Understanding the Environmental Impacts of Chemical Recycling

Ten concerns with existing life cycle assessments

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Introduction

Chemical recycling and recovery of plastics often refers to processes such as gasification and pyrolysis, in which polymers are chemically broken down to monomers. These monomers can be used to produce new polymers and plastics, either by reproducing the original or developing new types of polymeric products (Grigore, 2017). However, more often than not, plastic is simply turned to fuel and then burned, releasing the carbon into the atmosphere. This is not defined as recycling in the EU Waste Framework Directive.

Recently, chemical recycling technologies have been promoted as being environmentally friendly, with claims that they can contribute to reducing environmental and climate impacts from plastic. For the purpose of science-based political decisions, it is crucial to have a complete and correct understanding of the true environmental impacts of these technologies.

However, good data on environmental impacts of chemical recycling is difficult to acquire due to the limited maturity of the chemical recycling concept at commercial scale: there are currently no operational plants of significant scale available to recycle plastic to new plastic, despite five decades of attempted effort. Yet, life cycle assessments (LCAs) developed by, or in affiliation with, businesses are being used to make sustainability claims related to these chemical recycling and recovery technologies.

This paper presents key findings from a review of some of the most commonly cited chemical recycling and recovery LCAs, which reveal major flaws and weaknesses regarding scientific rigour, data quality, calculation methods, and interpretations of the results.

LCA is a tool which can contribute to determining favourable technologies through different sustainability impact categories. However, the findings from LCA studies are highly affected by the set of boundaries, assumptions, and data used. Merely changing one variable can sometimes turn the entire results on their head. For this reason, LCA studies are notoriously easy to misinterpret and are sometimes used to draw general conclusions based on assumptions which may only be applicable in a very narrow context, or even incorrect.

Currently, there are no comprehensive and fully independent LCAs on chemical recycling to provide a complete understanding of the environmental impacts. If the EU wants to successfully transition towards a circular and decarbonised economy, priority should be given to prevention and reuse. Subsequently, only the recycling technologies which can or have significant potential to recycle as much material as possible while minimising environmental impacts should be supported, rather than alternatives such as pyrolysis and gasification, which require large amounts of energy.

Recommendations

- **Policy-makers should be cautious towards using chemical recycling LCAs as a basis for decision-making.** In particular, comparative LCAs in which chemical recycling technologies are shown as more favourable than other options should never be interpreted without a full understanding of real life datasets, geographical and system boundaries, assumptions made, as well as calculation methods which may have heavily influenced results. Attention should also be paid to the attribution methods of 'avoided emissions' and the benchmarks to which the technologies are compared.

- **The European Commission should support the development of more independent, transparent, and comprehensive assessments of environmental and climate impacts of chemical recycling based on primary data sources before developing further legislative frameworks incentivising the technologies.** Further attention should also be paid to toxicity and purity levels, as existing LCA studies systematically exclude or fail to fully disclose toxic and harmful contaminants and emissions, both in outputs and emitted during chemical recycling processes. These studies should be guided by a robust methodology for assessing the environmental and climate impacts of chemical recycling, taking into consideration real process yields and all the process steps, including purification and repolymerisation.

- **Investments and EU funds should only support plastic recycling processes with a lower carbon footprint than the production of plastic from virgin feedstock, with consideration to the actual process emissions.** In particular, the accounting of 'avoided emissions' from alternative waste disposal options for plastic, as a way to claim that chemical recycling has a net negative carbon footprint, should be strongly discouraged.

In order to provide a better understanding of the environmental impacts of chemical recycling to inform policy-making or to guide investments, the results of LCA studies must be presented alongside key knowledge on the topic:

- There is currently no large scale industrial chemical recycling plastic-to-plastic plant in operation (Quicker, 2019).

- Chemical recycling is energy-intensive and has multiple intrinsic and ancillary energy demands, which render it unsuitable for consideration as a sustainable technology. Even if the products/byproducts are burned for energy, there isn't a chemical recycling technology that can currently offer a net-positive energy balance (Rollinson and Oladejo, 2020), and there is no evidence that points to an improvement in the foreseeable future.

