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QUANTITATIVE COMPARISON OF LCAS ON THE CURRENT STATE OF ADVANCED RECYCLING TECHNOLOGIES

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ADVANCED RECYCLING

Also called "chemical recycling," is a suite of sustainable technologies that transform used plastics into new products that can be recycled again.

Executive Summary

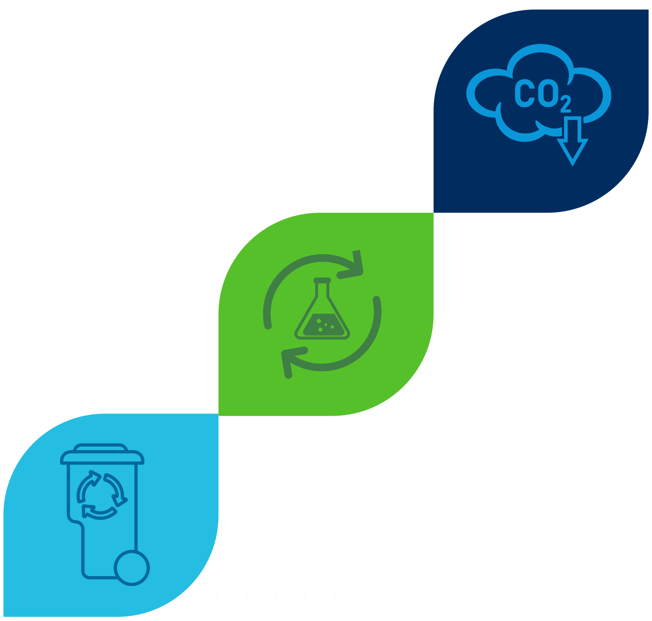
There is growing urgency to both increase plastics recycling rates and reduce the impact of plastic waste on the environment. Plastics often deliver many positive attributes when compared to alternative materials for the same products or packaging.[4] Therefore, efforts to ban plastics are often counterproductive to reducing environmental impacts. Evaluation of recycling growth options is an important part of a comprehensive approach to keeping post-use plastics in the economy.

Mechanical recycling rates for plastics in the United States have plateaued and many non-bottle plastics go unrecycled. Fortunately, plastics can be a feedstock for chemical synthesis—a process that can be achieved without combustion by several existing "advanced recycling" (sometimes called chemical or molecular recycling) technologies, which are being deployed and commercialized as a complement to mechanical recycling by a number of companies.[4, 5, 6, 7, 8] Advanced recycling (AR) processes break down the plastic polymers to their chemical constituents to enable downstream processes to re-manufacture new plastic products or plastic-derived chemicals. A review was conducted of thirteen recently completed Life Cycle Assessments (LCAs) on the advanced recycling of plastic material. The main objective was to summarize findings regarding the environmental impacts and assess similarities and differences in the resultant trends from those studies. The LCAs used different methodologies, but each included global warming potential data (GWP) from advanced recycling of post-use plastics.

The LCAs covered in this report include advanced recycling processes at large scale and high commercial readiness, which include pyrolysis, reforming, and gasification, as well as chemical depolymerization processes such as glycolysis, hydrolysis, and methanolysis. All the reviewed LCAs contain scenarios that show advanced recycling of plastics performs better than alternatives regarding greenhouse gas (GHG) emissions. Quantitative comparisons across those LCAs resulted in the finding that GHG emissions can be reduced up to 185%[5], or can be increased up to 267%[6] with the implementation of AR technologies. Over 30 other comparative scenarios were presented by the LCAs, with GHG emissions reductions ranging between -267%[6] (an increase) and +566%[7] (a decrease). Various impact categories in addition to GHG emissions were assessed, with performance of the AR technologies ranging from favorable, with pyrolysis of mixed plastic (MP) offering a 97% reduction in fossil depletion compared to waste to energy (WTE)[3], to unfavorable, with pyrolysis of MP offering a 400% increase in fine particulate matter compared to 30% municipal solid waste incineration (MSWI) and 70% refuse derived fuel (RDF)[3]. While there are performance differences between technologies, all LCAs asserted that the inclusion of advanced recycling contributed positively to a circular economy for plastics. In conclusion, highly versatile advanced recycling technologies can process a wide range of post-use plastics to produce in-demand chemicals and high-quality plastic products with a lower global warming potential than conventional processes.

CONTEXT

Given current substandard conditions on the state of plastics recycling rates, chemical and thermal recycling processes have gained interest as a complement to mechanical recycling. Advanced recycling and mechanical recycling together do not constitute the complete approach to managing post-use plastics. For example, combustion, i.e., WTE, manages nearly 16% of the post-use plastic to produce power and steam in the United States. The majority of plastic, about 76%, is captured by landfilling, which, compared to WTE and advanced recycling, is not a preferred method as per the United States Environmental Protection Agency (EPA),[8] even though landfilling currently manages the largest portion of the post-use plastic in the U.S.



OBJECTIVES

The LCA results in this report were evaluated based on best information and assumptions available when data was gathered and the report was published. Once advanced recycling facilities are continuously operating at commercial scale, it is essential to incorporate their actual operating performance to allow for confirmation or rethinking and re-evaluation of the processes and their precise environmental impact.

It is important to note that this report was not designed to provide a recommendation but rather to provide information to the many stakeholders evaluating the environmental performance of these technologies. Therefore, this is a quantitative informational report that should be evaluated with several other inputs in combination with the LCAs reviewed. In other words, LCA is one facet that must be considered in conjunction with several other factors not addressed in this report and requiring incorporation on a specific use-case basis. Regulatory and permitting procedures must be also evaluated on an individual technology basis when considering the deployment of a given process.

LCA COMPARISON OUTCOMES AND KEY FINDINGS

The selection of LCAs presented many discrete permutations of scenario analyses; from these, common trends emerged that cut across nearly all the studies. Those results are as follows:

A single value cannot be used to represent the environmental impacts of advanced recycling technologies. For example, the compilation of analyses demonstrate that use of AR reduces GHG emissions for a large majority of scenarios, yet there is a wide range, and the reductions are specific to a chosen parameter set.

Nearly two times more studies examining plastics in a circular economy were released in 2019 compared to 2010 - 2017. Research and publication are proliferating at an accelerating pace. Therefore, this analysis focused on data published from 2020 to present to include data that represents the current and imminent technology landscape.

Each LCA had some unique non-overlapping elements, however the commonality among the LCAs was an **assessment of global warming potential** of the thermal and/or depolymerization recycling of post-use plastics.

Compared to processes which use virgin fossil-based feedstock, advanced recycling technology can be used to produce in-demand chemicals and plastics with a global warming potential (GWP) ranging from an increase of 22% to a decrease of 185%, with the **majority of the data indicating reduction in GWP.**

Using advanced recycling technologies compared to alternative end-of-life processes, including production with fossil naphtha, incineration, and landfilling, can **reduce carbon dioxide equivalents (CO_2eq) emissions** by over 100%. **A reduction in excess of 100% signifies that emissions were prevented**, and such a reduction can be achieved due to credits earned from avoided products and/or energy.

Advanced recycling can significantly reduce the need for fossil energy resources by up to 97%.

All 13 LCAs reviewed consistently showed that advanced recycling yielded **favorable circularity results.** Circularity is further discussed in the Analysis Section I.b.

LCAs conforming with internationally accepted standards apply credits for avoided emissions to accurately capture emissions based on derived system boundaries.

Background

In order to explain the role of advanced recycling technologies in plastic conversion to products, a mass-based depiction of plastics use, disposal, and recycling lifecycle is shown in Figure 1. The process steps and mass fraction in each branch of the cycle are provided. The Combustion and Catalysis Lab (CCL) calculated the mass fraction of a 1 metric ton post-use plastic input stream based on sorting waste fractions and pyrolysis and methanolysis process yields pertaining to mixed plastics. Thermal depolymerization (represented in Figure 1 as "pyrolysis") and chemical depolymerization (represented in Figure 1 as "methanolysis") are positioned as two possible routes for post-use plastic processing to products. Each route, explored in this report, has suitable use cases, with some overlap. Therefore, the fractions α and β of post-use plastic to be recycled by each process, are situationally dependent. Fractions α and β sum to 1 to represent the total mass stream of plastic to be chemically recycled. Chemical depolymerization yields varied from 79%[1] to 84%[2]; the conservative value was employed. Figure 1 thus depicts possible routes for post-use plastic which result in an outcome with a high degree of circularity. Finally, Figure 1 provides a representation of pathways that captured plastics that cannot or are not recycled can follow. Yet other processes, such as solvent extraction, can be included to be more exhaustive.

