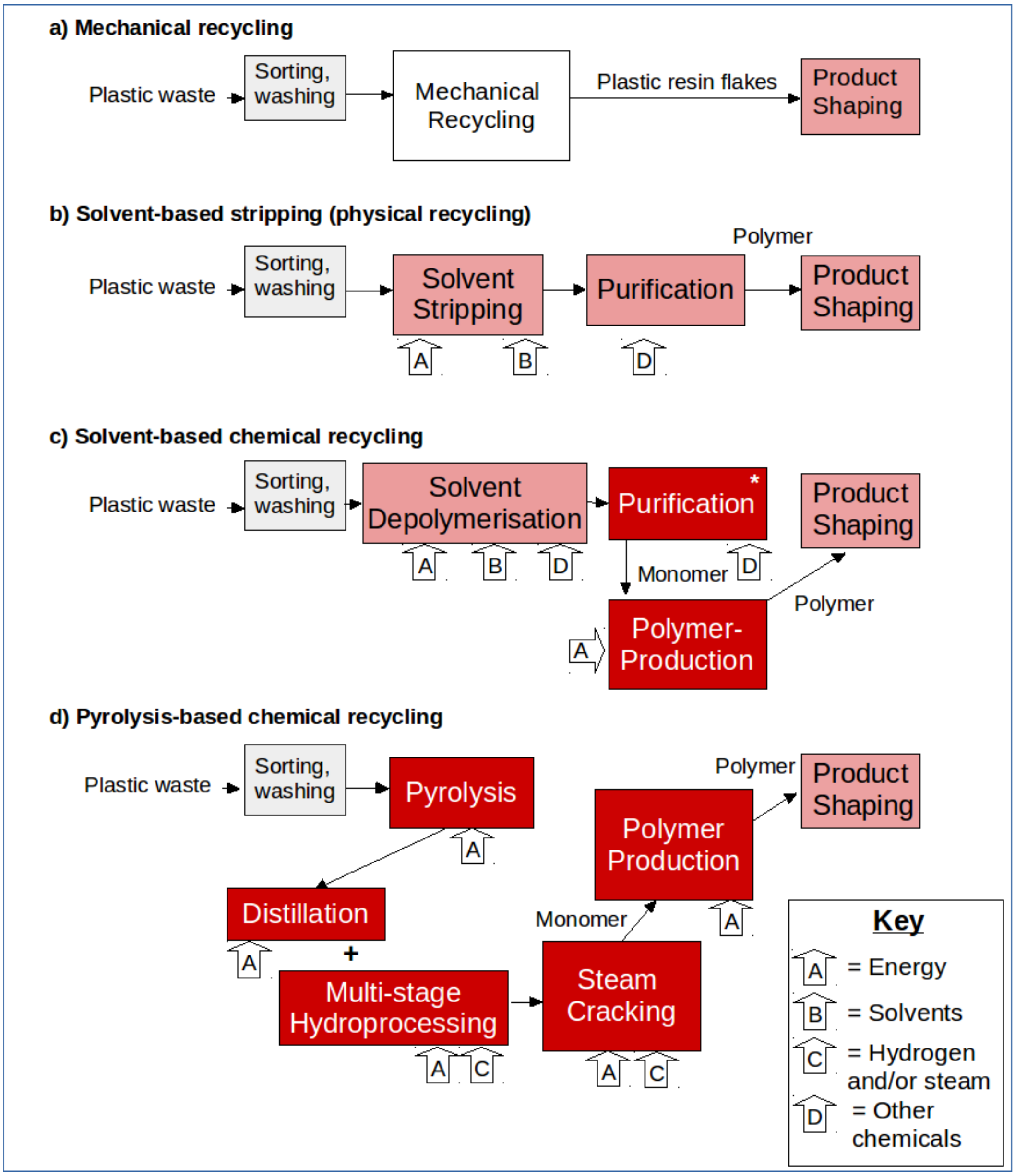

Figure 1. *The plastic recycling hierarchy showing stages involved in each process, and significant energy and resource inputs. Darker shading indicates highest energy and resource use. Each technique is discussed in further detail, later in this report. * = may involve multiple stages.*

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[6] The first law of thermodynamics states that energy must be conserved, thus providing a useful tool for quantifying system energy and mass balances. The second law states that whenever there is energy transfer some quantity must always be lost to a system's surroundings (measured as entropy).

Another way in which the MR > PR > CR plastics recycling hierarchy is illustrated is by considering the point where the first stage output re-enters the plastics production line. This is shown in Figure 2, with one metric (GHG emissions) applied. The further back in the plastic production process output re-enters the system, the more energy and resources will be needed to bring it back into use. For example, pyrolysis-based chemical recycling outputs with hydro-processing would not substitute 100% of the GHG emissions from virgin polymers: the process would only substitute the 20% for the extraction and/or mining of fossil fuels, but would also have to include its own processing on top which may cancel out the environmental benefit or may even be worse.

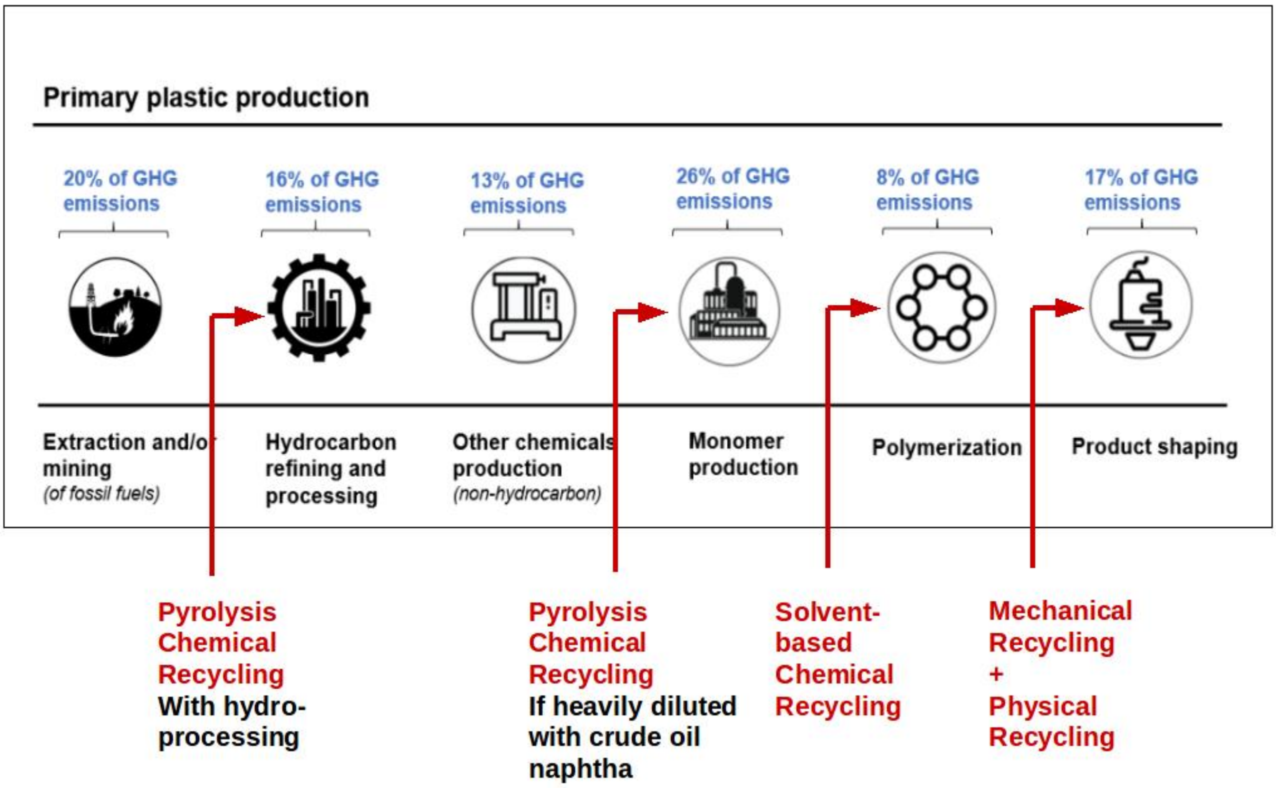

Figure 2. *The point where the product from three different plastics recycling techniques re-enters the plastics production line. Adapted from Karali et al. (2024).*

For chemical recycling only, a further sub-hierarchy can be made based on the same thermodynamic principles, this being **Solvent-based depolymerisation > Pyrolysis-based depolymerisation**. It comes from the energy needed to reverse the polymerisation reaction, a parameter known as ceiling temperature, shown for different types of plastic in Table 1. While there is some variance, it can be seen that polyolefins (PP and PE) have higher $T_{ceiling}$, and so will require more effort to revert them back to monomers; while for condensation polymers (like PET), depolymerisation requires less effort and can be facilitated using solvents. However, this is a simplification, because when the reactions settle at equilibrium the product is not just monomers from which the plastic was built, rather it is a complicated mixture of unwanted chemicals (including plastic additives) which then requires extensive effort to purify and upgrade. This complication affects both types of chemical recycling, and means that the limiting factor, where greatest environmental impact will likely occur, is not the depolymerisation step but subsequent purification and upgrading. This fundamental issue largely explains what is holding back chemical recycling. It also explains why it is easier (and less costly) to just burn the products of plastic depolymerisation, but then the question is relevant as to why use all the effort to depolymerise plastic in the first place.