- Due to its power consumption, chemical recycling is commonly considered to be a low-value form of recycling compared to "recycling as material" (Ministry of Infrastructure and Water Management, the Netherlands, 2017), and leads to significant material losses in the process (Patel et al., 2020).

- Outputs from pyrolysis are not a directly recycled usable plastic. Further upgrade and processing is needed. As the pyrolysis oil is diluted with virgin naphtha to meet cracker standards, it means that only a very low fraction of chemically recycled material can be seen in the end product (Eunomia and CHEM Trust, 2020).

- Despite industry claims that chemical recycling can process various sorts of mixed plastic waste, relatively clean and homogenous plastic waste is required to achieve high yields and non-fuel based outputs (Eunomia and CHEM Trust, 2020).

Scope and Methodology

The findings presented below are based on a critical literature review of existing and commonly cited chemical recycling LCAs. The selected LCAs focus on pyrolysis, gasification, and solvolysis. Plastic-to-fuel LCAs have not been included in the scope, as the purpose is to review chemical recycling LCAs which claim to turn plastic back into plastic. However, similar concerns have in fact been observed in studies focused on plastic-to-fuel, particularly regarding the lack of data transparency, questionable GHG accounting methods, and misleading communication of results to policy-makers and the general public.[1]

[1] As an example, one such study (Benavides et al., 2017) comparing conventional fuel with plastic-derived fuels has been found to include emissions from combusting the former but not the latter, which is clearly biased (Rollinson and Tangri, 2020).

A list of the studies included in this review can be found below[2]:

List of LCA studies reviewed
Including abbreviated names used to refer to the studies in this paper

1. [BASF] Sphera Solutions GmbH, 2020, Evaluation of Pyrolysis with LCA – 3 case studies

2 [CE Delft*] Broeren, M., Lindgreen, E.R., Bergsma, G. 2018, Chemical Recycling Study. How great - what will be - the opportunities for climate policy? CE Delft

3. [Keller] Keller, F., Pin Lee, R., Meyer, B. 2020, Life cycle assessment of global warming potential, resource depletion and acidification potential of fossil, renewable and secondary feedstock for olefin production in Germany, Journal of Cleaner Production, 250, 119484, doi: 10.1016/j.jclepro.2019.119484

4. [Plastic Energy] Quantis, 2020: Life Cycle Assessment of plastic energy for the chemical recycling of mixed plastic waste. Prepared for Plastics Energy.

Critique of chemical recycling LCAs

1. **Claiming negative greenhouse gas emissions:** The BASF study shows that the greenhouse gas emissions from producing plastic (LDPE) via pyrolysis are approximately 77% higher than producing plastic using naphtha.[3] Yet, when the results of the study are summarised, it is claimed that pyrolysis is favourable to virgin plastic production and that it even has negative GHG emissions. This is explained by the attribution of 'avoided emissions' from alternative treatments for the plastic waste - in this case, from incinerating it (see Figure 1). This misleading presentation of climate impact fails to present the real GHG emissions data from the pyrolysis process technique itself in a transparent way.

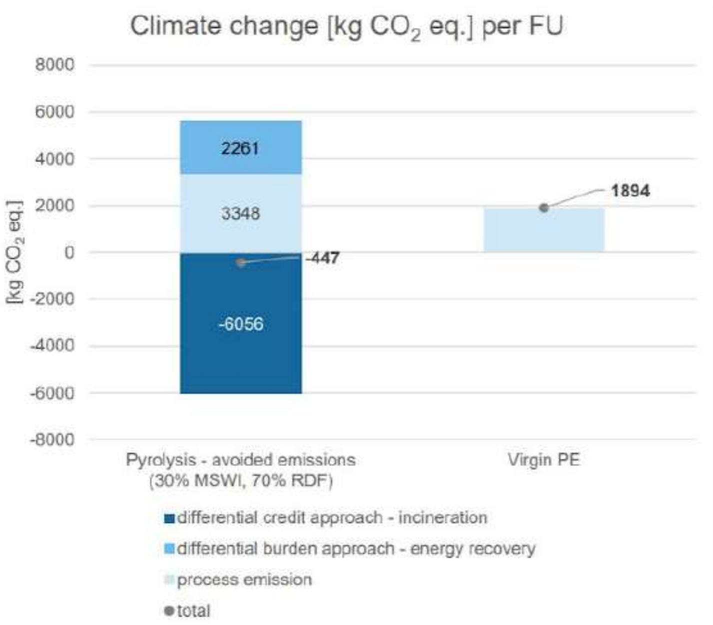

Figure 1 - BASF LCA and the use of "avoided emissions" to give climate credits to pyrolysis