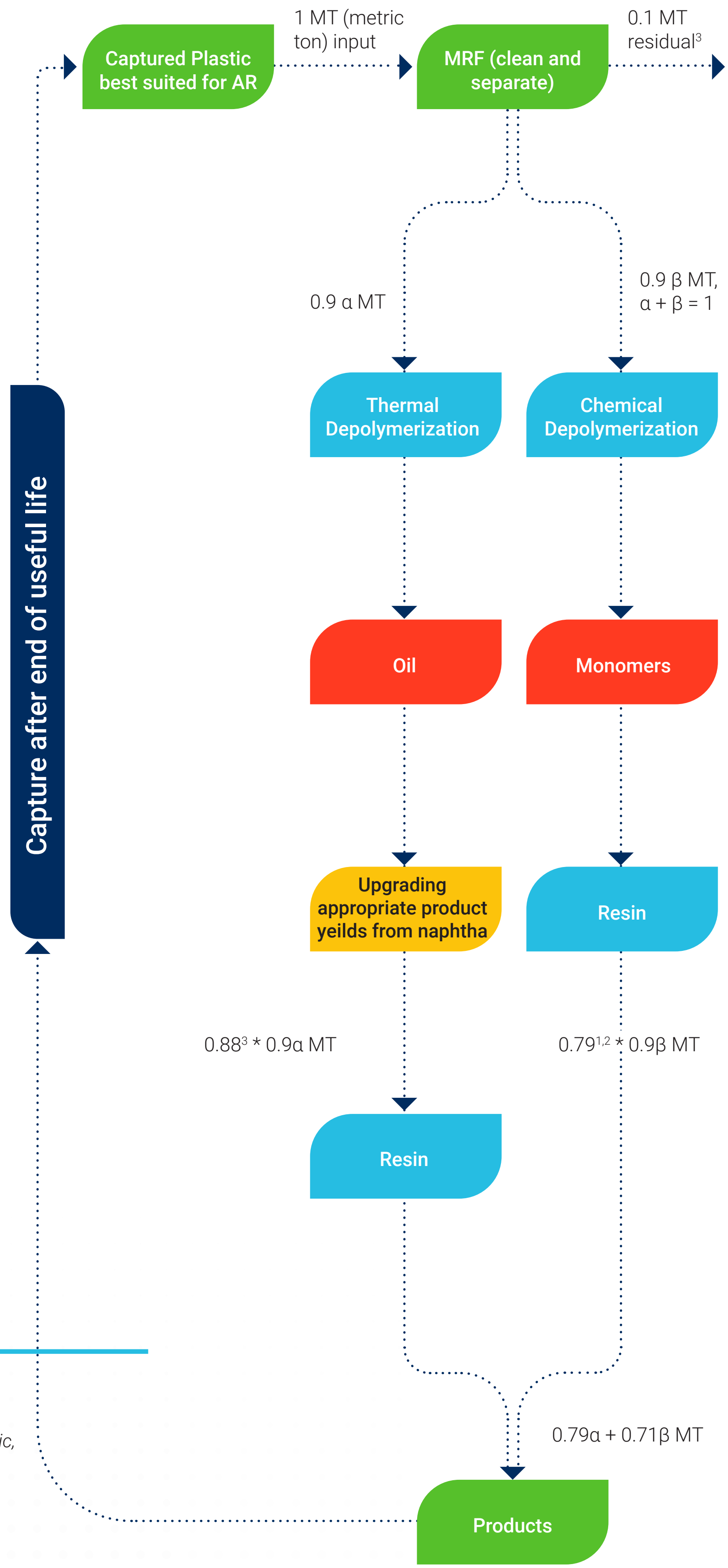
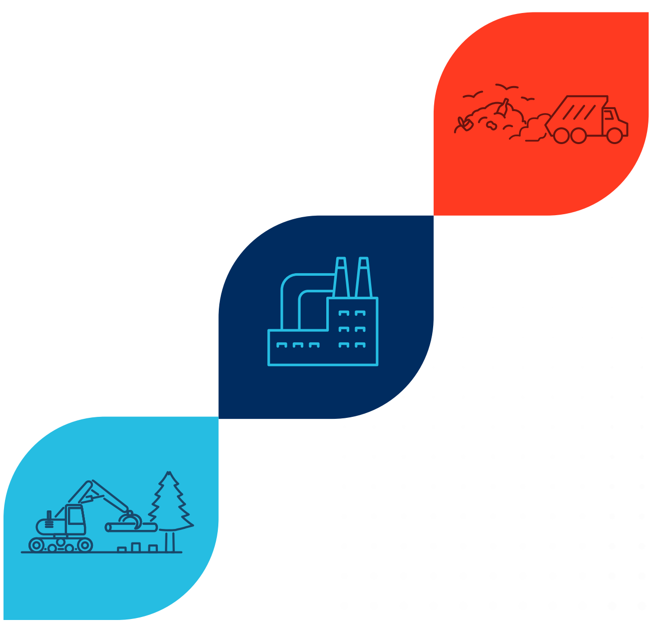


Figure 1. *Advanced recycling methods to process post-use plastic, with products and report scope.*

There exists a linear economy model, wherein products are derived from finite natural resources and have no use after the first use cycle, summarized by "take-make-waste"[9]. The circular economy model, on the other hand, is characterized by sustainability and seeks to keep existing products in use, thereby reducing the demand on finite natural, particularly fossil-based, resources. Circularity, in this report, is defined by the preservation of "raw materials, components, and products [of finite resources], enabling their highest value and utility at all times".[10] Circularity can be defined, and consequently calculated, in different ways, to the extent that entire publications are focused on reviewing or developing metrics to quantify it.[9, 11] Product level circularity metrics used in the calculation include the Circular Footprint Formula (CFF) which has been developed by the European Commission Joint Research Centre (JRC), the Material Circularity Indicator by the Ellen MacArthur Foundation and Granta[12], the Eco-efficient Value Ratio by Scheepens at al.[13], the Circular Economy Index by Di Maio and Rem[14], among many others.[11, 15]



Not all circularity metrics, of which there are at least 230 found in the literature[9], include the same circularity objectives, or inputs. Therefore, not only are various calculated circularity values sometimes not comprehensive in inputs, but they are also not directly comparable. Because there is currently no universally accepted standard for measuring and calculating circularity[15], it is reasonable that LCAs may use different metrics, but it is important for the sake of transparency that the LCAs specify which metric they used.

Essential to the circular economy is the post-disposal utilization of products as inputs to manufacturing processes. Through various recycling technologies ranging from mechanical recycling to advanced recycling, shown in Figure 2, plastics can be reused to manufacture desired products rather than landfilling. Thus, recycling allows for the re-introduction of used material into the plastics value chain and positions the circular economy model as an attractive alternative to the linear economy model.

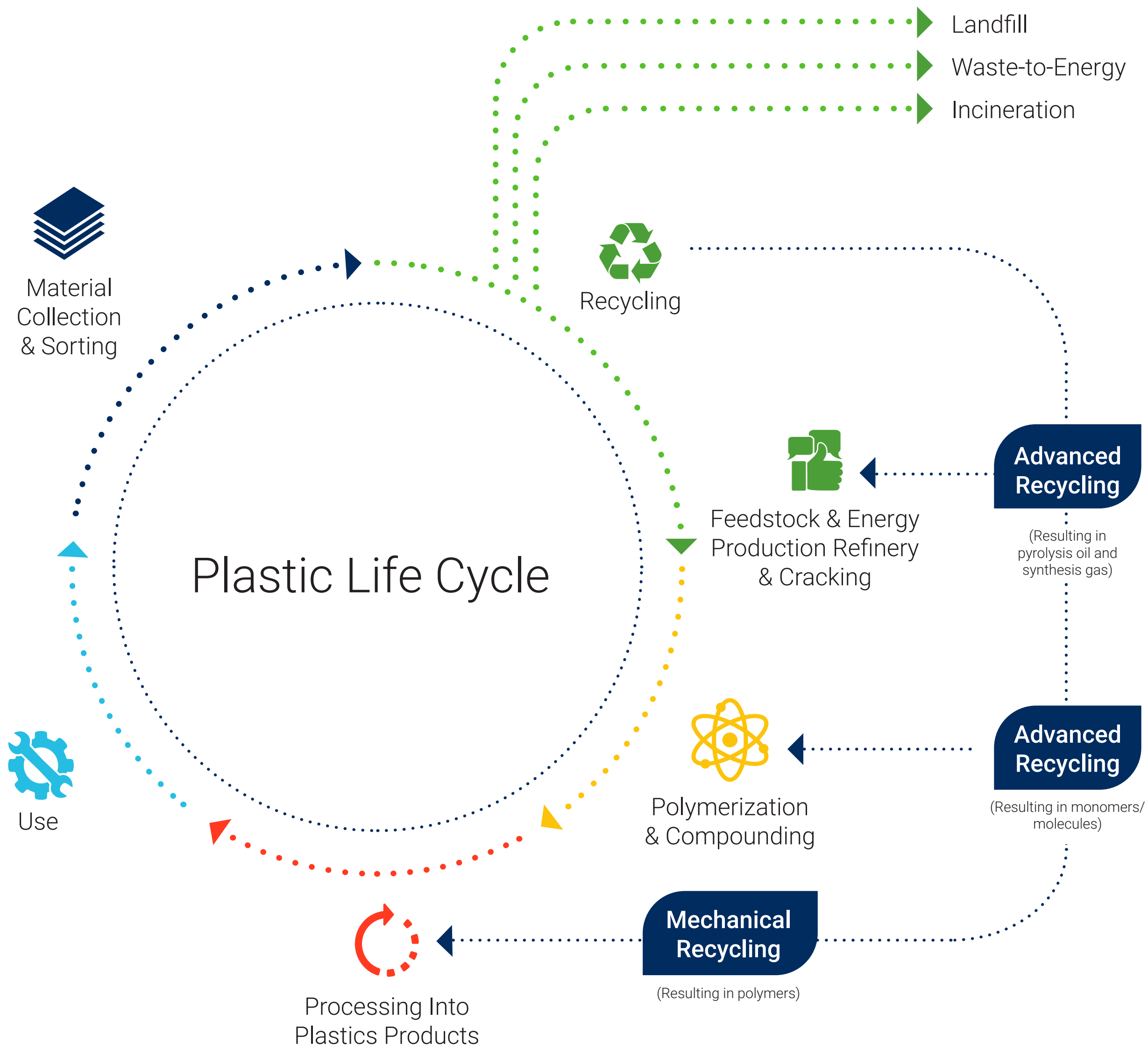


Figure 2. *Circular economy of plastics with the inclusions of various recycling technologies, adapted from Quantis, 2020*[16].

It should be recognized that limitations exist regarding circularity. As seen in Figure 2, collection and sorting are necessary and some portion of post-use plastics may be unsuitable as feedstocks, necessitating some degree of landfilling and/or WTE. With regards to technical limitations of certain plastic reuse scenarios, such as material degradation and cutoffs for acceptable contamination, the reader is referred to Brouwer et al., 2020[17] and Table A1. Since limitations exist and plastic materials that are mechanically recycled several times eventually lead to portions being disposed or combusted, it is imperative to fully understand the technologies and how they are deployed.

Scope

This report covered findings from 13 LCAs completed in 2020 through 2022. Each LCA had some unique non-overlapping elements, however, the commonality among the LCAs was an assessment of global warming potential of the thermal and/or depolymerization recycling of post-use plastics. The primary boundaries of the LCAs themselves were cradle-to-gate (resource extraction to factory gate) or cradle-to-grave (ending with product disposal) assessments[i] mostly focusing on greenhouse gas emission reduction potential and energy usage of one or more advanced recycling technologies. A particular focus was on utilization of advanced recycling technology to produce plastic and chemical products as opposed to recovery of materials to produce fuels or energy. This is consistent with the recognition by the U.S. Department of Energy's (DOE) Advanced Research Projects Agency that streams intended for landfills can be an abundant and sustainable source of valuable elements.[18] The agency has already embarked on issuing contracts and grants to further explore that opportunity.[18] The main driver behind DOE's effort is to capture the vast quantities of valuable materials lost due to landfilling of material.[18]

A particular focus was on utilization of advanced recycling technology to produce plastic and chemical products as opposed to recovery of materials to produce fuels or energy.