Table 1. *Reported ceiling temperature for the thermoplastic polymers assessed in the JRC study. Adapted from Vogt et al. (2021). * = data differs between sources.*

Polymer	$T_{ceiling}$ (°C)	Type (formation)	Type of chemical recycling usually applied
Polyethylene terephthalate (PET)	300	Condensation/step growth	solvolysis
Polystyrene (PS)	235, 395*	Addition/chain growth	pyrolysis
Polypropylene (PP)	466	Addition/chain growth	pyrolysis
Polyethylene (PE)	407, 610*	Addition/chain growth	pyrolysis

4. THE JRC STUDY'S METHOD

4.1. Technology Boundaries are Confused and Unclear – Figures and Tables

Table 2 shows the chemical recycling technologies modelled and reported by the JRC study. The acronyms in column 2 are the JRC study's own, while the 'Notes' column describes some comments provided by the JRC study authors as to the system boundaries.

Table 2 is necessary because the JRC study Figure 2 – showing results - is not easy to interpret: there are many acronyms, small print and symbols, colour codes, small resolution and high value scales on the y-axis, combined with some undefined concepts such as "*Net result baseline*". Making elucidation more difficult, the acronyms for all scenarios are not fully defined in the Figure 2 caption; and while they are expanded in a separate and earlier Table 1, this cannot be seen at normal screen magnification.

Table 2. *Chemical recycling scenarios (techniques) modelled by the JRC study.*

Polymer	Abbreviation	Technology	Notes
PET	CR(I)	Partial glycolysis	Why this is 'partial' and what the other 'part' is, are not explained. No operating conditions are given. Other by-products or wastes are marked as "*N/A*".
	CR(II)	Methanolysis and hydrolysis	This is a two stage solvolysis, so would expect higher use of solvents and processing (this is not discussed by the JRC study). Hydrolysis can be acid, alkaline or neutral, but this information is not given. No operating conditions are given. Two products are listed. Other by-products or wastes are marked as "*N/A*".
	CR(III)	Alkaline hydrolysis	No operating conditions are given. Three products are listed, one of which is sodium sulphate which suggests that there applies some recovery of a reagent, but this is not discussed as part of the system boundary.

PS	CR	Pyrolysis	The text describes this as “*pyrolysis-assisted*” rather than just ‘pyrolysis’, so there may be some other adjoining technique applied. The text in Table 1, is also unclear as it describes the product as “*styrene*”, with the by-products as “*other styrenics*”, “*naphtha*’, and “*pyrolysis oil*”. This is strange because the oil is the primary product. No process conditions are given.
Mixed polyolefins (MPO)	CR(I) CR(II)	*“Pyrolysis (including hydro-cracking of pyrolysis oil)”*	No operational parameters are given. There is also some text confusion surrounding hydro-treatment and hydro-cracking (see section 4.11)
	CR(III)	*“Hydro-pyrolysis (including hydro-cracking of pyrolysis oil)”*	

4.2. Technology Boundaries are Confused and Unclear – Text

The **technology system boundary is perhaps the most important aspect of an LCA**: It marks out what is, or is not, covered by the range of the model, thus determining whether the model is comprehensive or limited, and ensuring that one technology is being accurately compared against another. Knowing what the boundary is also allows the findings to be taken in context, assessed for credibility, and also compared with other studies. The JRC study system boundaries are not adequately described and there is confusion:

4.2.1. The methodology section has text that ‘describes’ the system boundaries[7]. But, it is opaque and omits information on the important components that have associated environmental impacts, such as the volumes of solvent used, along with amount of pH adjusting chemicals, whether these were recovered or burned/disposed of, hydrogen for hydro-cracking of pyrolysis oil, the catalysts used in the processes, the GHG emissions for steam cracking, etc. Whether these are, or are not, part of the system boundary is not stated.

4.2.2. But taking a step back, even the definition of what constitutes the technology is ill-defined. Under its section Definition of Scenarios, the JRC study cites where it obtained its definitions of chemical and physical recycling “*for the purposes of this study*”. Two references are given[8]:

4.2.3. For chemical recycling, it is a single publication (Delva et al., 2019), and there are a number of problems with this source:

  4.2.3.1. It is a publication about mechanical recycling and does not go into any detail as to what constitutes a chemical recycling system (*i.e.* for the model’s boundary). Instead, only two small paragraphs describe that “*waste is chemically degraded into its monomers or other basic chemicals. The processes involved are amongst others*

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[7] Section 2.3.

[8] Section 2.4.

hydrolysis, pyrolysis, hydrocracking and gasification. The output may be reused for polymerisation into new plastics for the production of other chemicals or as an alternative fuel". Thus:

4.2.3.2. It includes plastic to fuels, which does not align with EU policy.

4.2.3.3. It includes gasification, which is not reported by the JRC study.

4.2.3.4. It is factually misleading, although not absolutely incorrect. The output of a process such as pyrolysis – the most common plastics depolymerisation concept - cannot be used ***directly*** "*for polymerisation*"; instead it needs extensive upgrading and/or dilution first before it can be fed into a steam cracker, after which comes polymerisation (ECOS, ZWE, RPa, 2024; Rollinson, 2023). This key aspect is not described by the source reference.

4.2.3.5. In summary, the definition is most general and not practically accurate, which cannot have helped define how the JRC study authors set their model boundaries, and certainly does not help the reader. For example: for pyrolysis-based CR, did their system boundary include distillation, steam cracking, hydro-processing, and polymerisation, including the impacts of producing hydrogen, for all technologies, and if not, which ones? For solvent-based processes, were the impacts of solvent production included, along with the impacts of solvent regeneration or wastage, was the embedded impacts of chemical reagents included, and impacts of purification steps?

4.2.4. The source used to define physical recycling is Collias et al. (2021). This also provides no background information as to what the JRC study's system boundary is. Physical recycling is illustrated as a sub-set of 'Material Recycling', and only shown as being able to accept PP and PE. There is no other text description of what physical recycling is or how it is defined in terms of associated use of energy and resources, and the treatment of residues/waste.

4.2.5. With pre-treatment, the JRC study's model assumes that all waste has been sorted. Therefore it does not assume that chemical recycling can accept mixed waste streams, which formerly had been claimed by industry. This is good.

4.2.5.1. However, the JRC study could be clearer about what type of pre-treatment was applied, and for which techniques. For example, text states[9]:

> "*Where relevant, sorting and pre-treatment technologies are included, e. g. for chemical recycling, as well as any of the technologies transforming the plastic waste into plastic recyclates, co-products, energy and emissions*"

But it is not clear why the phrase "*where relevant*" is used, since all modelled scenarios, according to Figure 1, produce "*recyclates*". For purposes of transparency it should be stated what scenarios (technologies) were relevant, *i.e.* when the impacts of pre-treatment were applied to the model and when it was not.

4.2.5.2. Furthermore, washing and drying are common pre-treatments (which incur the use of energy and resources, and generate wastes), perhaps also shredding (energy use). But there are other pre-treatments depending on the type of technology, one being microwave-assisted pyrolysis which requires, in addition to homogenisation and shredding, mixing of the feedstock with catalyst or other wave absorbing media

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[9] Section 2.1.

(Rollinson and Oladejo, 2019). Were any of the pyrolysis techniques microwave assisted?

4.2.6. Taken together, what this means is that **the boundary is essentially unspecified, and the findings of the study should be treated with extreme caution.** The issue is important because to see the full picture, all these resources and energy usages, stages and inefficiency losses (waste generation and its safe disposal), along with those impacts embedded in the materials used, must be captured by an LCA and clearly shown to be so.

4.3. The Study has no Input Data – It is not Reproducible

The input data for the JRC study is not provided. Information such as what energy is used for each stage of the processing, what amount of solvent and anti-solvent were used per unit of waste, what happened to the solvent (flared or recovered), were the embedded environmental impacts of process reagents included (Technical Box 1), what was the yield and losses at each stage of the processing, and much more, are all missing.

Good models can provide valuable insights, but they are only as good as the input data. In other words, put poor data in, and poor results will come out. For this reason, full disclosure is required to ensure that the boundaries have been set correctly and that the input data is sensible. As stated (Pires Costa, et al., 2022):

"*All LCAs [of chemical recycling] should be better documented, particularly when system expansion is performed, so that the reader can reproduce the study independently and without considering the 'avoided impacts' in order to evaluate the process performance in more absolute terms and to optimize the chemical process*".

4.3.1. All scientific research must provide sufficient clarity on the input data and its provenance, so that the study can be reproduced by peers to arrive at the same result. It is a fundamental tenet of the scientific methodology, and rightly, transparency is also emphasised in the LCA standards (ISO, 2006):

> "*Due to the inherent complexity in LCA, transparency is an important guiding principle in executing LCAs in order to ensure a proper interpretation of the results*"

4.3.2. The lack of transparency on the input data is problematic because it does not allow the reader to confirm the JRC study's conclusions. Because the JRC study does not follow these fundamental principles, the findings cannot be supported, since they cannot be verified or reproduced. As such, for scientific purposes, the findings of the JRC study have little or no value.

4.3.3. At the end of the paper there is a statement "*Data will be made available on request*". This author asked, by email, for the raw data; but the response was that it would not be provided as it was confidential (Rollinson, 2025).