[2] Please note the CE Delft study has a later revised 2019 document, available only in Dutch https://www.cedelft.eu/en/publications/2173/exploratory-study-on-chemical-recycling-update-2019. The Plastic Energy LCA critique is based on the summary document made available to the public: https://plasticenergy.com/wp-content/uploads/2020/10/Plastic-Energy-LCA-Executive-Summary.pdf

[3] 3,348 vs 1,894 CO_2 equivalents per functional unit (1 tonne of LDPE granulate produced in virgin-grade quality)

The practice of using discounted emissions from incineration and thereby assuming an ad infinitum recycling of polymers without degradation can be seen in several studies, including the BASF, CE Delft, Keller, and Plastic Energy studies. The LCA by Plastic Energy shows how GHG emissions from LDPE production via pyrolysis are higher than via mechanical recycling, as well as when compared to virgin LDPE production. Yet, it summarises the climate impacts for pyrolysis as being lower only due to avoided emissions from incineration (Figure 2).

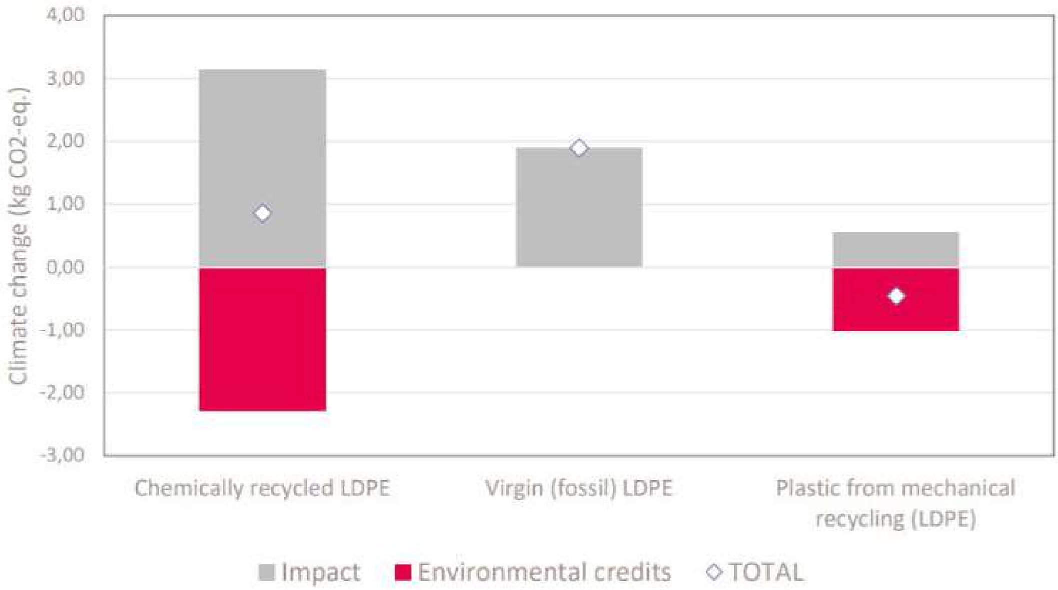

Figure 2 - Plastic Energy LCA and the use of "avoided emissions"

The Keller study similarly shows how olefin production via gasification has approximately 7 times higher Global Warming Potential than production from virgin crude oil.[4] However, its final results still state that olefin production via plastic waste gasification is associated with significant greenhouse gas emissions benefits, thereby portraying again gasification as favourable through the attribution of 'avoided emissions' from incineration. This selective presentation of key findings results is a misleading view of the real climate impact of chemical recycling, and cannot therefore be used to make claims on the climate mitigation potential of this technology, or used as a basis for decision-making.