Beyond scope considerations pertaining to product, those pertaining to technology scale were also applied. This report focused on technologies which were at high-processing capacity, and thus had high probability to quickly mature. The included technologies had pilot or commercial plants with input processing capacity on the order of 216,000 metric tons per year (glycolysis)[19], 22,000 metric tons per year (co-gasification/reforming)[20], approaching 100,000 metric tons per year (methanolysis)[21], and approaching 200,000 metric tons per year (pyrolysis)[19]. The report scope was limited to exclude technologies at a lower technology readiness level (TRL) or low capacity because this class of technologies often lacks robust operational data to base conclusions.

[i] All LCAs were bounded cradle-to-gate (product perspective) or cradle-to-grave (waste perspective and/ product or perspective with system expansion), with the exception of one (Granados, 2022) which was cradle-to-intermediate, classified as so because the chemical company did not sell the intermediate product, but rather used it internally as a feedstock in a separate manufacturing process.

TABLE 1. TECHNOLOGY OVERVIEW, REPRODUCED FROM LUU, 2021[ii].

Technology	Input	Output	Final Product
Thermal Conversion	Utilizes heat and catalysts to break the bonds in the polymer chain.		
Pyrolysis	Mixed plastic (E.g. PE, PP, PS, PET, PVC*)	Pyrolysis oil	Mixtures of chemicals I.e. • Paraffinic waxes • Base chemicals (methanol, BTX, hydrochloric acid, alkene monomers, olefins) • Hydrocarbon feedstocks (naphtha) • Fuels (e.g. diesel, hydrogen) • Elemental carbon products
Gasification	Mixed plastic (E.g. PP, PS, PET, PVC*)	Syngas	
Reforming/Co-gasification[ii]	Mixed plastic (Plastic types 1,2,4-7, PVC*)	Syngas	
Chemical Depolymerization (i.e., Solvolysis)	Utilizes solvents. Reverse polymerization reactions transform mono-material waste plastic into monomers, which can be re-polymerized into new products.		
Glycolysis	PET, Colored polyesters	EG, PTA/ BHET	Specific chemical outputs I.e. • PET pellets & yarn • Monomers for PET production • (EG, PTA, BHET) • Specialty low molecular weight polypropylene wax • Monomers for polystyrene production (styrene)
Hydrolysis	PET, PA, Colored polyesters	EG, PTA/ BHET	
Methanolysis	PET, Colored polyesters	DMT, EG	

> *This report incorporated appropriate LCAs only as far back as the published year 2020 in an effort to include data that represents the current and imminent technology landscape.*

[ii] Co-gasification/Reforming information not reproduced from Luu, 2021.

Finally, to summarize the current state of the various advanced recycling technologies, frequent updates on their evolving development are needed, particularly for technologies with a TRL for which existing results may not be fully representative. This report incorporated appropriate LCAs only as far back as the published year 2020 in an effort to include data that represents the current and imminent technology landscape.

Further, various types of life cycle assessments exist. The ones selected for this report were all attributional life cycle assessments (ALCAs), referred to in this report as simply LCAs. Consequential life cycle assessments (CLCAs) differ from ALCAs in that they investigate the environmental impact as a result of the production and use of the products. CLCAs consider the effect of changes of the environmental impact and of the lifecycle brought on by changes in demand and product markets. CLCAs, and more widely the discussion of merits of each type of LCA, can be referenced in other texts such as Zhao and You, 2021.[23]

The input feedstock and output products that have been assembled into the tables and figures in this report are a reflection of those specifically identified from the LCAs reviewed. Therefore, the quantitative summaries and trends only pertain to the feedstock and products evaluated. However, polyvinyl chloride (PVC) was a feedstock that was not evaluated in the LCAs. Nevertheless, based on the research and experience at the Earth Engineering Center, PVC could be included, and was identified with an asterisk in the tables. Importantly, feedstocks that were included using EEC judgement should not be interpreted as having the same results as those that were included in the LCAs.

Upon applying the aforementioned scope, the feedstocks, products, and technologies listed in Table 2 were covered in the various assessments. Considering that there are countless types of post-use plastic streams produced, the scope of this report could not have been inclusive of them all. Some streams, such as the majority of pre-consumer scrap plastic and some types of non-packaging plastic, remain unassessed by the selected literature. It is important to acknowledge that the total impact of advanced recycling on circularity likely has the potential to be higher (better) than proposed by some LCAs because if even a portion of these excluded plastics could be recycled via advanced recycling technology, that portion could be reintroduced into the supply chain. Consequently, the consideration of this untapped plastic in future LCAs could help capture a more accurate circularity measure.

TABLE 2. FEEDSTOCK, PRODUCTS, AND TECHNOLOGIES INCLUDED IN REPORT SCOPE.

Feedstocks	Products and Intermediates	Technologies
• Mixed plastic • Lightweight packaging • Multilayer food packaging • PET trays, films, bottles, green pallet strapping, and carpets • Colored PET • PET sourced from ocean bound plastics • Bromine-containing EPS • Hard-to-recycle plastics of various compositions with the exclusion of PET, PVC, and HDPE • LDPE • LLDPE • PP • Resin identification codes 1, 2, 4, 5, 6, and 7 • Top produced polymers such as PTFE • Plastics of unspecified form	• PET water bottles • Plastic film • Naphtha • Pyrolysis oil • Concrete aggregate material • LDPE • Syngas (for production of plastics such as cellulose acetate) • DMT (as a precursor to copolyester plastics)	• Solvent-based purification • Decomposition (depolymerization) • Pyrolysis • Methanolysis • Co-gasification / Reforming

Literature Selection Criteria

An extensive literature review was conducted to obtain a comprehensive survey of the existing body of knowledge, yet only those which fell within the predefined scope were included in this report. Additional selection criteria included technical and practical considerations, summarized below.

- Adherence to a standard preferred, such as International Standards Organization (ISO) or European equivalent (European Standards, EN). In exceptional cases where it was unclear if a standard has been met, robust explanation of methodology was required.

- Broadly applicable results.
  - Data from large regions with archetypical energy and used materials processing systems (e.g. pan-Europe data, U.S. data, data from major European nations).
  - Use of an energy mix that was representative of broad use regions as an input parameter.

No single LCA contained comprehensive coverage in terms of all technologies and all global regions. Therefore, the result of applying the selection criteria was an analysis of a group of LCAs that supplemented the lack of individual comprehensiveness. Ultimately, 13 LCAs were selected [3, 24, 25, 20, 21, 16, 26, 5, 6, 7, 27, 28, 22].

Findings

There were challenges with direct comparison across LCAs due to differences in scope, assumptions, functional units, and system boundaries, however with the alignment of data and informed analysis, *trends* were compared. A common trend across the LCAs was the reduction of greenhouse gas emissions that can be achieved by implementing any of the in-scope advanced recycling technologies.

The LCAs presented favorable results for CO_2eq reduction achieved by advanced recycling compared to most existing alternative post-use routes, with the exception of some permutations of landfill and virgin production scenarios. There were numerous unique comparison scenarios, the main ones being comparisons to landfill, WTE, and fossil-based intermediates. All LCAs presented a scenario in which the implementation of the advanced recycling technology would reduce CO_2eq emissions compared to selected existing alternatives. Table 3 shows that results of all comparative scenarios included in the selected LCAs vary for the reduction of CO_2eq emissions, with a quantitative reduction ranging from -267% to 566%. With the variety of technologies, inputs, outputs, and conditions covered by the LCAs, one single value of CO_2eq emissions cannot be ascribed to represent the impact of advanced recycling technologies overall.

There were two LCA studies that presented results that had a large range between the minimum and maximum CO_2eq emissions reduction.[6, 7] They presented a scenario[iii] wherein there was an increase in CO_2eq (poor result), and a scenario wherein there was a decrease in CO_2eq (favorable result)—and the decreases were among the largest of the reviewed reports. Three key observations about the CO_2eq results are:

1. The large spread in the values ([-267 to 66] and [-77 to 566]).
2. The large magnitude of the emissions reduction (333% and 643%).
3. The outcome of emissions reduction in some cases but emissions increase in other cases.

These observations indicate that a wide range of implementation conditions were evaluated by the LCAs, including some conservative (e.g. lower recycling efficiencies[6] compared to those used in other LCAs[3, 25]) conditions.

[iii] Scenarios were chemical recycling of low density polyethylene (LDPE) versus landfilling of LDPE and use of plastic in concrete aggregate versus landfill.

TABLE 3. PERCENT REDUCTION OF CO_2eq ATTAINED BY USE OF ADVANCED RECYCLING OVER BASELINE NON-RECYCLING TECHNOLOGIES.[iv]

LCA	1	2	3	4	5	6	7	8	9	10	11	12	13
CO_2eq reduction min, max	100, 137	13, 89	17, 73	79, 185	50, 133	-267, 66	42, 124	-77, 566	39, 139	29, 35	22, 50	-20, 48	-22, 45

The key takeaways from Table 3 are:

- Most favorably, implementation of advanced recycling technologies can reduce CO_2eq emissions by over 100% meaning that emissions are avoided.
- In some cases, there is not much of a difference in CO_2eq by implementing advanced recycling compared to the reference technology it is being suggested to replace or supplement.
- In other cases, implementation of advanced recycling technologies can *increase* CO_2eq emissions, but every LCA that showed an increase also showed an alternative scenario in which there was a decrease. This indicates that within the various system boundaries of any single LCA, it was not possible to construct a set of scenarios which *all* showed an increase in CO_2eq emissions. In other words, some individual scenarios showed poor results, but an overall assessment of all scenarios in each LCA showed, at worst, mixed GHG results.

In Table 3, advanced recycling technologies are compared to baseline technologies which are existing alternatives such as incineration, WTE, and production using virgin feedstock. Numerical ranges represent lower and upper values for percent reduction of the impact category relative to the reference technology. The percent change of each impact area was calculated as

$$\textit{Percent Reduction} = \frac{X_{baseline} - X_{technology}}{X_{baseline}} \times 100\%$$

[iv] To understand the differing boundaries and baselines of the various LCAs, see 'Analysis' section.

In the case where an LCA presented multiple advanced recycling technologies, data for all of those technologies were included. The data in the table covers various technologies, thus, a single percentage range may cover more than one technology. For an illustrative example, if LCA X presented data on a gram CO_2eq per gram polymer basis of 10 for WTE, 9 for advanced recycling technology A, and 12 for advanced recycling technology B, the table box would have the range [-20, 10].

$$\textit{Example Percent Reduction} = \frac{10 - 9}{10} \times 100\% = 10\%$$

$$\textit{Example Percent Reduction} = \frac{10 - 12}{10} \times 100\% = -20\%$$

Therefore, it should be clear that the range of values presented can be for a set of mixed technologies/processes where the first number (minimum value) may be reporting on a different advanced recycling technology than the second number (maximum value). All of the LCAs examined focused on advanced recycling technologies, yet some included scenarios that incorporated plastics to fuels as well and these results were also included in the report tables. That incorporation resulted in ranges that were larger than those considering technologies that produced a non-fuel product.