4.3.3.1. The JRC study's lead author went on to say that this statement was addressed only to peer reviewers. When asked whether the peer reviewers were given the raw data, the reply was that they were not. This means, if the peer reviewers did not see the raw data, how can they support the acceptance of the results? **It is important, essential even, for checking the veracity of a paper, that peer reviewers see the input data.**

***Technical Box 1**. Embedded carbon emissions of solvent-based recycling.*

Solvents
Solvents are volatile organic compounds (VOCs) made from petroleum. Most are toxic or hazardous, so covered by REACH, with also high boiling points meaning they need intensive treatment for distillation and recovery if they are to be re-used (Sherwood, 2020; Ügdülier et al. 2020).

Reagents
Nitric acid (HNO_3) is predominantly made from ammonia which is created via the Haber-Bosch process using hydrogen. Most of the world's hydrogen is made by the steam reforming of natural gas, an industrial process that is very energy and GHG intensive, emitting 1.3Mt CO_2 per year globally (Fink et al., 2024).

Most of the world's sulphuric acid (H_2SO_4) comes from natural gas or petroleum/crude oil. Some is made from the sulphur by-product of metallurgy, but this involves burning at high temperature (1030 °C).

Over 95% of sodium hydroxide (NaOH) is produced by the electrolysis of salt water – the chlor-alkali process, which also creates chlorine gas. The process requires 1MWh per tonne of sodium hydroxide (Kumar et al., 2021). Salt-water electrolysis is a tremendously energy and GHG-intensive process, which also requires high water consumption, along with the need to extract, and purify, salt from sea-water.

There are two industrial methods of making phosphoric acid (H_3PO_4), both energy intensive and heavy GHG emitters (Bertau et al., 2025). The wet process involves acid digestion of phosphorous-bearing rock, using sulphuric acid (see above). The dry process involves chemical reactions of phosphate ore with coke (from coal) in an electric arc furnace.

Recovering Solvents and Reagents
Solvents can be recovered using steam distillation, but this is a high-energy process (Uekert, et al., 2023). However, because they are cheap, and due to the effort and energy costs needed for their recovery, common industrial practice is to incinerate them on-site (flaring).

Sulphuric acid is not easy to regenerate and it is cheap to buy. It can be neutralized by Sodium hydroxide to form sodium sulphate which is highly soluble in, and difficult to remove from, water, so its discharge causes environmental pollution.

Nitric acid is expensive. In theory there is a process to use ammonia (Schnabel Process) and steam heating to recover the reagents, but these are both resource and energy intensive.

4.4. Provenance and Range of Input Data is not Disclosed

4.4.1. The provenance of the input data is not stated. So, it is not known whether the results were based on input data from test tubes in a laboratory, pilot scale trials, or large industrial plant.

4.4.2. And, it is not disclosed what extrapolations were made, if any, to account for the differences in technology readiness. This is another limitation in data provision.

4.4.3. It is not stated how many datasets there were per recycling technique. There may have been just one for, say, PET methanol-hydrolysis, and this may have been a lab-experiment. The fewer datasets there are, the weaker the results.

4.5. Methodology of Data Collection is Obscure

The JRC study's text says that primary data was "*provided by stakeholders participating in a data collection exercise*" "*in the EU27*".[10] While this raw data is not provided, neither is information on who the stakeholders were, nor is there disclosure of the survey used.

4.5.1. This practice is not in line with robust methodology. Surveys and data collection should be systematic to avoid leading questions and the receipt of biased answers. The robustness of this methodology cannot therefore be assessed.

4.5.2. Notwithstanding, reliance on stakeholder provision is not a good thing. Such provenance sources are not independent. Stakeholders, by nature, have a stake in the concept. The data supplied could represent favourable snapshots of operation, incomplete datasets, or merely projections based on optimistic predictions. The 'use of primary data' is used as a selling point of the JRC study, but it is, in fact, a weak point.

4.5.3. It is not absolutely clear whether some of the data could originate from recycling technologies in third countries. The relevant text on this subject says:

> "*Primary data [was collected] via a dedicated stakeholder consultation involving operators for plastic waste management in the EU27*".
>
> The key term here "*operators for plastic waste management*" is not defined, and vague. It could mean companies with a global reach, that have facilities outside the EU from which they presented data.

4.6. The Input Data was Adjusted, but it is not Explained How

The JRC study text says that "*Wherever needed, these data (sic) were complemented with additional data from existing databases, the literature, or specific assumptions*"[11]. This is concerning because:

4.6.1. There is no comprehensive information as to when the data was supplemented, which literature and databases were used and when and what specific assumptions were made. Again, this further undermines the credibility of the results.

4.6.2. While the text goes on to say that such information is "*…as described in the following sections*", it is not.

4.6.3. What the text does say is that "*Forty seven mechanical, physical and chemical recycling operators provided primary data, which was thoroughly checked and adjusted to ensure that the mass balance was closed*"[12]. The key word here is "*adjusted*". The adjustments are not described, and although the sentence goes on to state:

> "*…i.e. the amount of input waste (with impurities) was equal to the mass of recovered useful products/co-products plus residues and losses.*"
>
> it would have been orthodox practise to disclose the adjustments, perhaps in the supplementary material, for **the impact of these adjustments on the JRC study's findings remains unknown.**

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[10] Section 2.5 and Section 1.

[11] Section 2.5.

[12] Section 2.5.2.

4.7. A Selective and Unstructured Literature Review

There are formal methodologies for how to conduct a literature review. The literature review in the JRC study has no methodology assigned to it. Rather, it is a very brief list of some LCA papers. How they were chosen is not described.

4.7.1. Structured review methodologies ensure that the research remains robust against accusations of selective citing. In common language, selective citing is known as **‘cherry picking’**, which then gives an improper, biased, portrayal, which in-turn can be used to shape a pre-conceived narrative, such as ‘chemical recycling is environmentally sound and needs political support’.

4.7.2. Though it is not the intention to accuse the JRC authors of selective citing, to give one example, the JRC study omits a very similar LCA by U.S. government Department of Energy researchers. This stated that pyrolysis [and gasification] have economic and environmental impacts 10 to 100 times higher than virgin polymer production due to high energy requirements, subsequent need for upgrading, and low yield of suitable monomers (Uekert et al., 2023). This conflicts with the findings of the JRC study.

4.7.3. The same high energy use and GHG emissions are associated with solvent-based stripping (Uekert et al., 2023). The JRC study does not show that these aspects of solvent use and management were incorporated into their modelled system boundary, nor are they discussed.

4.7.4. There is also no critique of the findings of the studies reviewed, such as where other LCA models set the boundaries of the LCA, other than they did not use primary data[13]. Comparing the differences in modelling method of past LCAs, particularly the system boundary, would provide a valuable insight.

4.7.5. **What is also missing from the JRC study is a review of reports (independent or otherwise) that explain the reasons for historical plant closures, such as from real-life case studies**, i.e. closure of chemical recycling plants seems to be constant (Bell, 2023; Smith, 2025). A discussion on the reasons behind these closures would have been very relevant, for the best way to understand is to learn from history. This might also help to “*close knowledge gaps and advise policymakers*”. For example:

4.7.5.1. Recently in the U.S.A., Brightmark’s chemical recycling plant closed due to bankruptcy, with the chief restructuring officer saying that the hydro-treater that was supposed to clean the pyrolysis oil and a fractionator that separated the cleaned oil had not worked; with the plant only processing 5% of its design capacity; and operational running costs of $800,000/week all while working under $172 million of debt (Greenwood, 2025).

4.7.5.2. Though the JRC study does not assess PVC recycling – which is correct, for chemical recycling of PVC is not feasible since it largely produces toxic and corrosive by-products (ZWE, 2021) - it would have been relevant to discuss the former VinyLoop [solvent-based stripping] plant in Belgium. This plant closed in 2018 having been operational for sixteen years, and the lessons learned would apply to all solvent-based recycling methods. Plastic containing PVC was dissolved in a mixture of two solvents, then precipitated out by steam-drive solvent evaporation. Phthalate esters – additives in the plastic - transferred into the recyclate (which may be advantageous

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[13] Section 1, page 2.

for recycling), but phthalate esters are toxic and new REACH regulation dictated that companies importing, using, or isolating these substances needed authorisation, which VinyLoop didn't have (Sherwood, 2020).

4.7.5.3. Another example is a case study on the failed Creasolv plant in Indonesia, which would have helped guide on the low yield and liquid waste issues. It was reported that between 40% to 60% of the feedstock because waste residues, while there were alleged reports of bright blue effluent being dumped at the site and the emission of black smoke contaminating surrounding neighbourhoods (Aliño et al., 2022).

4.8. Weaknesses on the Functional Unit

In the JRC study, the model's functional unit is "*1 tonne of (sorted or pre-treated) plastic waste, wet weight, containing any impurities embedded within it*".

4.8.1. It is not clarified whether this input is post-consumer or pre-consumer waste. This is very important, since many of the chemical recycling technologies are so very sensitive to impurities that post-industrial waste is a more suitable feedstock. But accepting pre-consumer waste has little environmental benefit and should not be considered 'recycling'. Avoiding pre-consumer waste is mostly part of an efficient production process and industrial ecosystem. Currently, the real difficulty lies in the collection and recycling of post-consumer waste. Ensuring that plastic products have indeed reached consumers before being called 'recycled' is crucial in the spirit of the circular economy.

4.8.2. What fraction of post-consumer of pre-consumer plastic waste and whether this was fixed across all technologies raw data is not specified. Differences here may give a distorted outcome of a technology's capabilities and lead to inappropriate comparisons.

4.9. Weaknesses on Products Substitution Factors and Yields

The study has several uncertainties on the recycling yields linked to the functional unit. **The yields are largely undisclosed, and how they were calculated is not disclosed at all.** This issue impacts on the waste valorisation assumptions or the system boundaries used for calculating them.