2. **Assuming pyrolysis requires little to no external energy:** Energy use of the chemical recycling process is generally the most important aspect to consider in an LCA, as it is the aspect that most influences both environmental and economic performance (Eunomia, 2020). In particular, pyrolysis is an energy-consuming endothermic process that requires substantial amounts of externally applied energy to raise reactor temperatures and maintain internal temperature stability (Rollinson and Oladejo, 2019; Patel et al., 2020). The industry, even via the BASF LCA, claims that the gas produced during pyrolysis of the plastic waste can be used to cover almost all of the energy required for the process. The company publicly claims that less than 1% of external energy input is needed for start-up processes[5]. However, the amount of gas produced in the process is not stated in the BASF study, nor is its projected calorific value.[6] There is a clear trade-off between the use of the pyrolysis products and by-products (pyrolysis oil, char, and gas) to make new products and their use for energy to feed the pyrolysis process itself. If the goal is to maximise yield (and future yield increase is another

[4] As shown in Figure 7 of the paper, chemical recycling has approximately 7 times higher GWP at ca. 12.5 kg CO_2 eq./kg olefin produced in comparison to that produced from virgin crude oil (value = 1.56 GWP) https://www.sciencedirect.com/science/article/pii/S0959652619343549
[5] See response under question 5:
https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach/chemcycling/FAQ_ChemCycling.html
[6] The study assumes a 71% carbon conversion efficiency in the most conservative scenario (based on confidential data) and a 87% yield in an imagined "future scenario" which assumes technology improvements. From the given mass flows and byproduct losses in the study, the total amount of gas available for energy supply would thus be, at a maximum, 19%.

assumed factor in the LCA), then there will be very little gas by-product left to run the process, which would then lead to further need for external energy input.

Regulatory analysis by Agilyx Tigard Plant (Patel et al., 2020) shows that combustion of 1 m3 of natural gas is needed for every kg of plastic processed by pyrolysis. As the full energy and mass balance data has not been provided, the BASF study does not adequately address the claim that the pyrolysis plant can be sufficiently supported by its own by-products while also producing high enough yields to make its outputs competitive with raw material for virgin plastic production. It is also worth noting that reported emissions from energy use in LCA studies are frequently based on extrapolated data, often with multiple assumptions.

In the CE Delft study, it is also not clear whether the authors have accounted for the energy costs of pyrolysis, as this part of the methodology is not stated. However, as the report claims that the hydrous pyrolysis technology 'does not cause direct emissions'[7], it is assumed that the real energy costs are not truly attributed, thereby falsely inflating the technology's environmental credentials. The Keller study is equally vague on the energy balance for chemical recycling and the inclusion of energy costs of all the post-processing systems, which would have a great impact on the GHG emissions. We demand transparent energy balances as proof and full disclosure of the energy demands of all process steps.

3. **Extrapolated and undisclosed datasets:** none of the studies fully discloses the datasets used. Hence, there is no possibility to reproduce the studies to verify their findings, which undermines their credibility. For the CE Delft study, the authors themselves state that, since many chemical recycling technologies are still in development and have not yet been implemented at industrial scale, there are uncertainties in the results and they should be considered as indicative.[8] For solvolysis, the study refers to data being obtained from a confidential source. In the BASF study, not even the reviewers were given access to the original data in order to evaluate its quality and comprehensiveness. In that study, only data from one single provider of pyrolysis oil was used and, despite the study being set within a German geographical boundary, the provider was located in Spain. The link between feedstock inputs and product outputs were thus hypothetical. Furthermore, the purification steps of pyrolysis outputs were based on primary lab-scale data, meaning the findings have merely been extrapolated to imagine a full-scale commercial scenario. This is unsuitable data for assessing pyrolysis, as the key technological difficulties lie in the transition from lab to semi-industrial scaling of operations (Rolinson and Oladejo, 2020).