Similarly, Table 4 compares the LCAs in performance areas which probe the benefits of the technologies and the merits of the methods used in the underlying assessments. Where the aspects can be quantified, numerical values are included; where specification is relevant, descriptive text is included. For example, in Table 4, LCA 5 found advanced recycling to contribute toward circularity with a circularity measure of 62% and pyrolysis of mixed plastic to produce lower CO_2eq emissions than waste to energy processing of mixed plastic. The circularity measure is defined as a mass weighted replacement amount. The post-use scenario with the highest degree of circularity can only be supported by a restrictive set of input product types, and limits on material degradation and contamination are more stringent compared to less circular scenarios. Thus, different targets of acceptable material properties must be achieved depending on the post-use fate, indicating that a one-size-fits-all approach is not applicable for every application type or final product. Recognize that Table 4 has been assembled to provide a nominal overview of the LCAs evaluated. Several of the LCAs contain multiple functional units and both waste and product perspective, and therefore, a more descriptive breakdown on that perspective requires the reader to review the LCAs of interest in their complete form.

TABLE 4. CATEGORIES AND CONSIDERATIONS ADDRESSED BY THE VARIOUS LCAS

Performance Area ⟶	Advanced recycling technology contributes to circularity?	LCA conforms to an established standard?	System boundary takes product quality into account for circularity calculations?	Credits are applied for avoided products and/ or energy in calculations?	Only contains current (not projected) data?	Pyrolysis outperforms the specified alternative process for CO_2eq emissions?
LCA 1	Yes	N.R.	No	Yes	No	WTE
LCA 2	80%	N.R.	Yes	Yes	N.R.	• WTE (PET, LDPE-PP foil, ABS w/ flame retardants) • Energy Recovery (PET, LDPE-PP foil, ABS w/ flame retardants)
LCA 3	90%	ISO	No	Yes	Yes	N.R.
LCA 4	Yes	ISO	No	Yes	No	WTE (HDPE, LDPE, LLDPE, PP)
LCA 5	62%	ISO	Yes	Yes	No	WTE (MP)
LCA 6	Yes	Yes	Yes	Yes	Yes	WTE (LDPE)
LCA 7	Yes	Yes	Yes	Yes	No	• MSWI (MP) • RDF (MP) • 30% MSWI 70% RDF (MP, comm. plastic mix)
LCA 8	Yes	Yes	No	Yes	No	Landfill
LCA 9	Yes	ISO	No	Yes	N.R.	• 50% WTE 50% Landfill • 17% WTE 83% Landfill
LCA 10	Yes	ISO	No	Yes	No	N.R.
LCA 11	Yes	ISO	No	Yes, but not for avoided waste treatment	No	N.R.
LCA 12	Yes	ISO	Yes	Yes	No	• 45% WTE 55% Landfill • 100% WTE (MP)
LCA 13	Yes	ISO	No	Yes	No	17% WTE 83% Landfill (MP)

The key takeaway notes from Table 4, above, are:

- All LCAs present advanced recycling technologies that contribute to a circular economy, with some LCAs calculating and quantifying that circularity.
- Most LCAs use projected data for system performance, efficiencies, and feedstock mix.
- Depending on the comprehensiveness of impact areas addressed by an LCA, it is possible for the best performing technology assessed to be an advanced recycling technology, but that is not always the case. Most commonly it was found that an advanced recycling technology performs the best in some, but not all, impact categories.
- Not all LCAs explicitly consider product quality. Specifically, the quality of products produced by all recycling technologies is not the same or not equal to a product derived from virgin material.[19, 29, 25] Input plastic streams can be converted to plastic product via secondary (open loop) mechanical recycling with some degree of material degradation[25] or can be converted to polymers of virgin-quality via advanced recycling[3, 24]. Some considerations for quality are as follows:
  - "Changes in inherent properties (e.g., due to downcycling)"[28]
  - "Differences between market values of primary and secondary materials"[28]
  - "Value of the recycled material compared to the primary raw material"[28]

Some LCAs applied a quality factor into their calculations for circularity which aids comparisons between different recycling technologies and provides more comprehensive analysis for multiple use-cycles. The incorporation of a quality factor was achieved in slightly different ways between the LCAs but were largely based on a substitution approach. One LCA[25] used an extensive literature review to convert product substitution to a quantifiable quality factor, which was 0.5 for secondary (open loop) mechanical recycling of polymer pellets. The quality factor for primary (closed loop) mechanical recycling would likely be much higher. Another LCA[6] drew on the Product Environmental Footprint (PEF) guidance to determine a range of quality ratios, which were from 0.75 to 0.9. Yet another LCA[28], with reference to limitations of mechanical recycling, applied a factor that incorporated deterioration from accumulation of additives to the plastic, which are desirable for the product use but act as contaminants in the product recycling, over several cycles.

The comparison Tables 3 and 4 show an overview of the category data presented from the 13 LCA sources. Deeper analysis of the source material indicates several findings. Importantly, all LCAs provided data revealing that an advanced recycling technology resulted in CO_2eq emissions reduction from a baseline case, however, the implication is not that only one advanced recycling process should be implemented at the exclusion of all other processes, mechanical or chemical. Thus, while it may be the case that through a waste perspective, one process is favorable to another, considering the practical limitations of the product perspective, a combination of technologies may be the optimal solution. Advanced recycling technologies emerge as complementary solutions to mechanical recycling because they accept many types of post-use plastic as inputs and produce high quality products. The versatility of advanced recycling technologies enables processing of streams that cannot be tolerated by mechanical recycling such as contaminated and/or multi-layer flexible film packaging and heterogeneous mixes of plastic and biomass.

The data available from the 13 sources provide the basis for an aggregate assessment of these technologies; the assessment being that advanced recycling can be a viable solution to contribute to the plastics circular economy in furtherance of environmental sustainability.

Analysis

Comparison of the LCA findings alone is insufficient due to risk of being oversimplified. Analysis is needed to evaluate the underlying assumptions to these findings and to develop a nuanced and specific assessment. Analysis on key areas is presented below.

I. DATA QUALITY

A. TECHNOLOGY READINESS AND MATURITY

Data will not be as robust for technologies with a low technology readiness level. Specifically, operational data at the commercial scale may not be available for technologies with lower TRLs. Equipment with a higher TRL will tend to have sufficient operational data to impart confidence that the technology will perform as planned when fully deployed. High TRL technologies also have relatively higher confidence of viability at commercial scale. Processes that are more mature will tend to have detailed information about process conditions, inputs, yields, etc. Particularly in cases with modeling, years or decades worth of real operational data, as has been recorded at mature operational facilities, can feed into models for newer technologies. For example, coal gasification is a deployed conventional process which has yielded years of energy consumption data as well as manufacturing data and utility systems data.[21] Models of the newer process, co-gasification with plastics (i.e. reforming), in which mixed post-use plastics replace a portion of the traditional feedstock (coal, which is not strictly needed for the gasification process and could be theoretically substituted, however that would likely require redesign of the gasifier)[20], can benefit greatly from using the real primary data as inputs.[20] Not all technologies have a foundation of information about process conditions, and without this, assessments of technologies with low TRLs may rely more heavily on projections, assumptions, and extrapolation of limited data.

The technologies for advanced recycling of plastic feedstock vary in their maturity. It is imperative to draw the distinction between TRL of the established technology being used for what it is purposely designed with that of the same technology being adapted for a new feedstock (and, potentially, new process conditions). For example, the co-gasification of coal has a high TRL, whereas the co-gasification of municipal solid waste (MSW) has a low TRL.

For those plastic feedstock technologies already operating commercially, variation exists in their scale.[19] Processing plant working capacities, in metric tons annually, as of 2020 range from 25,000 (CuRe Technology, depolymerization through glycolysis)[16], to 80 (Jeplan, depolymerization through glycolysis)[16], to 7,000 (Plastic Energy, pyrolysis)[19]. A facility in development has a planned capacity, in metric tons annually, of 50,000 (Carbios, hydrolysis)[19], another planned in the near-term has a capacity of 200,000 across several plants (Plastic Energy, pyrolysis)[19], another (Eastman, co-gasification) slated for 2023 in North America at 100,000, and yet another (Eastman, methanolysis) in 2025 made possible by a one-billion-dollar investment in France is planned to recycle 160,000[30].

There is debate about how to classify each technologies' readiness level. For example, a particular depolymerization through glycolysis process has been classified as low TRL by some sources[16] and as medium TRL by others[19]. Further, proprietary technologies such as those which are based on pyrolysis, may not be accurately classified without additional information.[7, 27] More detailed information about the technologies would inform whether they should be classified in the same TRL as pyrolysis, or if the propriety elements would require them to be classified independently. Technologies with higher TRL tend to have more of their data and information published which prevents ambiguity of TRL classification.

One should consider limitations of technologies in terms of efficiency due to lack of maturity and economies of scale. Lack of maturity and commercial scale data can lead to poor assumptions. A thorough LCA is one that considers and addresses the ramifications of such assumptions.