4.9.1. It would be interesting to see, or at least have comments from the JRC study's authors on, how the results would change if the functional unit was back end. For purposes of standardisation, the functional unit of an LCA model can also be back-end, *i.e.* per unit of product from a variable quantity of waste. The JRC study is however vague on how the yields were determined, while the quality aspect of the product is just assumed to be good (1:1 in many cases). This perhaps reflects the fact that the model was derived from industry claims that were not independent.

4.9.2. The text goes on to say that "*the focus is on the valorisation of the waste, and the co-products generated via the management operations are (sic) credited by replacing corresponding market products, according to their respective quality and substitutability*"[14]. But there are clearly errors here:

4.9.2.1. In Supplementary Table 3, char from pyrolysis of CR (III) or MPO is assumed as a 1:1 replacement for virgin bitumen. This is despite the fact that char from pyrolysis is nothing like bitumen. As such, the model has applied a 'substitution potential' that does not exist for this scenario, which will have given the chemical recycling technique an inappropriate and favourable environmental impact score.

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[14] Section 2.2.

4.9.2.2. Also, for CR (II) and CR(II), the same table shows that carbon black is produced. This is not correct. The char is the final repository for many of the contaminants and is likely to be hazardous waste, so will not substitute carbon black (Bell, 2023; Rollinson and Oladejo, 2020). Rather such residues have to be incinerated or treated otherwise for disposal (Quicker, 2023; Schade et al., 2024). This again will have given the chemical recycling technique an inappropriate and favourable environmental impact score.

4.9.3. Some values for processing yield are given, but they are few and not defined, so the reader cannot assess what they mean[15].

4.9.3.1. Personal correspondence with the JRC study's lead author revealed that there was a mistake in the manuscript, and that the yield values stated for "*material recovery*" (41-42%) were for mechanical recycling (Rollinson, 2025). All the reader is told here is that this gave "*lower substitution revenues*" for mechanical recycling in comparison to chemical recycling (the chemical recycling yield is not given). This is very subjective reporting, for the system boundary is not defined, and it is also not explained what the chemical recycling yield was with which to compare it.

4.9.3.2. A further yield range is given (53-65%) but it is not assigned to any technology. Personal correspondence revealed that this should read "53% for MR, 65% for CR." But, again, to assess what this means one needs to know the system boundary, in other words what equation was used for calculating the yield.

4.9.3.3. The above is very relevant because of all the losses associated with the many stages involved in chemical recycling; for which a model using a 'front-end' functional unit may not have captured. It is grossly incorrect to assume that 100% of the plastic waste fed into a chemical recycling depolymerisation step will ultimately create 100% monomers oil yield. The recycling utility of pyrolysis oil, for example, is nowhere near to 65% as the oil is unsuitable due to contaminants and off-specification hydrocarbon chemistry (ECOS, ZWE, RPa, 2024; Rollinson, 2023). So, what does the yield refer to? And is credit mass balance used to calculate it, and, if yes, using which attribution method?

4.9.4. It is hard to see the benefit of comparing plastic recycling with incineration/energy recovery. Such counterfactual modelling has already been criticised as having little worth (Tabrizi et al., 2020). As elsewhere stated (Pires Costa et al., 2022):

> *"It is important to compare distinct chemical recycling strategies among themselves, instead of comparing with dubious technological competitors that include mechanical recycling, landfill disposal and incineration. Then, results of attributive LCA analyses should be compared with each other, considering the plastic production based on recycled plastic streams, fossil raw materials, and renewable raw materials."*

4.10. The Enduring Issue of Intermediates

For mechanical recycling, the point where a recyclate becomes 'end of waste' is simple: the output can be used directly into plastic product shaping. However, t**he chemical recycling technologies do not make an 'end of waste' material; they create intermediates that need substantial use of resources and energy for purification and upgrading.** For the pyrolysis route, even after upgrading,

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[15] Section 3.1.3.1

the oil must be fed into the high energy intensive steam cracker to be made into plastic monomers thus putting this technique at the bottom of the plastic recycling hierarchy.

Yet, it is an enduring misunderstanding as to just what constitutes the chemical recycling boundary, and its extent is seldom, if ever, resolved. The concepts that are just the first treatment stage (e.g. pyrolysis or solvolysis), are not chemical recycling. **The JRC study does not evidence that it has captured the extensive amount of post-processing involved, and hence captured the full environmental burdens of resource and energy use, along with wastes generated.** For example, in Figure 1 (of the JRC study) a simple box diagram has the caption "*simplified diagram of the system boundary*". Here, there is just one box titled "*physical or chemical recycling (including pre-treatment)*". So:

4.10.1. It is not clear as to why pre-treatment is applied here and not to the mechanical recycling scenario.

4.10.2. It is not clear whether this includes purification and upgrading, or blending with virgin naphtha, steam cracking and oil refining. At least this is not shown.

4.10.3. This is then fed into "*polymer or chemical production*", so does one assume that the model has excluded the steam cracking impacts?

4.10.4. The output is "*chemical (sic) or polymers*". But just what these are is not explained.

4.10.5. This lack of understanding is currently causing problems in the drafting of other EC recycled content definitions (see ECOS, ZWE, RPa, 2024). It is also common in previous LCAs of chemical recycling, where the energy use and resource use of downstream clean-up processes are significantly underestimated (Biessey et al., 2023).

4.11. Specific problems with hydro-treatment/hydro-cracking

There are specific problems with the JRC study's presentation of hydro-cracking and hydro treatment. This suggests confused understanding, which may have translated into the model and affected its results.

Hydrocracking and hydro-treatment are two different methods, often combined in series, one operating at high temperature to 'crack' the hydrocarbons, the other operating at lower temperature to remove impurities (see Technical Box 2). Yet:

4.11.1. Table 1 of the JRC study says that for chemical recycling of MPO, techniques CR(I) and CR(II) used "*Pyrolysis (including hydro-cracking of pyrolysis oil)*". But, the "*main product*" is "*Hydro-**treated** pyrolysis oil*", [author's emphasis] not hydro-cracked oil.

4.11.2. Contradicting the above, Supplementary Table 3 reports "*Hydrotreated pyrolysis oil*" is only a product of CR(II). It is not listed as a product of CR(I) and CR(III), both of which, according to Table 1, have "*Hydro-treated pyrolysis oil*" as a product.

4.11.3. It may be the authors have got confused with CR(III) in Table 1 which is described as "*hydrothermal pyrolysis*", and they have assigned this to the wrong technology in Supplementary Table 3 (CRII). This can only be guessed.

4.11.4. Both processes are resource and energy intensive. As such, the energy needed for high temperatures and pressures, effects of coke build-up on plant components (reducing yield and increasing energy consumption), the waste disposal of components such as filter media), the extraction costs of mining catalyst, the poisoning of catalysts or the energy and resources needed to regenerate catalysts, along with gaseous emissions such as CO, SOx, NOx, VOCs and particulates, and also hazardous wastewater containing suspended solids, H_2S, NH_3 are all part of the process and all should be included in technical and economic assessments. Yet, there is no evidence of such in the JRC study.

4.11.5. Though the JRC study describes hydro-processing, it is unclear whether the very production of hydrogen and its environmental impacts have been factored in for hydro-processing.

Technical Box 2. Hydro-processing.

Hydro-treatment and **hydro-cracking** are different oil-refinery upgrading techniques. They are used to clean out impurities and improve oil chemistry, often combined in series. Both come under the umbrella of **hydro-processing**.

Although used in petroleum refining for years, there is no evidence that either can operate successfully with plastic-derived pyrolysis oil even at pilot scale. The problem is that plastic-derived pyrolysis oil is more contaminated with additives than petroleum, and it has a different hydrocarbon chemistry.

Hydro-treatment

Hydro-treatment is used to improve the quality of an oil by removing contaminant chemicals, but not significantly 'crack' the oil hydrocarbons. Hydrogen is needed in greater quantities than with hydrocracking and costs are greater; and it requires catalysts that are selective for the type of oil and the target contaminant, usually Ni, Ca, Mo are active metals supported on alumina or silica, but platinum group catalysts have been trialled. (Faisal, et al., 2023). The operating temperature is in the range of 190°C-340°C with pressures of 20-204atm (Belbessai et al., 2022).

The outstanding issue with hydro-treatment of plastic-derived pyrolysis oil is finding the right catalyst that can cope with the different halogen and metallic additives from plastic that transfer into the pyrolysis oil. This might require other upstream measures to remove contaminants such as physical filtration. But this is just another domino cascade, requiring more resources, energy, effort and costs, and creating spent media that contain the hazardous contaminants that then need disposal.

Hydro-cracking

A petroleum-oil hydro-cracker typically operates at between 420-440°C and pressures around 100 atm. So, the energy use and GHG emissions will be greater than hydro-treatment. It is a bit like a second stage pyrolysis reactor but with hydrogen, used to change some of the heavy oil components into simpler molecules more suited for steam cracking.

For petroleum distillates, the catalyst is typically Ni-Co-Fe or Mo-Wu-U on a silica/alumina support. But, what is the right catalyst for plastic-derived pyrolysis oil with all its many contaminants is hardly researched and unknown.

Hydro-processing catalysts

Hydro-processing catalysts are very sensitive to poisoning from contaminants and coke build up from heavier hydrocarbons. Catalyst activity declines as soon as the process comes on-line, and operating temperature has to be gradually increased to maintain the same efficiency, while increasing hydrogen content helps to slow catalyst deactivation. Unless terminally damaged (such as by sintering), catalysts may be regenerated in a stream of oxygen at high temperature to burn off coke deposits, followed by a dilute stream of hydrogen to reduce the catalyst.