   The Keller LCA is also vague on the parameters and assumptions made, including the assumption that the process is unaffected by the feedstock used. In reality, gasifiers are highly complex, involving multiple interconnected parameters and with feedstock composition having the most important influence on product quality (Rollinson and Oladejo, 2019). This unreliable and unsupported use of assumed and confidential data does not provide a strong basis for claims on environmental impacts of pyrolysis. If the data used to develop LCA studies cannot be communicated publicly, neither should their results.

4. **The use of future scenarios:** despite being unable to model a current scenario, considering the lack of large-scale pyrolysis plants to provide the data, the baseline for the BASF study is the anticipated situation in 2030 of the waste management and pyrolysis technology in Germany, as well as an anticipated 2030 national energy mix for the country.[9] The specific assumptions for the future scenario, as well as their impact on the results, are not fully presented in the study. This means the study results are largely based on unverifiable assumptions which are only valid as long as these assumptions are met in the future. Similarly, the CE Delft study has assumed large-scale applicability of the technologies while simultaneously revealing that 'some chemical technologies have sometimes been in development for decades, [and] it is unknown to what extent these are useable for current plastic flows'[10]. It should be noted that the use of future scenarios in chemical recycling LCAs has not taken into account a situation in which there are also improved conditions for

[7] CE Delft LCA, p.33
[8] Extended summary, p.4 https://www.cedelft.eu/en/publications/2173/exploratory-study-on-chemical-recycling-update-2019
[9] BASF LCA p.20
[10] Delft LCA p.6

mechanical recycling and waste prevention (see point 6). This has particular impact on studies which compare mechanical and chemical recycling, and suggests a biased use of future scenarios.

5. **Biased assumptions on alternative treatments of plastic waste**: through their comparative approach, all of the studies have assumed chemical recycling will replace incineration or energy recovery for plastic discards. This may be the current practice for plastic rejects in some parts of Germany and elsewhere, but it is not the case everywhere. Many countries - even within the EU - do not even have incinerators or have small capacities, and the circular economy agenda refrains them from investing into larger ones. In those areas, plastic rejects typically go to landfills, where carbon is sequestered. There are also companies that process low-grade plastic rejects through extrusion, which - under the scope of this document - may be considered equal to mechanical recycling. Furthermore, recent political developments[11] at the interface of waste and climate are moving plastics away from incineration, as this is becoming an outlier in the decarbonisation policy of the EU and member states.

   The EU Plastic Strategy mentions incineration as a large emitter of GHGs, and lately there have been public announcements in countries like Denmark and Belgium to reduce reliance on incinerators for plastic discards in order to to align with its agenda on decarbonisation[12]. These policies - coupled with the ambitions of the Single Use Plastic (SUP) Directive to promote Deposit Return Schemes (DRS), higher quality of collected plastic and, above all, phasing out of the hard-to-recycle plastics - will create a better enabling environment for waste prevention and mechanical recycling. The quantities of plastic packaging waste sent to recycling have almost doubled since 2006 (PlasticsEurope, 2019). Hence, assuming the availability of a consistent percentage of plastic discards from separate collection, and from sorting platforms which could be used as feedstock for "chemical recycling" or alternatively incineration, is a weak assumption of the studies which is not aligned with the EU circular economy agenda.

6. **Biased portrayal of mechanical recycling:** Mechanical recycling requires less energy input than chemical recycling (Levidow and Raman, 2019). Despite claims that chemical recycling will not compete with mechanical recycling waste streams, a comparison of climate impacts of the two processes has been made in various LCA studies, including BASF (chemical vs mechanical recycling of PE, PP, and PS) and Plastic Energy (chemical vs mechanical recycling of LDPE). In the BASF study, chemical recycling was compared with mechanical recycling despite the chosen waste fractions not being ideal for mechanical recycling prior to sorting, during which the rejects were sent for incineration[13]. It is important to highlight this fact when presenting the results of the study, as 90% of mechanical recycling emissions have been attributed to the incineration of rejects - a number that would have been far lower for a waste stream more suitable for mechanical recycling. Furthermore, the modelling assumed that by-products from the pyrolysis process are treated in cement kilns to replace lignite while discards from mechanical recycling process were treated through incineration. In fact, it is a common procedure in Europe to treat mechanical recycling residues in cement kilns as well. This different assumed treatment of by-products between the two processes has an impact on final results.