There may be concern with using lab-scale or demonstration plant-scale data as their associated "process emissions [may be deemed] *too optimistic* compared to what might be emitted from processes deployed at a commercial scale".[16] Extrapolation of demonstration data to commercial scale data, often with the application of an assumed efficiency improvement factor, is speculative.[16] The same LCA quoted above also predicates statements with a provision that "chemical production systems have been adapted to accommodate the required technological adjustments, emissions associated with chemical recycling could be as low as 0.2 t CO_2eq per ton of plastics".[16] Another LCA makes similar assumptions in that commercial scale implementation is assumed to perform similarly to smaller scale for purpose of calculations.[26]

B. CALCULATION OF CIRCULARITY

In the context of this report, circularity aims to avoid extraction and waste of raw materials and to close material loops. The selected LCAs, as shown in Table 4, addressed circularity, but the exact definition of circularity used by each is not always made clear. Of the selected LCAs, only two specify the method used to calculate circularity; both used the CFF.[3, 5] This method for calculating circularity considers recycled content, energy recovery, and material quality. The aforementioned LCAs, despite specifying what circularity is and how it is measured, do not quantify it, whereas other LCAs quantify but do not specify the basis on which it was calculated. EEC|CCNY suggests a circularity calculation based on mass, where inputs are virgin material (circularity = 0) or renewable material (including recycled material, circularity = 1), and outputs are waste (circularity = 0) or recoverable material (circularity = 1). Similar material-loop based circularity assessments exist.[15] Other circularity metrics go beyond "the fraction of a product that comes from used products" to also include economic value for which market prices are used as a proxy.[11] By using those metrics, the consideration that not all post-use products have an active market, due to material degradation or color, for example, is incorporated into the circularity metric. From the information available in the assessed LCAs regarding the quality of the advanced recycling products, and from the ability for such technologies to produce commodity chemicals and plastics, especially highlighted in one LCA which evaluated the technologies for the top 25 produced polymers in Europe[25], a simplified metric was developed which assumes a market exists for the products of the chemical recycling technologies. With this simplified circularity metric, shown below, a mass-replacement based quantitative measure of circularity can be calculated for any LCAs which report the necessary data, such as yields.

$$\textit{Circularity [\%]} = \frac{\sum \text{inputs } c_i X_i + \sum \text{outputs } c_i X_i}{2}$$

Where c_i is the circularity of each component of material inflow to or outflow from the process. c_i can be 0 for virgin materials and 1 for recycled materials for the input stream and 0 for waste and 1 for recovered valuable product for the output stream. X is the mass fraction of each component. In this way, circularity can be calculated for LCAs which do not directly report a numerical value for the circularity of the advanced recycling technology being assessed[3, 5-7, 20, 21, 26-28], and circularity can be normalized between LCAs which do report a numerical value for circularity but may not be using the same metric as each other[16, 24, 25]. Applied to proprietary data made available to EEC|CCNY for a methanolysis-based advanced recycling technology[21], this formula calculated circularity to be 87%, thus quantifying and supporting qualitative claims about technology circularity. Though there are limitations to any metric for circularity, emphasis on using metrics to quantify circularity allows for more rigorous evaluation and comparisons of technologies. Many technologies are circular; it is worthwhile to know the degree to which they are in order to make informed decisions about the benefits of their implementation. Such a circularity measure could be used to calculate circularities that were only discussed in the abstract, but key data on materials and yields are needed to do so. Therefore, the most useful LCAs would be those that contain thorough raw data for analysis by discerning readers.

C. DATA SOURCES AND AVAILABILITY

Many LCAs draw on the same source data. Future LCAs which include new operational data, preferably from commercial scale facilities, will be well-positioned to contribute significant value to the subject area. As the technologies are continuously becoming more mature, timely studies that capture the most up-to-date performance of those technologies will serve as a key resource. EEC|CCNY encourages more information to be available from technologies with less and/or lower quality publicly available data to ensure a robust analysis slate.

II. ASSUMPTIONS AND SYSTEM BOUNDARIES

A. INPUT STREAM

Each LCA defines their own input stream which may or may not resemble real-world input streams. This is significant for several reasons. First, if the input stream processed in real-world implementation varies significantly from the input stream studied in the LCA, actual results, such as percentage of material diverted from landfill and global warming potential per each kilogram of input material, may differ from theoretical results. Second, if the LCA has only one classification of input stream in scope, such as polyethylene terephthalate (PET) water bottles, the technology is only being assessed on its performance to processing that one material. As made explicit in one LCA, and is readily applicable to the others, *"not all waste streams that are potentially suitable for chemical recycling have been included […] the potential of chemical recycling to contribute to climate change reductions may therefore become larger if other waste streams are also considered"*.[26]

The definition of the post-use plastic feed in each LCA is important—sometimes it is not specified, which is important to consider if attempting to directly compare results across assessments as the material streams may or may not be the same. Selected definitions of post-use plastic streams from LCAs are:

- **High calorific mixed plastic** (Lower heating value (LHV)= 44 MJ/kg, only comprised of PE, PP, and PS).[3]
- **Mixed plastic** (LHV: 20-30 MJ/kg, mainly polyethylene (PE), polypropylene (PP), polystyrene (PS), maximum 10 % of impurities in sum, paper and cardboard < 5 %, metals < 2 %, PET bottles < 3 % , PVC < 0.5 %, others < 3 %).[3]
- **Lightweight packaging** (only comprised of PE and PP).[3]
- **Multilayer food packaging** (comprised of PET 58%, LDPE 32%, ethylene vinyl alcohol 10%).[24]

Beyond choices regarding the composition of the analyzed input stream, the LCAs may differ in some assumptions they make about the stream itself. One such assumption, that all rejects from mechanical recycling can be chemically recycled[16], is too ambitious. Other LCAs are more tempered with their assumptions about the supply chain, with an input stream of mixed plastic having 17% by weight removed in a preprocessing step, of which only 1.5% can be recycled in an alternate facility.[27] Differences in realistic versus idealistic assumptions are occasionally cast in the light of current data versus projected future data (e.g. energy mix). Attention should be drawn to this distinction when comparing data across LCAs which take different approaches.

Given that the LCAs present the waste perspective and/or the product perspective, the following characteristics should be investigated to assess whether assumptions or claims to their effect are reasonable:

- Whether the input streams for processing are realistic, thus addressing real-world need for processing of material destined for landfills.
- Whether the products created (either final products or intermediates) have a market, thus avoiding traditional virgin production.

Estimated volumes of input waste streams assessed by the LCAs are significant, with the exception of bromine-containing expanded polystyrene (EPS), which is smaller in volume yet presents an interesting and worthwhile edge case.[26]

It is true that waste streams vary in composition from one geographical source to the next, but it is likely that waste streams will continue to contain plastics. The mechanical recycling rates for plastics in the United States have increased only from 6% to 9% between 2000 and 2015 and have plateaued near 9% in the three years following despite efforts to increase the rate. These plastics, consequently, largely go unrecycled and remain in waste streams. Even with an increase in separation of plastics into existing mechanical recycling streams, some of these plastics will be better candidates for advanced recycling. Compared to mechanical recycling methods, advanced recycling processes are not as impacted by contamination or streams comprised of mixed plastics and therefore have the potential to enable a higher recovery rate for plastics. Specifically, plastic products typically incorporate performance additives to provide attributes such as ultraviolet protection, strength, and flame resistance, which can make them more desirable when compared to alternative materials for the same products or packaging. Importantly, once those additives or enhancers are intimately assembled into the final product they cannot be mechanically separated and therefore are less desirable for most recycle markets. However thermal conversion and dissolution processes can deconstruct the product and separate the additive material from the plastic components. Knowing this context, it is worthwhile for LCAs to be specific and transparent about the waste streams they are assessing to aid in determining whether the right types of waste streams, those that support complementary recycling solutions, have been addressed.

B. CREDITS SYSTEM

All the LCAs considered in this report implemented a credits system for the offset products and/or energy as a result of implementing *any* technology for which those offsets are applicable. In other words, credits were applied to the advanced recycling technologies, and they were also applied to the comparative technologies such as WTE (for energy recovery) and to mechanical recycling (for avoided production of virgin plastic granulate and for avoided incineration).[26] Therefore credits were not applied exclusively (i.e. in a biased manner) to the advanced recycling technologies in an attempt to favorably present them. Thus, any underlying assumptions made in the LCA in the magnitude of the applied credits were also applied across all compared technologies, and any potential under-or-overestimation of offsets would similarly be applied across the board.

Conservative assessment parameters were used, in some cases, where LCA practitioners have chosen to forgo possible reasonable credits toward CO_2eq reduction. For example, given a feedstock of plastic that would be destined for landfill, a system boundary in one LCA was drawn to *exclude* credit for avoided landfill.[21] Even with such an exclusion in that LCA, the trend resulting from implementation of the advanced recycling technology was a reduction of CO_2eq compared to the conventional baseline process.[20] One possible approach could be to use absolute calculated mass of CO_2eq reduction with respect to a baseline system or product since that is unlikely to change using a credit or burden approach. Knowing this, when interpreting publicly available results, particularly in a summary form, the primary data may not necessarily represent the most favorable case reasonably possible.

C. ENERGY MIX

Depending on the report, and mostly based on origin of the report commissioners, an energy mix was selected to be representative of that in the United States or of that in Europe. Further, as highlighted in Table 4, some LCAs[28,3] included scenarios in which a future estimated energy mix was used, with this future energy mix having a higher contribution from renewable energy sources compared to the current energy mix[28]. The continued increase in renewable energy to the American and European energy portfolios has a twofold effect on the evaluation of advanced recycling technologies. First, a decarbonized electricity mix results in a lower global warming potential for any energy used in the advanced recycling process, or any process for that matter. This is an absolute improvement and would impact, for example, the global warming potential of transporting and sorting plastics. Second, there is a relative improvement, whereby the conventional process of waste-to-energy would be impacted by a decrease in credits for energy offset, thus improving the relative standing of alternate technologies such as advanced recycling. It is worth mentioning that not only will the decarbonization of the energy mix impact the global warming potential of comparative technologies, such as WTE, regulatory changes may also contribute. One LCA compared advanced recycling to WTE and specified that the datasets used were specific to WTE facilities “with dry flue gas cleaning and selective catalytic reduction (SCR) for NOx-removal to meet the legal requirements”.[28] Energy consumption for WTE is dependent on all process steps, some of which are regulatory requirements, thus a changing regulatory landscape is likely to impact the relative greenhouse gas emissions of WTE versus advanced recycling.

D. OTHER ASSUMPTIONS

Various assumptions other than those pertaining to input streams and credit systems were applied by each of the LCAs. A critical evaluation of such assumptions, and to what extent they may impact the overall results, is valuable in the effort to understand and qualify the potential benefits of advanced recycling technologies. Due to the large number of assumptions across the 13 LCAs, not all can be addressed in this report, however a selection of assumptions is detailed below.

One LCA, when trying to generalize the data, assumed that "various polymer product systems are expected to be comparable".[5] This assumption is not necessarily true. Based on the laboratory testing experience of EEC|CCNY and other literature reports, high density polyethylene (HDPE) needs a much higher severity factor to process compared to LDPE.[31] Because of the lack of data in some areas, there may be a desire to generalize LCA data to additional input streams or products; this should not be done because generalizations fail to consider incompatibility between processing technologies and input material, acceptable degradation, or acceptable contamination, for example.

Additionally, in several LCAs, some data is presented with a range of values due to differing assumptions about electricity mix[26], or low and high values for efficiency of current system versus projected future system[7], for example. In one case, the electricity requirement for pyrolysis was reported to be from 455 kWh to 1300 kWh per ton of feedstock, which is a large range.[24] Various key assumptions, or lack thereof, may result in wide ranges of the input parameters for calculations of the impact areas such as CO_2eq emissions. Thus, selecting a value for the electricity requirement from one extreme or the other could potentially alter the results of that particular analysis. Hence, the motivation for conducting sensitivity analyses is made clear to determine the influence of the modeling assumptions. Some LCAs contained detailed and transparent information about their approach to uncertainty[3, 6], varying up to 30 parameters in a single LCA[3]. Variation of the selected parameters did not change the overall trends.