5. SCIENTIFIC ANOMALIES IN THE JRC STUDY'S RESULTS

This section shows how the shows the limits of the JRC study methodology that have translated into biased results. To illustrate, a selection of results from the JRC study are presented and discussed.

5.1. The JRC study reports that the $CO_{2..}$eq. emissions (*climate change*) for *processing - non-energy* for all pyrolysis and hydro-processing techniques are all less than mechanical recycling option 1[16]. This is highly implausible due to the high heating requirements of hydro-processing which need steam and hydrogen, catalysts and catalyst regeneration, as well as the resources needed for producing hydrogen. The only way that it can be so is if these were, inappropriately, set outside the model's process boundary, hence not looking at the full life cycle impacts.

5.2. Similarly strange results are presented for PET chemical recycling: Of the three PET solvent-based CR processes, CR(II) is a combined process so **should use more solvent and reagent** (resources), but for some reason, the JRC study finds the opposite in the category of energy expended for "*Resource use, fossils*":

5.2.1. For *processing - energy*, CR(II) is claimed to use **twenty two times less energy** than CR(I) and **thirty one times less energy** than CR(III)[17]. This anomaly is not discussed by the JRC authors.

5.2.2. For *processing - non-energy*, CR(II) is reported to use **three times less energy** than CR(III).[18]

5.2.3. All three chemical recycling methods have the same value (667 MJ) for energy used in treatment of resources. Why this should be is not explained. It likely represents an assumption based on weak input data, but possible implications are not discussed.

5.2.3.1. A probable, and significant, impact of this anomaly on the JRC study's findings is that climate change emissions for *treatment of resources* with all three PET CR technologies are around the same order of magnitude as for MR of PET[19], a finding that is clearly incredible and can only mean that the embedded energy in solvents, catalysts, etc., plus their post-process treatment for the CR technologies have been set outside the system boundaries.

5.3. In Figure 2, PET hydrolysis-methanolysis - CR(II) – appears to be zero for *Climate Change* impacts for *processing energy*, meaning that processing energy results in no greenhouse gas emissions. This time, the oddity appears to be due to another error in the manuscript, namely the information has been 'missed' from the results when Figure 2 was created, for the data in Supplementary Material gives the *Climate Change* impact for *processing energy* for PET CR(II) **double that** of CR(I) and **1.3 times greater** than for CR(III) both of which are shown on Figure 2[20].

5.4. Further unreasoned results are how *climate change* impacts (GHG emissions) from physical recycling of PE can be less than for mechanical recycling of the same plastic waste in the categories: *processing energy*[21]. Physical recycling is also reported to use less processing –

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[16] Supplementary Material, Section 10: MR = 6.3 kg $CO_{2..}$eq, CR(I) = 4.56 kg $CO_{2..}$eq, CR(III) = 0.618 kg $CO_{2..}$eq.

[17] Supplementary Material, Section 10: CR(I) = 284 MJ, CR(II) = 6300 MJ, CR(III) = 8700 MJ.

[18] Supplementary Material, Section 10: CR(II) = 3920 MJ, CR(III) = 12500 MJ.

[19] Supplementary Material, Section 10: CR(I), CR(II), and CR(III) all = 159 kg $CO_{2..}$eq. MR = 123 kg $CO_{2..}$eq,

[20] Supplementary Material, Section 10: CR(I) = 373 kg $CO_{2..}$eq. CR(II) = 769 kg $CO_{2..}$eq, CR(III) = 557 kg $CO_{2..}$eq.

[21] Supplementary Material, Section 10: PR = 296 kg $CO_{2..}$eq. MR = 345 kg $CO_{2..}$eq.

energy (*Resource use – fossils*) than mechanical recycling[22], and perhaps most surprisingly of all, mechanical recycling is claimed to use **over three times** the *processing - non-energy* fossil resources than physical recycling[23]. This cannot be correct because physical recycling uses large amounts of solvents and other reagents compared to a process that merely grinds plastic into flakes.

5.4.1. Unless there have been errors in data processing by the authors, one must assume that **the true impacts of the physical and chemical recycling processes have either not been disclosed by the 'stakeholders' or not appropriately captured by the model's system boundaries which does not consider the full life cycle impacts.** These should however have been picked up by the authors, for is a fundamental part of research analysis to first check over results to see if there is anything strongly amiss.

5.5. Perhaps the most improbable result is with pyrolysis CR of PS. The JRC study finds that climate change emissions from processing energy are 246 kg CO_2 eq. per tonne of waste processed[24]. Absurdly, this is somehow claimed to be less than that for mechanical recycling of the same plastic (273 kg CO_2 eq.).

5.5.1. To put these, and other, findings in context: here we have, on the one hand, a process (mechanical recycling) that merely grinds up the plastic for re-shaping; versus another (pyrolysis) that requires the burning of large amounts of fossil fuels for external heating to attain and maintain temperatures of about 500°C so that the plastic can be broken down to its component parts using heat, maybe using catalysts and hydrogen, then following pyrolysis there is equally high temperature hydro-processing, further high temperature steam cracking, and subsequent re-polymerisation.

5.5.2. Here, the errors can however be quantified against a real-life example. The former Agilyx (pyrolysis of PS) plant emitted over 3 t of CO_2 for every tonne of plastic waste processed in 2019, and a huge 47 t of CO_2 per tonne of plastic waste processed the year before; this came from burning over 250,000 m^3 of natural gas per year to heat pyrolysis along with burning some of the plastic waste itself (Patel et al., 2020). Using these values as a comparator, the results of the JRC study have **underestimated climate change impacts by between 12 and 191 times for the chemical recycling of PS by pyrolysis, and illogically reported that it is better than mechanical recycling.**

5.5.3. But, even this is an underestimate, for these quantified emissions concern only the pyrolysis stage. They do not include all the emissions from purifying the pyrolysis oil (by hydro-processing), nor steam cracking the monomers, nor polymerisation when looking at the full life cycle impacts.

5.6. Similarly, the JRC study's results are dubious in terms of *processing – energy* (*resource use, fossils*) for the same technology – CR of PS. These suggest that pyrolysis chemical recycling of PS uses less processing energy (4190 MJ) than mechanical recycling (4590 MJ) per tonne of plastic waste[25].

5.6.1. Comparing these values against the data for the former Agilyx plant: In 2018 the Agilyx plant burned 50, 645 MJ of natural gas per tonne of PS processed, and in 2019 it burned 19, 610

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[22] Supplementary Material, Section 10: PR = 4940 MJ, MR = 5740 MJ.

[23] Supplementary Material, Section 10: PR = 368 MJ, MR = 1110 MJ.

[24] Supplementary Material, Section 10.

[25] Supplementary Material, Section 10.

MJ of natural gas per tonne of PS processed[26]. Against these figures, the JRC study has underestimated the *resource, fossil use* processing energy by between 5 to 12 times. As above, **this is still an underestimate as it concerns only the initial pyrolysis stage and not the full life cycle impacts.**

5.7. There is only incineration/energy recovery with which to compare car tyre pyrolysis (defined as CR, though this is not a plastic to plastic recycling technology); but some inaccuracies are worth mentioning, as they emphasise the same limitations of the JRC study.

5.7.1. The climate impacts of processing energy are only 114.8 kg CO_2 eq. per tonne of tyres[27]. Compare this with the Agilyx plant data (3000 to 47000 kg CO_2 eq), which although fed with PS, one would expect the CO_2 emissions to be approximately the same. The JRC study **CO2 emission values are 26 to 409 times less than what they probably are.**

5.8. It has been common for some technology providers to say that pyrolysis could self-sustain on its own products, in other words that it needs no external heating (Rollinson and Oladejo, 2019). Due to the input data being confidential and from industry sources, this may be one explanation for the unusual and implausible results concerning pyrolysis-based chemical recycling. But, even if the pyrolysis stage just burns its own products and does somehow self-sustain, it will still generate GHG emissions, as the only way to operate pyrolysis is to burn fuels to continuously supply it with heat. Of course, **this also does not account for the subsequent hydro-processing, steam cracking, and polymerisation stages**. The GHG emissions cannot be as low as estimated by the JRC study.

5.9. For some reason, the JRC study paper does not present or discuss any results on the **toxicity factors** associated with its modelled technologies. This is despite both human toxicity (cancer and non-cancer) plus freshwater ecotoxicity being three of its modelled impact categories[28] (in line with the PEF impact category indicators). The results are tabulated without discussion in Supplementary Material, and upon scrutiny they yield some very strange results:

5.9.1. The freshwater ecotoxicity score associated with the treatment of residues for physical recycling of PE is less than that for mechanical recycling of the same polymer[29]. Once again, it is hard to see how this can be so, due to the use of solvents and reagents in solvent-based stripping, against none in mechanical recycling.

5.9.2. A similar trend is reported for freshwater ecotoxicity from processing non-energy with MR values being approximately double those of PR[30].

5.9.3. The scores reported for non-cancer human toxicity associated with treatment of residues, is again greater for MR of PE than PR of the same polymer[31]. Granted, the numbers here are very small, but being approximately the same is an anomalous result.

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[26] This data is not in the aforementioned paper by Patel et al., 2020. It is based on the same source data, this being: For 2018, the plant processed 196 tonnes of PS and used 231631m^3 of natural gas having a total energy content of 9960151MJ. For 2019, the plant processed 581 tonnes of PS and used 265045m^3 of natural gas having a total energy content of 11396945 MJ

[27] Supplementary Material, Section 10.