7. **Incomplete sensitivity analysis**: In the CE Delft study, the results do not provide any statistical analysis, nor do they offer any range values though they assess a range of technologies. Some of the results provide instead an absolute 'best case' outcome illustrating only 'the technology that scores best with respect to the environment'[14]. It is, thus, impossible to know whether the other chemical recycling technologies were comparable, worse, or far worse than incineration. In the BASF study, when adjusting different variables to see how they might affect the final emission results, key variables related to the pyrolysis process itself, such as the energy demand, have been ignored. As pyrolysis is a highly energy-intensive process, the amount of energy needed and its source have a substantial impact on the final emissions and climate impact. The variability of input waste quality was also not considered, although the study focuses on a waste fraction from one of the most modern sorting plants in Europe. In general, sensitivity analysis should not only focus on one impact category.

[11] Including the EU Sustainable Finance Taxonomy and the Just Transition Fund

[12] https://translate.google.de/translate?sl=da&tl=en&u=https%3A%2F%2Fmfvm.dk%2Fnyheder%2Fnyhed%2Fnyhed%2Fregeringen-vil-have-co2-regningen-for-affald-ned%2F

[13] BASF LCA p.95

[14] CE Delft LCA, p.29

8. **Selective presentation of results:** when compared to pyrolysis, incineration performed better in 10 out of 19 impact categories in the BASF LCA (such as acidification or eutrophication). Pyrolysis only outperformed incineration in 3 impact categories. Yet, communication efforts from the study focus mainly on one of these three impact categories: climate change. The communication of the results even goes as far as to make broad claims that 'chemically recycled plastics cause significantly lower CO2 emissions than those produced from primary fossil resources'[15] even though this is only in comparison with incineration, for only one plastic type (LDPE), in a German geographical context, and with a number of other assumptions made. The Keller study similarly found that the gasification route resulted in higher emissions of all airborne parameters (CO2, CO, dust, NOx, SO2), and had a higher acidification potential in comparison to virgin crude oil/shale gas olefin production. None of these findings were reflected in the abstract, which focused on portraying gasification favourably in the climate impact category by comparing it with incineration.

9. **Unknown purity and toxicity levels of outputs and processes**: toxicity indicators are frequently left out in LCAs and environmental impact studies of chemical recycling, although this impact category should be of high importance when assessing a new technique known to generate highly polluted waste streams. For example, gasification of plastic feedstock is associated with production of phthalates, BPA, polybrominated diphenyl ethers, toxic brominated compounds, and PAHs - many of which are mutagens, carcinogens, and disruptive to respiratory or neurological systems (Verma et al., 2016). Pyrolysis is also well known to create toxic organic products, and emission factors of mutagenic PAHs from polyethylene increase markedly with temperatures above 700°C (Rollinson and Oladejo, 2020). The CE Delft study excluded all environmental effects other than climate change, yet it claims its objective is to provide an understanding of the environmental performance of chemical recycling technologies to help 'guide policymakers in policy choices'.[16] Similarly, the Plastic Energy study only focused on climate and resource use indicators. In the study commissioned by BASF, toxicity results were described as having a high uncertainty. Furthermore, material composition, toxicity, and fate of waste streams remain unclear for several processes such as pyrolysis, purification, and steam cracking. Therefore, no reliable data on human toxicity and ecotoxicity impacts from chemical recycling processes have been made available.