> *A critical evaluation of such assumptions, and to what extent they may impact the overall results, is valuable in the effort to understand and qualify the potential benefits of advanced recycling technologies.*

Comparison of Additional Impact Categories

Beyond CO_2eq emissions, some LCAs with a wider scope contained data pertaining to additional impact areas. Indeed, global warming potential is a vital impact area to assess, however inclusion of data from additional impact areas provides a more complete picture of the advantages and disadvantages of implementing the technologies. These additional impact areas are presented in Table 7. As the purpose of the table is to *compare* the proposed impacts across LCAs, LCAs that contained no data about the additional impact areas were omitted, and impact areas that lacked at least two LCAs to *compare* to each other were omitted.

TABLE 7. PERCENT REDUCTION OF VARIOUS IMPACT AREAS ATTAINED BY USE OF ADVANCED RECYCLING OVER BASELINE TECHNOLOGIES.

Comparative Impact Area	LCA 2	LCA 4	LCA 6	LCA 7	LCA 8	LCA 9	LCA 10	LCA 12
Fossil depletion	N.R.	Reduction	[17, 51]	[-1, 97]	N.R.	[82]	[73]	[76, 89]
Acidification	N.R.	Reduction	N.R.	[-460, -70]	[-1794, 15261]	N.R.	[95]	N.R.
Marine eutrophication	N.R.	Increase	N.R.	[-655, -94]	[0, 102]	N.R.	[77]	N.R.
Photochemical oxidant formation	N.R.	Reduction	N.R.	[-225, -75]	[-548, 3571]	N.R.	[80]	N.R.
Particulate matter	N.R.	Reduction	N.R.	[-400, -66]	N.R.	N.R.	[81]	N.R.
Water depletion	N.R.	Increase	N.R.	[-122, -195]	N.R.	[46]	[106]	N.R.
Resource use, minerals and metals	N.R.	N.R.	N.R.	[-825, -100]	N.R.	N.R.	[-72]	N.R.
Ozone depletion	N.R.	N.R.	N.R.	[-43900, -2744]	[-79, 218]	N.R.	[~100]	N.R.
Human health: carcinogens	N.R.	N.R.	N.R.	[170, 788]	[110, 1110]	N.R.	[48]	N.R.
Human health: non carcinogens	N.R.	N.R.	N.R.	[-336, -275]	[99, 145]	N.R.	[95]	N.R.
Respiratory effects	N.R.	N.R.	N.R.	[-233, -75]	[-527, 5378]	N.R.	N.R.	N.R.
Ecotoxicity	N.R.	N.R.	N.R.	[33, 476]	[0, 1143]	N.R.	N.R.	N.R.
Recycling efficiency [100% maximum]	[10, 95] [v]	N.R.	[70] [vi]	[71, 87]	N.R.	N.R.	N.R.	N.R.

Decrease in LCA impact category compared to baseline technology (green)

Increase in LCA impact category compared to baseline technology (hatched)

Mixed results in LCA impact category compared to baseline technology (yellow)

Note: Impact areas designated only with "Reduction" or "Increase" were not quantified in the LCA.

[v] Data is available but not compared relative to a baseline.

[vi] Data is available but not compared relative to a baseline.

The LCA studies that contained a comprehensive set of impact categories showed that advanced recycling technologies performed well in terms of CO_2eq emissions yet had uneven performance for some categories. Fossil fuels depletion data was consistent among the four LCAs that reported this data. Nearly 97% of virgin resources were saved through advanced recycling compared to the landfilling.[3]

With regards to uneven performance, Table 7, as a whole, shows that when taking into account results from multiple LCAs, results are not all favorable or all unfavorable. One LCA[5] may show a reduction in photochemical oxidant formation, while another LCA[3] may show an increase. This is not necessarily conflicting as two different LCAs may employ different system boundaries and assumptions, with one, or both, of those LCAs using either aggressive or conservative parameters. Similarly, at the individual LCA level, these mixed results were also found. One LCA found that "purification, depolymerization and conversion each had processes that performed better than the virgin system, just as each technology category had processes that performed worse than virgin" and subsequently concluded that "meticulous due diligence is important for the success of this early-stage and nuanced sector".[22] This call for due diligence is worth emphasizing, particularly as more operational data from these processes continues to become available.

Interrogating further a specific table category, the results for the impact area of 'Resource use, minerals and metals' require more resolution in the available databases. Only two of the reviewed LCAs included this impact area, an impact area which has been described as "not internationally accepted"[3]. The JRC recommends to apply this impact area with caution due to unsatisfactory robustness of background data.[32] Product and waste perspective cases were analyzed in a pyrolysis-focused LCA in three different contexts, and in all of those contexts, relative to the reference processes (100% MSWI, virgin PE, and 30% MSWI/70% RDF), the pyrolysis process resulted in *higher* mineral and metal use but *lower* metal depletion.[3] This indicates that the mineral use data is driving the apparent results in the 'Resource use, minerals and metals' category. Beyond pyrolysis, the only other LCA reviewed that included the mineral and metal category showed consistent results, where relative to the reference process (conventional Dimethyl terephthalate (DMT) from virgin resources), the methanolysis process resulted in higher mineral and metal use, though no comparison to metal depletion is available.[21] Even so, the scale of the resource depletion in the mineral and metal depletion impact area (milligrams) is small in comparison to that of metal use (kilograms), on a metric ton (of MP waste or of PE product) basis, dwarfing its impact.

Also important in the results is the scale of metals present in the input streams containing MSW which is several orders of magnitude larger than those containing MP. Even with WTE recovering minerals and metals at a much larger rate than pyrolysis, the large recovery rate applied to an outsized input amount of minerals and metals results in a net higher use of such resources per functional unit compared to pyrolysis. Indeed, this result is seen in the data for metal depletion, but it is not seen in the data for mineral and metal use, again highlighting the confounding effects that the underlying dataset for the mineral and metal category is imparting. Given the caution issued by the JRC, the robustness of the databases for the mineral depletion data is questionable. That, along with process knowledge that no appreciable amounts of minerals and metals are directly used as inputs in the methanolysis case[21], casts uncertainty on the significance of this impact area. The resolution of the analyses combined with the existing data sets are not compatible. In other words, the existing data sets do not enable high resolution results to be obtained. Data for resource use at a very small scale for which uncertainty in the background datasets can result in an improbable favorability outcome must be presented with sufficient context to be well understood by those unfamiliar with its origins.

Extending further the discussion on impact areas with low levels of confidence, such as 'Resource use, minerals and metals', a different LCA also provided qualification of the life cycle assessment model's ability to accurately measure impact in certain areas.[22] This LCA pointed to the initial attempts to evaluate the accurate human health impact as "pre-emergent", arguing that "life cycle impact assessments are not comprehensive enough in scope or depth to adequately capture all of the elements of a complex and dynamic system, much less quantify their impacts" with respect to human health impact.[22] It is outside the scope of this report to evaluate the basis for this statement, but a key point taken is that authors of LCAs should discuss any limitations that they have identified. That discussion and disclosure would make it transparent to the reader and aid in interpretation of results. Simply reporting numerical results without providing background, context, and discussion, runs the risk of, as in the case of 'Resource use, minerals and metals', disseminating information that could be misinterpreted.

Even with the additional data, Table 7 is not comprehensive in its inclusion of impact areas. Additional impact areas inherent to all LCAs that present landfill as a baseline include, to name a few:

- Reduction in landfill volume due to diversion from landfill.
- Increase in share of total post-use plastic eligible to be recycled as a result of implementing advanced recycling.

By diverting a subset of plastic material from landfill to recycling in any form, the linear economy loop can be closed to form a circular economy.

Some additional impact areas were evaluated by the LCAs but did not conform with the common impact areas listed in Table 7. For example, impact areas of "bluewater"[22] and "natural resource energy, total (NREt)"[22] are analogous to the table impact areas of "water depletion" and "fossil depletion". Though the impact categories of bluewater and NREt, for example, are not the same as categories found commonly in several of the other LCAs, the trends are the same, with the advanced recycling technologies reducing bluewater consumption and NREt use by -23% to 65% and 14% to 80%, respectively. This reinforces the results shown in Table 7, that across the row for water depletion, there are mixed results, and that across the row for fossil depletion, there are overwhelmingly favorable results. The reader is referred to the report by Luu for definitions of bluewater and NREt, as well as results therein.[22]

All LCAs asserted that the inclusion of advanced recycling contributed positively to the plastics circular economy, and some[24, 25] even quantified this circularity. Most of the LCAs did not quantify this circularity impact, only stating the trend, which was found to be positive. Co-gasification yielded favorable circularity results for top production commodity plastics but not for acrylonitrile butadiene styrene (ABS) plastic with flame retardant.[25] Other impact areas not related to the environment were considered in some LCAs, such as profitability.[24]

The comparison table shows a range of performance, from poor to favorable. Trends of uneven performance, depending on the applied use case, were observed.

Potential Applications for Various Technologies

In order to address a wide range of plastic stream inputs and desired high-value outputs, a complementary suite of technologies may be implemented. The following table highlights some potential applications of several recycling technologies and is not intended to be comprehensive.

TABLE 8. SELECTION OF APPROPRIATE RECYCLING TECHNOLOGIES TO USE FOR VARIOUS INPUTS AND OUTPUTS.

Input material type	Applicable technology
Multilayered packaged products	Solvent dissolution (purification)[24], pyrolysis[33], gasification
PET	Solvolysis[24], Depolymerization, Hydrolysis[25]
PP	Feedstock recycling (Pyrolysis, Co-gasification)[24]
PS	Feedstock recycling (Pyrolysis, Co-gasification)[24], Dissolution[34], Food contact mechanical recycling[34], Depolymerization[34]
PE	Feedstock recycling (Pyrolysis, Co-gasification)[24]
MP	Pyrolysis[34], Co-gasification[34]
Thermosets (PUR, Epoxy)	Dissolution[25]
PLA, Nylon 6	Depolymerization[25], Hydrolysis[25]
LDPE	Co-gasification[25]
Polyolefins	Co-gasification[25]
Polymers (HIPS, EPS)	Pyrolysis[25]
Waste electric and electronic equipment WEEE	Co-gasification[25], Pyrolysis[25]
Celluosic plastics	Co-gasification[20]
Low quality polyester	Methanolysis[21]
PVC*	Pyrolysis, gasification, co-gasification

Conclusion

Advanced recycling is growing as a technology area with substantial ongoing research. Global companies continue to increase its implementation to produce plastics and chemicals derived from post-use materials. Between 2010 and 2019, a steady increase in published literature about advanced recycling has been observed, with associated LCAs following a similar increase, thus providing a robust set of publications. Nearly two times as many LCAs about the plastics circular economy were published in 2019 than 2010 to 2017, corroborating the growing interest.[29]

SUMMARY OF FINDINGS

Advanced recycling can be used to produce high-quality products in a way that, in some scenarios, emits less CO_2eq than conventional alternatives, such as using virgin feedstock and landfilling post-consumer plastic.