[28] Section 2.6.

[29] Supplementary Material, Section 10: PR = 498 CTUe, MR = 674 CTUe

[30] Supplementary Material, Section 10: PR = 1790 CTUe, MR = 3160 CTUe

[31] Supplementary Material, Section 10: PR = 2.33E-7 CTUe, MR = 2.61E-7 CTUe

5.9.4. It would be expected, due to all the solvents and other reagents used in physical recycling, compared to none used in MR, that the toxicity scores for PR would be much greater. Indeed, this is what is reported by Uekert et al. (2023) who show high toxicity scores for various PR techniques all associated with waste disposal.

5.9.5. The impact of microplastics emissions is also relevant for plastic recycling technologies. It should be further assessed in a full life cycle perspective

5.10. The impact of water use for the different technologies is not adequately reported by the JRC study. It will obviously be high with hydrolysis CR, but it is also high with other solvent-based techniques:

5.10.1. The study by Uekert et al. (2023) reports the huge water use impacts of PR and CR, predominantly for cooling water. This is not evident in the JRC study results, even though text says that the burdens of processing – non energy include water use.

5.10.2. Nor is it apparent that the use of water for post process purification has been captured by the JRC study model. Quicker (2023) describes the use of water during PET alkaline hydrolysis:

> "*The recovery of monoethylene glycol is realized via condensation of the vapor in a first step or later stage in the process by distillation. The remaining sludge is dissolved in water and impurities like PP, PE and other plastics are removed by consecutively course and fine filtration steps. Finally, terephthalic acid is recovered by applying an acid (e.g.* H_2SO_4*) and purified*."

5.11. Scientific Anomalies in the Sensitivity Analysis

There is an interesting comment in the Sensitivity Analysis section[32], which is that "[certain results occurred because the model assumed] *a larger portion of energy (electricity and heat) being used in the production of the substituted (displaced) virgin products compared to the portion that is used in the recycling plants*". This appears to be saying that the authors assumed that recycled materials use less energy than virgin products, but any scientific basis for this assertion is not given.

5.11.1. This differs from the findings of Uekert et al. (2023) who reported that the economic and environmental metrics of pyrolysis are 10-100 times higher than virgin polymers due to the low yields of monomers suitable for repolymerisation (material retentions of 0.01 ± 0.003 to 0.14 ± 0.07) and the high energy requirements for the conversion and subsequent upgrading processes.

5.11.2. This relates to the uncertainties about system boundaries. It would be interesting to know whether the JRC study's model considered where each recycling technique introduces its outputs back into the plastics production line. **Each modelled scenario needs to include the energy and resources use for all stages AFTER it is included**, as shown in Figure 2 of this report.

5.12. Limited Limitations

5.12.1. Good scientific research reporting is to comment on limitations and on where results deviate from prior studies. Such comments on data quality should also have been discussed according to the ISO standard for LCAs (ISO, 2006):

> "*Descriptions of data quality are important to understand the reliability of the study results and properly interpret the outcome of the study*".

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[32] Section 3.2.

The JRC study does not mention the limited value of the non-independent 'primary data' at all. Nor does it comment on how the quality might be affected by any extrapolations to cover lab-scale studies or pilot-scale trials.

5.12.2. It is also conventional to discuss any clear anomalies in the results which relate to real-life case studies, such as the technical aspects listed in this section. The JRC study does not do this either.

5.12.3. It is common in scientific studies to use statistical analyses, such as error bars on graphs, to reveal variations in results across a range. No error analysis is provided by the JRC study. This may be due to their only being one or a few technology dataset on chemical recycling, as earlier stated, but this should have been discussed in the Limitations section.

5.12.4. The JRC study <u>*does*</u> discuss its LCC analysis as a limitation, namely that the findings are "*very uncertain and should be used carefully*" because the authors "*received very few primary data [and] had to supplement these data with equally poor data from the grey literature/databases*"[33]. Some further analysis would have helped and some disclosure of the data used, along with provenance. Consequently, and compounded by the fact that this LCC also relied upon the weak methodology and outcomes as the LCA, a critique of the LCC findings is not considered necessary.

6. PECULIAR STATEMENTS IN INTRODUCTION AND CONCLUSIONS

6.1. In the introduction to the JRC study, the authors say that:

"*Developing innovative recycling technologies is key to increase recycling rates and potentially improve environmental performance compared with existing treatment technologies*".

It is hard to understand why the authors make this point, unless they are setting up their findings at the outset, since:

6.1.1. There is no citation appended to this statement. Indeed, there is no evidence that it is true.

6.1.2. What the JRC authors omit to say is that regulating the plastics industry to make materials that are easier to recycle, is an alternative. Such upstream measures would reduce the entropy in plastic waste and so constitute a more efficient method than back-end clean up of a high entropy waste.

6.2. The Conclusions also include two stand-out comments:

6.2.1. The first is:

"*The development of advanced recycling should be incentivised to lower costs and environmental impacts, making recycling more competitive and viable for challenging waste streams like PS, MPO, PE and multilayer films*".

The introduction of this statement is also difficult to explain because:

6.2.1.1. Firstly, the study does not model multilayer films for chemical recycling.

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[33] Section 3.4.

6.2.1.2. Secondly, the study does not assess any relation between technical viability and financial support.

6.2.1.3. Thirdly, it is not clear how incentives can lower environmental impacts. It is certainly not discussed within the JRC study.

6.2.1.4. Fourthly, the repeated closure of chemical recycling plants occurs despite heavy financial subsidies (Mitchell, 2023). There are other technical factors involved as described in section 3 and section 8. Discussion of this subject from technical, social science, and industry perspectives, can be found in Vogt et al. (2021), Rollinson (2023), Bell (2023), Tulla (2022); Mederake (2022).

6.2.2. The second is:

> *"the sectors of physical and chemical recycling are experiencing rapid technological developments…"*

6.2.2.1. This is also not discussed in the paper.

6.2.2.2. Neither is it true. What is factual is that chemical recycling and physical recycling have received a lot of public attention in the last five years, mainly from plastics and petrochemical industry stakeholders and academia where funding has been made available. But this does not equate to rapid development. In fact, **technical development has been essentially stagnant since the 1970s** (Bell, 2023).

7. RECOMMENDATIONS ON THE JRC STUDY'S FINDINGS

It was not the intention of this research report to hypothesise whether the JRC study's authors have intentionally or inadvertently used their LCA model for "support rather than illumination". It has merely critiqued the review against the backdrop of high political ambition that chemical and physical recycling can step up to meet the EU's ambitious recycling targets. It is however worth mentioning that the use of statements in the JRC study's introduction and the conclusion, which are not supported by evidence nor the findings of the research, do not strengthen the credibility of the authors' position. The narrative of any study should only be drawn entirely from the results or literature included in its contextual analysis.

A critique of the JRC study provides lessons on the fundamentals of LCA modelling and scientific reporting. It reveals:

- The dangers inherent with relying on stakeholder data sets, particularly when the topic is politically charged as with plastic recycling, and even more particularly when the input data is kept confidential. It evidences the very good reason why **full disclosure is considered essential for good scientific research**.
- The dangers of not providing the input data to peer reviewers. If this had been done, the abnormalities in the results could likely have been identified. Even if the peer reviewers may not have requested access to the input data (it is unknown), for purposes of transparency and to properly test their research (which is the objective of peer review) **the authors should have insisted that the peer reviewers had the input data.**
- The consequences of a non-thorough literature review:
    - Common failings in LCA methodology for chemical and physical recycling LCAs were seemingly not taken into consideration by the JRC study authors and a critique of the paper indicates that most were repeated.
    - LCAs that showed chemical recycling as being worse environmentally than virgin plastic production, and hence which contradicted the findings of the JRC study, were not discussed.

A critique of the JRC study also reveals mistakes and multiple non-trivial weaknesses in its methodology such as lack of disclosure on model 'adjustments', poor resolution of the technology system boundaries including yields and intermediates, defects in attribution of substitution factors, and confusion as to the functioning of engineering processes. This has created multiple instances of seemingly implausible results, anomalies which are not discussed by the authors. Combined with 'guidance' by way of an unsubstantiated text narrative, **the JRC study shows physical and chemical recycling in a falsely favourable light in terms of many environmental impacts. As such, the JRC study and its findings should not be used as a guide for policymakers.**

8. RECOMMENDATIONS FOR FUTURE LCAS OF PLASTIC RECYCLING TECHNIQUES

In this section, greater detail is provided on the solvent- and pyrolysis- based chemical recycling techniques, along with solvent-based stripping. The focus is on illustrating the system boundary and environmental impacts, with the aim of providing a template for future LCAs. After a description of each technique, a list of parameters for accurately assessing the environmental impacts is offered.

8.1. Solvent-based Stripping – Physical Recycling

These methods do not seek to break the polymers, rather to strip out certain target components (polymers and/or additives) from the wider plastic matrix. Techniques are based on traditional wet chemistry involving the use of solvents, followed by other methods to extract the target substance such as adding chemicals to force precipitation, filtering, or using more solvent (anti-solvent). Readable accounts, with information on practical examples at pilot scale, are provided by Ügdüler et al. (2020) and Sherwood (2020).