10. **Claiming virgin quality outputs:** the BASF study assumes that the pyrolysis process can eventually lead to plastic products with a quality comparable to virgin plastic. The CE Delft study also assumes that chemical recycling products can be sold and are of sufficient quality to replace conventional plastic production. However, numerous studies have found that pyrolysis oil from plastic waste has very high levels of toxic pollutants (Rollinson and Oladejo, 2020) and, thus, only a very low proportion of pyrolysis oil can currently be fed into existing cracking processes (Eunomia and CHEM Trust, 2020). There are two possible solutions to this problem. One is to purify and upgrade the pyrolysis oil until it meets the cracker specifications. However, this process is energy-intensive, carbon-intensive, and low-yield (Seidl et al., 2020; Mamani-Soliz et al., 2020). The other option is to dilute a small amount of pyrolysis oil with a much larger quantity of virgin fossil feedstock. This will sufficiently reduce the total contamination to allow production. However, this also means that the amount of recycled content in the new plastic is so low that it can hardly be considered recycling. It may be possible that running an equivalent cracking process using only pyrolysis oil is not even technically feasible. If a certain proportion of naphtha is necessary to run the process, environmental impacts from this fossil-based material must be included in the LCA as well. Moreover, it still remains unclear whether emission data, energy requirements, and quality demands of pyrolysis oil inputs are still valid for high shares of pyrolysis oil in the cracker input.

[15] https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach/chemcycling/lca-for-chemcycling.html
[16] CE Delft LCA p.44

Conclusions and Recommendations

It is very easy for results of LCA studies to be misinterpreted. This review has revealed ten ways in which existing chemical recycling LCAs are using undisclosed datasets, flawed assumptions, and creative accounting methods to provide misleading information on the climate and environmental impacts of the technologies.

Businesses have shown a tendency to report the main findings of LCAs without providing the full context. LCAs are often conducted within a narrow geographical boundary, with the energy mix of that country, on a specific waste fraction, and using assumptions which, using other variables, would have provided vastly different results. Yet, the results are communicated broadly without full disclosure of the circumstances, giving the illusion that decisive conclusions may be drawn from the study.

If the data used to develop LCA studies cannot be publicly communicated , neither should their results.

As such, chemical recycling LCAs should not be used for public communication or as a basis for decision-making or investments, but rather as a tool to support wider discussions.[17] **We strongly recommend policy-makers to take a precautionary approach** when interpreting environmental and climate impacts of chemical recycling-based on LCAs given the critical findings of this review.

Finally, we call for the development of more independent, transparent, and comprehensive assessments of environmental and climate impacts of chemical recycling based on primary data sources prior to developing further legislative frameworks incentivising these technologies.[18]

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Author(s): Shanar Tabrizi, Andrew Neil Rollinson, Marieke Hoffmann, Enzo Favoino
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Zero Waste Europe is the European network of communities, local leaders, businesses, experts, and change agents working towards the same vision: phasing out waste from our society. We empower communities to redesign their relationship with resources, to adopt smarter lifestyles and sustainable consumption patterns, and to think circular.

The EEB is the largest network of environmental citizens' organisations in Europe. It currently consists of over 160 member organisations in more than 35 countries (all EU Member States plus some accession and neighbouring countries), including a growing number of European networks, and representing some 30 million individual members and supporters.

Environmental Action Germany (DUH) has been campaigning to preserve the natural foundations of life for more than 40 years. In doing so, it brings together protecting the environment with consumer protection like no other organisation in Germany.

ECOS is an environmental NGO with a network of members and experts advocating for environmentally ambitious technical standards, policies, and laws. We ensure the environmental voice is heard at the table where these standards, policies, and laws are developed, challenging policymakers and industry players to implement strong environmental principles.

GAIA is a worldwide alliance of more than 800 grassroots groups, non-governmental organizations, and individuals in over 90 countries. With our work we aim to catalyze a global shift towards environmental justice by strengthening grassroots social movements that advance solutions to waste and pollution. We envision a just, zero waste world built on respect for ecological limits and community rights, where people are free from the burden of toxic pollution, and resources are sustainably conserved, not burned or dumped.

Rethink Plastic, part of the 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), European Environmental Citizen's Organisation for Standardisation (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.

Founded in 1899, NABU (Nature And Biodiversity Conservation Union), is one of the oldest and largest environment associations in Germany. The association encompasses more than 770,000 members and sponsors, who commit themselves to the conservation of threatened habitats, flora and fauna, to climate protection and energy policy. NABU's main objectives are the preservation of habitats and biodiversity, the promotion of sustainability in agriculture, forest management and water supply and distribution, as well as to enhance the significance of nature onservation in our society.

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