CO_2eq emissions, followed by circularity and fossil depletion were metrics evaluated by several of the LCAs. These were areas in which advanced recycling technologies performed very favorably overall.

Robust assessments of various advanced recycling technologies showed a wide range of results, showing favorable results for some impact categories toward some advanced recycling technologies but suggesting that there may be tradeoffs compared to alternate technologies.

A multitude of post-use plastic stream composition and desired impact conditions cannot be adequately addressed by a one-size-fits all approach to recycling technology. Therefore, the appropriate technology should be implemented depending on the use case.

The most up-to-date operational data on the versatile suite of advanced recycling technologies should be continuously sought out when refining assessments of potential benefits and applications of these technologies. Thus, given current data, there is a strong case for the targeted implementation of certain technologies in specific use cases. However, some uncertainties still exist, e.g., surrounding technologies with low technology readiness levels, LCAs with tenuous assumptions, LCAs with a smaller operational data pool compared to decades-established alternative waste management methods, and LCAs with qualitative claims with limited support. Despite some limitations, well supported trends can be observed across the literature which indicate that these technologies show promise.

Final Observations

To ensure the best transparency and confidence in LCA results, the calculation parameters must be clearly defined. For example, all assumptions, criteria, system boundaries, material details, and reference databases must be presented.

- Data in the LCAs must be contextualized and fully understood to avoid an oversimplified assessment of the relative benefits and detriments of implementing the various highlighted technologies. Particularly, the functional unit and comparative (baseline) technology should be well defined to understand the significance of reported data.

A context specific GHG impact should be evaluated when considering implementation of AR technologies and processes as opposed to assignment of a single representative impact value.

When assessing impact areas with low level of resolution in the underlying data, such as data extracted from external databases, one must employ robust calculations and methodology and sensitivity analysis, otherwise the result, and its implication, may be meaningless.

Post-use plastics are well suited to product manufacturing, which is the preferred option to energy generation because it increases circularity from both the product perspective and the waste perspective. Both outcomes, where feasible, should be used to divert as much as possible from landfills.

Plastics that can be sufficiently sorted and cleaned resulting in a reasonable level of contamination should be considered for pyrolysis-based recycling; those that can be highly sorted and cleaned should be considered for chemical depolymerization processes such as glycolysis, hydrolysis, and methanolysis.[17]

The important aspect to increasing plastic, or any, recycling rate is to better capture the material prior to entering the mixed waste stream. Therefore, any technology that encourages and permits improved collection should be developed.

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The Material & Energy Recovery (MER) Division and the Research Committee on Energy, Environment, & Waste (RCEEW) Committee of ASME supports this publication and is aligned with the findings.

Glossary

ABS	Acrylonitrile butadiene styrene	**LDPE**	Low density polyethylene
ALCA	Attributional life cycle assessment	**LHV**	Lower heating value
AR	Advanced recycling	**LLDPE**	Linear low-density polyethylene
BHET	Bis-(2-hydroxyethyl) terephthalate	**MP**	Mixed plastics
BTX	Benzene/toluene/xylene mixture	**MSW**	Municipal solid waste
CCL	The Combustion and Catalysis Lab at The City College of New York	**MSWI**	Municipal solid waste incineration (without energy recovery)
CFF	Circularity footprint formula	**MT**	Metric ton
CLCA	Consequential life cycle assessment	**NOx**	Nitrogen oxides
CO2eq	Carbon dioxide equivalent, the number of metric tons of carbon dioxide emissions with the same global warming potential as one metric ton of another greenhouse gas	**NREt**	Natural resource energy, total
Comm.	Commodity	**PA**	Polyamide
DMT	Dimethyl terephthalate	**PE**	Polyethylene
EEC	The Earth Engineering Center at The City College of New York	**PET**	Polyethylene terephthalate
EG	Ethylene glycol	**PLA**	Polylactic acid
EPA	Environmental Protection Agency	**PP**	Polypropylene
EPS	Expanded polystyrene	**PS**	Polystyrene
GHG	Greenhouse gas	**PTA**	Purified terephthalic acid
gm, g	Gram	**PTFE**	Polytetrafluoroethylene
HDPE	High density polyethylene	**PUR**	Polyurethane
HIPS	High impact polystyrene sheet	**PVC**	Polyvinyl chloride
ISO	International Standards Organization	**RDF**	Refuse derived fuel
JRC	Joint Research Center, as in The European Commission Joint Research Center	**t, e.g. 0.2 t**	Metric ton, e.g. 0.2 metric tons (= 440.9 pounds = 0.1968 imperial tons)
kg	Kilogram	**Tonne**	Metric ton
kWh	Kilowatt hour	**TRL**	Technology readiness level
LCA	Life cycle assessment	**WTE**	Waste-to-energy

References

(1) Biermann, L.; Brepohl, E.; Eichert, C.; Paschetag, M.; Watts, M.; Scholl, S. Development of a continuous PET depolymerization process as a basis for a back-to-monomer recycling method. *Green processing and synthesis* **2021**, *10* (1), 361-373. DOI: 10.1515/gps-2021-0036.

(2) Kurokawa, H.; Ohshima, M.-a.; Sugiyama, K.; Miura, H. Methanolysis of polyethylene terephthalate (PET) in the presence of aluminium tiisopropoxide catalyst to form dimethyl terephthalate and ethylene glycol. *Polymer degradation and stability* **2003**, *79* (3), 529-533. DOI: 10.1016/S0141-3910(02)00370-1.

(3) Russ, M.; Gonzalez, M.; Horlacher, M. *Evaluation of Pyrolysis with LCA – 3 Case Studies* Sphera Solutions GmbH, 2020. https://www.basf.com/global/documents/en/sustainability/we-drive-sustainable-solutions/circular-economy/selected-down_load/BASF_ChemCycling_LCA_Study.pdf (accessed 2022/02/01).

(4) Andrady, A. L.; Neal, M. A. Applications and societal benefits of plastics. *Philos Trans R Soc Lond B Biol Sci* **2009**, *364* (1526), 1977-1984. DOI: 10.1098/rstb.2008.0304 From NLM.

(5) *Certified Circular Polymers via Advanced Recycling of Mixed Plastic Waste;* Saudi Basic Industries Corporation (SABIC), 2021. https://www.sabic.com/assets/en/Images/certified-circular-polymers-life-cycle-assessment-lca-study-summary_tcm1010-29345.pdf (accessed 2022/02/01).

(6) *Life Cycle Assessment of Plastic Energy Technology for the Chemical Recycling of Mixed Plastic Waste;* Quantis, 2020. https://plasticenergy.com/wp-content/uploads/2020/10/Plastic-Energy-LCA-Executive-Summary.pdf (accessed 2022/02/01).

(7) *Hefty EnergyBag Program Life Cycle Assessment;* Sustainable Solutions Corporation, 2020. https://www.hefty.com/sites/default/files/2021-01/Hefty-EnergyBag-Program-Life-Cycle-Assessment-Aug-2020.pdf (accessed 2022/02/01).

(8) Sustainable Materials Management: Non-Hazardous Materials and Waste Management Hierarchy. United States Environmental Protection Agency.

(9) Kick, M.; Kadner, S.; Greiff, K.; Jarchow, S.; Stuchtey, M. R.; Weber, T.; Kobus, J. *Making Circular Economy Count - What You Can't Measure, You Can't Manage;* Acatech, Munich/London, 2021. https://www.systemiq.earth/wp-content/uploads/2021/04/CE-Metrics-Report-1404.pdf (accessed 2022/02/01).

(10) Schulte, A.; Maga, D.; Thonemann, N. Combining Life Cycle Assessment and Circularity Assessment to Analyze Environmental Impacts of the Medical Remanufacturing of Electrophysiology Catheters. *Sustainability* **2021**, 13 (2), 898.

(11) Linder, M.; Sarasini, S.; van Loon, P. A Metric for Quantifying Product-Level Circularity. *Journal of Industrial Ecology* **2017**, *21* (3), 545-558. DOI: https://doi.org/10.1111/jiec.12552.

(12) Design, T. E. M. F. a. G. Material Circularity Indicator (MCI). https://ellenmacarthurfoundation.org/material-circularity-indicator (accessed 2022/07//19).

(13) Scheepens, A. E.; Vogtländer, J. G.; Brezet, J. C. Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. *Journal of cleaner production* **2016**, *114*, 257-268. DOI: 10.1016/j.jclepro.2015.05.075.

(14) Di Maio, F. a. R. P. A Robust Indicator for Promoting Circular Economy through Recycling. *Journal of Environmental Protection* **2015**, *6*, 1095-1104. DOI: 10.4236/jep.2015.610096.

(15) Dräger, P.; Letmathe, P.; Reinhart, L.; Robineck, F. Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database. *Environmental Sciences Europe* **2022**, *34* (1), 13. DOI: 10.1186/s12302-022-00589-0.

(16) *Chemical Recycling: Greenhouse Gas Emission Reduction Potential of an Emerging Waste Management Route;* Quantis, 2020. https://cefic.org/app/uploads/2020/12/CEFIC_Quantis_report_final.pdf (accessed 2022/02/01).

(17) Brouwer, M. T.; Thoden van Velzen, E. U.; Ragaert, K.; ten Klooster, R. Technical Limits in Circularity for Plastic Packages. *Sustainability* **2020**, *12* (23), 10021.

(18) ARPA-E. No Title. Washington, DC, 2020.

(19) Hann, S.; Connock, T. *Chemical Recycling: State of Play;* Eunomia, 2020. https://chemtrust.org/wp-content/uploads/Chemical-Recycling-Eunomia.pdf (accessed 2022/02/01).

(20) *LCA carbon footprint summary report for Eastman carbon renewal technology;* Eastman Chemical Company, 2020. https://www.eastman.com/Company/Circular-Economy/Resources/Documents/CRT-Technical-LCA-report.pdf (accessed 2022/03/14).