The type of solvent is highly specific for the target substance to be stripped out, and in turn the anti-solvent (if used) to strip it out from the first. Basic chemical reaction principles dictate that the amount of solvent used has to be much greater than the plastic being treated, and the amount of anti-solvent much greater than the primary solvent. Consequently, the use of resources is substantial, which has practical implications, for while in theory it is possible to use a series of stages each extracting a certain additive, the resources, logistics and overall costs involved makes this totally unrealistic, all of which comes back to the enormous entropy built into plastic waste, and the resources needed to take it apart and re-build it.

As with any solvent-based technique, the solvents have an embedded environmental burden since they derive from petroleum refining and many have hazardous characteristics. Though they can be recovered after use, many have high boiling points meaning this is an energy intensive procedure. As stated by Uekert et al. (2023):

“*The economic and environmental impacts of dissolution are linked to the solvent, antisolvent, and steam for solvent recovery. The high impacts of the organic solvents and antisolvents are associated with fossil feedstock use and GHGs emitted during their production*.”

Also, the stripping reaction process can be slow, but this can be speeded up by using more resources and energy, such as more aggressive solvents, greater quantity of solvent, applying higher temperatures, or altering the pH of the reaction mixture (using reagents). Less hazardous solvents are often not as effective as the more hazardous ones (such as dichloromethane), which means that less of the target substance will be captured or the time necessary to reach equilibrium will be excessively long.

What happens to the large quantities of solvents, how much are regenerated, how much energy is needed for regeneration, how much solvent carries over into the recyclate, and the fate of plastic additives are largely undisclosed by industry and therefore unknown. The answers to such questions should be sought when considering any LCA model. Equally important are the quantities of water used and wastewater generated, the amount of electricity used for processing, and not least, the capture efficiency and where uncaptured additives go.

The matter of solvent recovery is modelled by Ügdüler et al. (2020) who suggest median values of 90% for solvent recovery, but do not address the important question of where the unrecovered solvent goes. If it goes into the recycled output this is just swapping one contaminant for another. The authors go on to conclude about the most commonly applied technique – dissolution-precipitation:

“*It is not feasible in terms of environmental and economic aspects. It is thus important to note that unless the process allows a highly efficient extraction of additives by using low amounts of relatively cheap solvents at moderate conditions, the process might not be applicable, even in the long term*”.

A general process schematic, with some major environmental impacts, is shown in Figure 3. Some key parameters are:

- Volume of solvents used (including anti-solvent)
- Embedded environmental impacts of solvents
- Energy use
- Water use
- Disposal impacts if solvents not regenerated (such as GHG emissions from flaring)
- Impacts from manufacture and disposal of filter media.
- Fate of plastic additives and other plastic residues
- Yield of process (for each stage)

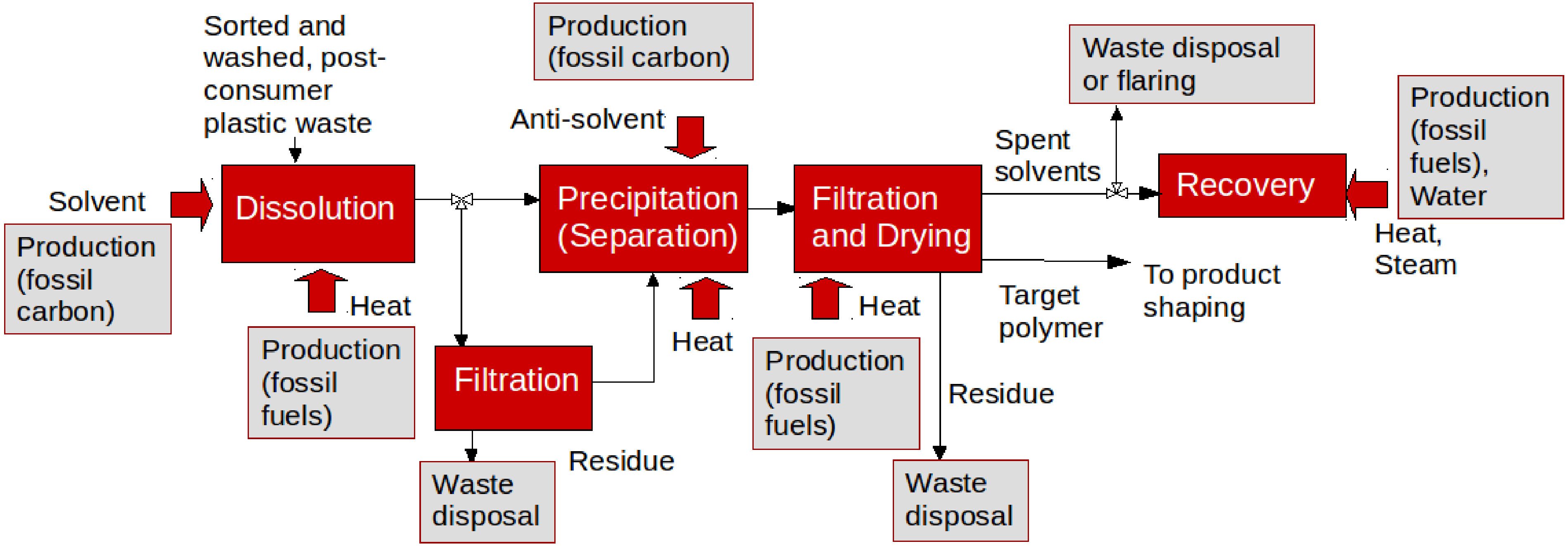

Figure 3. *The key processing stages involved in solvent-based stripping (physical recycling) of plastics, with major environmental impacts. Note that methods vary and this is a general schematic.*

8.2. Solvent-based Chemical Recycling

Information for this section was drawn from the following sources: Biessey et al. (2023), Quicker (2023), Ghosal and Nayak (2022), Polk (2003), Vogt et al. (2021).

Solvent-based chemical recycling needs temperatures in a range (60 ≤ °C ≤ 350), so uses less energy than pyrolysis-based depolymerisation. Additional environmental burdens occur with the use of catalysts to speed up the process and increase yield, plus in some cases the application of pressures up to 50 atm. along with the inclusion of other chemical reagents.

Consequently, there are considerable disposal costs associated with solvent-based depolymerisation. High water use, large electricity use, cost and hazardous nature of solvents, and slow reaction speed, on top of which are the costs of additional process chemical, are all factors which work against the concept being practically feasible.

Chemical engineering fundamentals constrain the technique, such as larger volumes of solvent needed to generate a high yield of recycled material, and a monomer/oligomer/solvent mixture from which it is difficult to purify the target molecules. To increase the yield, more extreme conditions are needed, such as temperature, pressure, catalyst, or more aggressive solvents, thus increasing energy and operational cost, and also creating more waste.

The techniques are sensitive to impurities and need a high-quality, single-polymer, homogeneous feedstock which makes them a direct competitor with mechanical recycling, rather than a complementary technique. They are not suited for the removal of co-polymers, colorants/dyes, or other additives.

8.2.1. **Glycolysis of PET – CR(I)**

The technique to depolymerise PET, was invented in the 1950s parallel with the manufacture of the polymer at commercial scale and then continually investigated by many companies with little sustained commercial success. Process conditions for depolymerisation require an absence of oxygen at temperatures of 180 ≤ °C ≤ 240 and pressures of 1 to 5 atm. in a glycol solvent, often with catalyst such as metal hydroxides

The reasons for its lack of commercial uptake is partly because the glycolysis reaction is very slow and produces low yield without catalysts, which are then difficult to separate out from the product. It also has difficulty with impurities, making it more appropriate for post-industrial scrap.

8.2.2. **Hydrolysis of PET – CR(II)**

Here two variations of hydrolysis are briefly summarised. This is to cater for the unspecified type of hydrolysis in the JRC study CR (II). The specific alkaline hydrolysis – CR (III) in the JRC study – is detailed separately

As the name suggests, all hydrolysis of PET uses water as solvent. Neutral hydrolysis occurs under pressure (1-4 MPa) and high temperatures (200 to 300°C), with the reaction being slow and improved by higher temperatures, and/or catalysed by alkali metal acetates. It yields unwanted chemicals that need repeated separation steps. The product also contains most of the impurities present in the PET waste, so extensive and therefore expensive purification processes are required to obtain a Terephthalic acid (TPA) output of commercial purity.

Acid hydrolysis usually uses concentrated sulfuric, nitric or phosphoric acid. This creates severe corrosion issues and the generation of large amounts of liquid wastes containing inorganic salts.

8.2.3. **Alkaline Hydrolysis of PET - CR(III)**

Alkaline hydrolysis involves reacting PET with NaOH under pressure and temperatures 200-250°C to form the sodium salt of TPA. Acids are then added to precipitate the TPA from solution. This results in large quantities of inorganic salts that are waste products which may also be contaminated with alkali metals.

8.2.4. **Methanolysis of PET – CR(II)**

The use of methanol results in a complex product mixture of glycols, alcohols and phthalate derivatives. This then requires high effort in separation and purification. Usual engineering conditions are 180 to 280°C and pressures of 20-40 atm. with or without catalyst. Trialled catalysts are magnesium, zinc or cobalt acetates, and lead dioxide.

Vogt et al. (2021) suggest that it is the high costs of glycol (for glycolysis of PET) that is behind the use of (less effective) methanol. Despite this, other authors suggest that the cost of producing recycled PET by methanolysis is still twice that of virgin PET production (Ghosal and Nayak, 2022).

8.2.5. **Recommendations for Future LCAs**

There are two main issues in assessing this system: firstly the environmental impacts associated with depolymerisation, but also the higher effort (resources and energy) needed to clean up the product of depolymerisation. Therefore, determination of product quality after each stage is essential and it should not just be assumed that the product of depolymerisation is good enough for 1:1 substitution in virgin plastic production lines.

The key impact assessment parameters are similar to solvent-based stripping, but it must be remembered that purification might involve multiple steps (see Figure 4):

- Volume of solvents used
- Embedded environmental impacts of solvents
- Volume of reagents used
- Embedded environmental impacts of reagents
- Energy use
- Water use
- Disposal impacts if solvents not regenerated (such as GHG emissions from flaring)
- Disposal of reagents and by-products
- Impacts from manufacture and disposal of filter media
- Fate of plastic additives and other plastic residues
- Yield of process (for each stage)

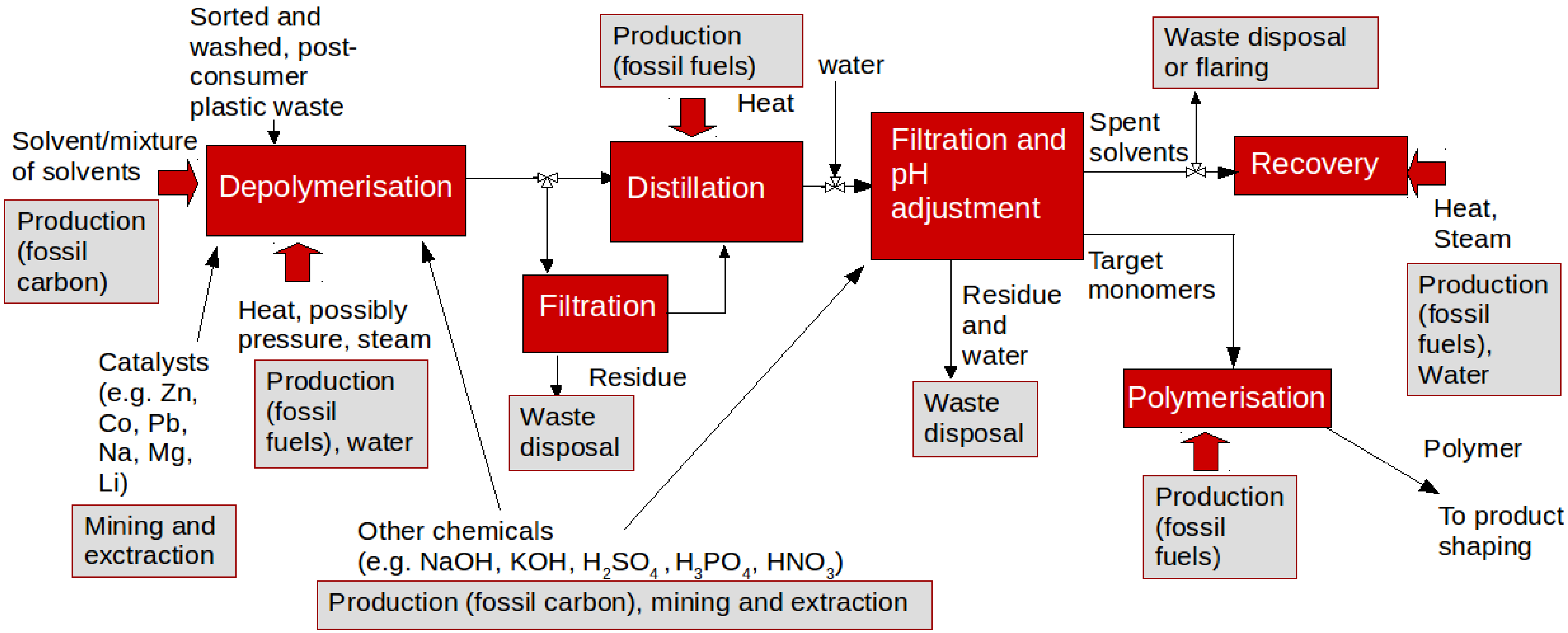

Figure 4. *The processing stages involved in a single type of solvent-based chemical recycling of plastics, with major environmental impacts. Note that techniques vary and this is a general schematic.*

8.3. Pyrolysis

Pyrolysis is the most commonly attempted depolymerisation technique for plastics, and further information on the technique and its system boundary can be found in Rollinson (2023) and ECOS, ZWE, RPa (2024). In summary, pyrolysis requires constant external heating and therefore results in high GHG emissions. Despite this the oil created from pyrolysis of plastic waste is a contaminant in plastic production lines (see Rollinson, 2023; Erkmen et al., 2023; Kusenberg et al., 2022). It has been quantified that **the oil is so poor that to mitigate just one of the many contaminants (oxygen) it would need diluting with at least 99.97% virgin petroleum naphtha** (ECOS, ZWE, RPa, 2024). **So the oil needs extensive upgrading or heavy dilution.**

It is essential for accurate LCA that the system boundary captures the **full extent of purification and upgrading of the oil**, and does not merely set the boundary around the pyrolysis stage (see Figure 5). It is also important that **the energy needed for creating monomers from the oil (steam cracking) and the energy needed for polymerisation are included in the system boundary too, along with the environmental impact of virgin naphtha if the oil is diluted**. Certain process parameters are not disclosed by industry, such as the pyrolysis oil yield, and quality of the said oil.

- Pyrolysis stage
  - Embedded impacts of catalysts (if used)
  - Embedded impacts of steam and hydrogen (if used)
  - Energy use (GHG emissions)
  - Oil yield useable for next treatment stage
  - Waste (liquid and solid) produced
  - Fate of plastic additives
- Hydro-processing (may be multiple stages)
  - Embedded impacts of catalysts
  - Embedded impacts of hydrogen
  - Energy use (GHG emissions)
  - Waste produced
  - Fate of plastic additives
  - Energy and resources used in regeneration of catalysts (or impacts associated with the disposal of catalysts)
  - Yield (quantity of product passing to next stage)
- Steam cracking
  - Energy (GHG emissions)
  - Yield (quantity of product passing to next stage – for recycling, this should only be the fraction used to make new plastics)

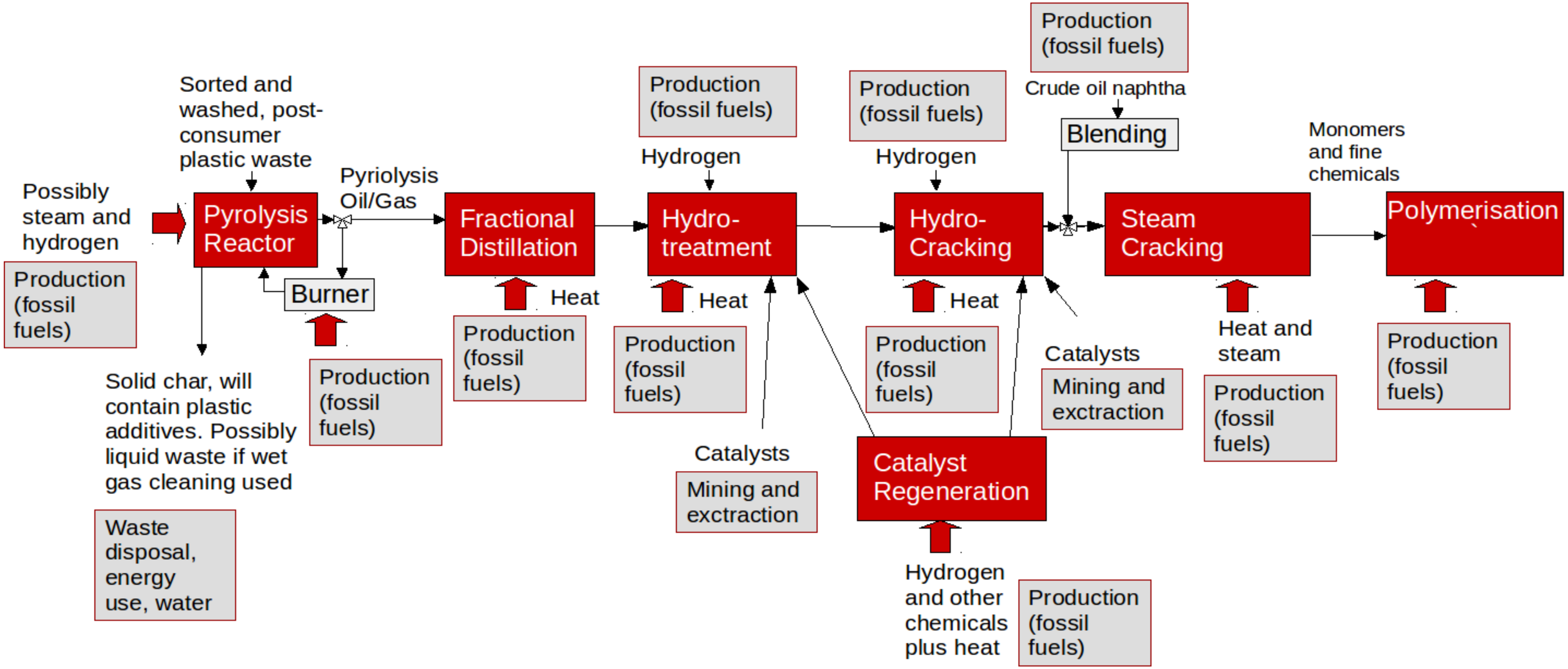

Figure 5. *The key processing stages involved in pyrolysis-based chemical recycling of plastics, with major environmental impacts.*

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