(21) Granados, P.; Russ, M.; Pierce, C. J.; Waymire, R.; Brown, N. *LCA summary report for Eastman methanolysis technology (North America);* Quantis, 2022. (accessed 2022/03/14).

(22) Luu, P. *Transitioning to a Circular System for Plastics;* Environmental Clarity, https://www.closedlooppartners.com/appendix-molecular-recycling-technologies (accessed 2022/05/15).

(23) Zhao, X.; You, F. Consequential Life Cycle Assessment and Optimization of High-Density Polyethylene Plastic Waste Chemical Recycling. *ACS Sustainable Chemistry & Engineering* **2021**, *9* (36), 12167-12184. DOI: 10.1021/acssuschemeng.1c03587.

(24) Chaudhari, U. S.; Lin, Y.; Thompson, V. S.; Handler, R. M.; Pearce, J. M.; Caneba, G.; Muhuri, P.; Watkins, D.; Shonnard, D. R. Systems Analysis Approach to Polyethylene Terephthalate and Olefin Plastics Supply Chains in the Circular Economy: A Review of Data Sets and Models. *ACS Sustainable Chemistry & Engineering* **2021**, *9* (22), 7403-7421. DOI: 10.1021/acssuschemeng.0c08622.

(25) Schwarz, A. E.; Ligthart, T. N.; Godoi Bizarro, D.; De Wild, P.; Vreugdenhil, B.; van Harmelen, T. Plastic Recycling in a Circular Economy; Determining Environmental Performance through an LCA Matrix Model Approach. *Waste Management* **2021**, *121*, 331-342. DOI: https://doi.org/10.1016/j.wasman.2020.12.020 (acccessed 2022/02/01).

(26) Broeren, M.; Bergsma, G. *Exploration Chemical Recycling;* CE Delft, Delft, 2020. https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_2P22_Exploration_chemical_recycling_Extended_summary.pdf (accessed 2022/02/01).

(27) *Environmental Assessment of Full Brightmark Products;* Environmental Clarity, 2021. https://77f90741.flowpaper.com/BrightmarkLCA/#page=1 (accessed 2022/02/01).

(28) Viveros, A., CerenLoske, Fabian. *Life Cycle Assessment of Chemical Recycling for Food Grade Film;* Sphera, 2022. https://www.theconsumergoodsforum.com/wp-content/uploads/2022/04/Life-Cycle-Assessment-of-Chemical-Recycling-for-Food-Grade-Film.pdf (accessed 2022/05/15).

(29) Davidson, M. G.; Furlong, R. A.; McManus, M. C. Developments in the Life Cycle A ssessment of Chemical Recycling of Plastic Waste – A Review. *Journal of Cleaner Production* **2021**, *293*, 126163. DOI: https://doi.org/10.1016/j.jclepro.2021.126163 (acccessed 2022/02/01).

(30) Eastman to invest in France and circularity. Eastman Chemical Company: 2022.

(31) Tarach, K. A.; Gora-Marek, K.; Martinez-Triguero, J.; Melian-Cabrera, I. Acidity and accessibility studies of desilicated ZSM-5 zeolites in terms of their effectiveness as catalysts in acid-catalyzed cracking processes. *Catal. Sci. Technol.* **2017**, *7*, 858-873. DOI: 10.1039/C6CY02609E (acccessed 2022/05/31).

(32) Fazio, S. C.; V. Sala, S.; Schau, E.; Secchi, M.; Zampori, L. Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods. Ispra, Ed.; European Commission: 2018.

(33) Alatas, A. Life cycle assessment study on pyrolysis of post-consumer plastic waste. Lappeenranta-Lahti University of Technology LUT, https://lutpub.lut.fi/, 2021. https://urn.fi/URN:NBN:fi-fe2021080642280 (accessed 2022/08/15).

(34) Faulkner, C. A. Polystyrene Food Contact Recycling via Depolymeisation. In *Move to Zero. Zero Waste. Zero CO2. Powered by Styrenics. : Implications of rPS' Favourable LCA Results for the Value Chain,* 2021/06/01, 2021; Styrenics Circular Solutions: Webinar, 2021.

References - Selected LCAs for Comparison

LCA 1	Broeren, 2020	Broeren, M.; Bergsma, G. *Exploration Chemical Recycling*; CE Delft, Delft, 2020. https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_2P22_Exploration_chemical_recycling_Extended_summary.pdf (accessed 2022/02/01).
LCA 2	Schwarz, 2021	Schwarz, A. E.; Ligthart, T. N.; Godoi Bizarro, D.; De Wild, P.; Vreugdenhil, B.; van Harmelen, T. Plastic Recycling in a Circular Economy; Determining Environmental Performance through an LCA Matrix Model Approach. *Waste Management* **2021**, *121*, 331-342. DOI: https://doi.org/10.1016/j.wasman.2020.12.020 (acccessed 2022/02/01).
LCA 3	Chaudhari, 2021	Chaudhari, U. S.; Lin, Y.; Thompson, V. S.; Handler, R. M.; Pearce, J. M.; Caneba, G.; Muhuri, P.; Watkins, D.; Shonnard, D. R. Systems Analysis Approach to Polyethylene Terephthalate and Olefin Plastics Supply Chains in the Circular Economy: A Review of Data Sets and Models. *ACS Sustainable Chemistry & Engineering* **2021**, *9* (22), 7403-7421. DOI: 10.1021/acssuschemeng.0c08622.
LCA 4	Sabic, 2021	*Certified Circular Polymers via Advanced Recycling of Mixed Plastic Waste;* Saudi Basic Industries Corporation (SABIC), 2021. https://www.sabic.com/assets/en/Images/certified-circular-polymers-life-cycle-assessment-lca-study-summary_tcm1010-29345.pdf (accessed 2022/02/01).
LCA 5	Quantis, 2020/10	*Chemical Recycling: Greenhouse Gas Emission Reduction Potential of an Emerging Waste Management Route;* Quantis, 2020. https://cefic.org/app/uploads/2020/12/CEFIC_Quantis_report_final.pdf (accessed 2022/02/01).
LCA 6	Quantis, 2020/09	*Life Cycle Assessment of Plastic Energy Technology for the Chemical Recycling of Mixed Plastic Waste; Quantis,* 2020. https://plasticenergy.com/wp-content/uploads/2020/10/Plastic-Energy-LCA-Executive-Summary.pdf (accessed 2022/02/01).
LCA 7	Russ, 2020	Russ, M.; Gonzalez, M.; Horlacher, M. *Evaluation of Pyrolysis with LCA – 3 Case Studies* Sphera Solutions GmbH, 2020. https://www.basf.com/global/documents/en/sustainability/we-drive-sustainable-solutions/circular-economy/selected-down_load/BASF_ChemCycling_LCA_Study.pdf (accessed 2022/02/01).
LCA 8	Sus. Solns. Corp., 2020	*Hefty EnergyBag Program Life Cycle Assessment;* Sustainable Solutions Corporation, 2020. https://www.hefty.com/sites/default/files/2021-01/Hefty-EnergyBag-Program-Life-Cycle-Assessment-Aug-2020.pdf (accessed 2022/02/01).
LCA 9	Env. Clarity, 2021/10	*Environmental Assessment of Full Brightmark Products;* Environmental Clarity, 2021. https://77f90741.flowpaper.com/BrightmarkLCA/#page=1 (accessed 2022/02/01).
LCA 10	Quantis, 2022	Granados, P.; Russ, M.; Pierce, C. J.; Waymire, R.; Brown, N. *LCA summary report for Eastman methanolysis technology (North America);* Quantis, 2022. (accessed 2022/03/14).
LCA 11	Eastman, 2020	*LCA carbon footprint summary report for Eastman carbon renewal technology;* Eastman Chemical Company, 2020. https://www.eastman.com/Company/Circular-Economy/Resources/Documents/CRT-Technical-LCA-report.pdf (accessed 2022/03/14).
LCA 12	Sphera, 2022	Viveros, A., CerenLoske, Fabian. *Life Cycle Assessment of Chemical Recycling for Food Grade Film;* Sphera, 2022. https://www.theconsumergoodsforum.com/wp-content/uploads/2022/04/Life-Cycle-Assessment-of-Chemical-Recycling-for-Food-Grade-Film.pdf (accessed 2022/05/15).
LCA 13	Env. Clarity, 2021/02	Luu, P. *Transitioning to a Circular System for Plastics;* Environmental Clarity, https://www.closedlooppartners.com/appendix-molecular-recycling-technologies (accessed 2022/05/15).

Appendix

TABLE A1. CLASSIFICATION OF RECYCLED PLASTICS IN RELATION TO THEIR APPLICABILITY, REPRODUCED FROM BROUWER ET AL., 2020.[17]

Application Type	EoL Fate	Product Types	Typical Acceptable Degradation	Typical Acceptable Contamination
Food no contamination (F-NC)	Circular Closed-loop	Bottle-to-bottle (PET, HDPE) Bottle-to-tray (PET) Clear Film-to-film (LDPE)	Very limited PET bottle: IV > 0.76 HDPE bottle: MFI < 3 PET tray: IV > 0.70 LDPE film: 1<MFI < 6 HDPE film: MFI < 0.4	Very limited Other polymers: In PET < 50 ppm In PO: Other PO < 1% Non-PO < 50 ppm Non polymers < 50 ppm Specific for film: only clear Melt filtration < 50 µm
Non-food Low contamination (NF-LC)	Circular Semi-closed-loop	Bottle-tobottle (HDPE, PP) Bottle-to-fibre (PET) Non-clear Film-tofilm (LDPE, HDPE) – e.g, garbage bags, agricultural film Thin-walled injection moulding products (PP, PE) Pipe (PP)	Limited for PET fibre: IV > 0.62 LDPE, PP film: MFI < 0.4 HDPE, PP bottle: MFI < 3 PP pipe: MFI ≈ 2 Significant for PE, PP injection moulding (MFI can be > 3, up to 30)	Limited PET fibre and LDPE, PP film as F-NC Injection moulding and bottle (PO): Other polymers: Ohter PO < 5% Non-PO < 1% Non-polymers < 50 ppm Specific for film: all colours Melt filtration < 200 µm
Non-food Significant contamination (NF-SC)	Circular Open-loop	Extrusion of bulky products like decking, panels and street furniture (MPO)	Significant MPO: 2 < MIF < 7	Siginificant Other polymers (PET, others) < 10%-20% (depending on processing conditions) Non polymers < 5% (depending on size) Melt filtration < 800 µm
Non-recycling High contamination (NR-HC)	Linear	High-caloric combustibles (cement industry) incineration with energy recovery	Unlimited	Quasi-unlimited Non-polymer contaminations will affect efficiency of incineration