Chemical Recycling

A White Paper by:

Circular Matters

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The use of plastics in general and plastic packaging in particular are being judged based on recyclability. Our industry recognizes with the broad use of plastic packaging a responsibility exists to look at the entire value chain, including end-of-life. There is a need to move beyond our current linear economy where packaging is disposed after use to a Circular Economy where this valuable resource is collected, re-processed and used again as another package. The material structures, technologies, and systems required to fully realize this end state will not occur overnight. However, urgency and industry collaboration are a priority. Through this White Paper, we hope to share useful insights and learnings on the potential role chemical recycling can play in making progress toward a Circular Economy.

- Phillip Crowder, Director, Corporate Sustainability, Winpak

1. Executive Summary

According to the U.S. Environmental Protection Agency the U.S. plastics packaging recycling rate was 13 percent in 2018 and this low recycling rate has been stagnant for the past decade.[1] Globally there are concerns that plastics resources are, at a minimum, being wasted due to their low recycling rates, and in some areas are mismanaged at the end of their life and being leaked into the environment. Consumer packaged goods companies have responded to these concerns with commitments to only use plastic packaging that is recyclable, reusable, or compostable, and to use recycled plastic in their products and packaging to develop circular plastics loops.

How is this going to happen? Plastic used in packaging, including recycled plastic, must meet high standards of food safety, product protection, and brand image. Virgin plastic made from fossilized carbon sources – primarily natural gas and oil – can meet these requirements and can be produced inexpensively at large-scale plastics facilities. Producing an equivalent quality at a reasonable cost from recycled plastics is difficult and is a major reason why plastics packaging recycling rates remain low.

A family of emerging technologies, referred to by many as chemical recycling, is pointed to by advocates as a pathway for all plastics to be collected and recycled, either "mechanically" by cleaning and reusing the raw material – the predominant approach to plastics recycling today – or using new chemical recycling approaches that can break plastics down into feedstocks that the chemical industry can substitute for virgin materials to manufacture plastics and other products. Others are unsure of chemical recycling. Most arguments for or against chemical recycling are centered on three questions:

1. Can mechanical recycling provide recycled plastic of sufficient quality that it can be reused circularly in the packaging applications it was originally used in?
2. Is the family of chemical recycling technologies financially viable?
3. Is mechanical recycling better than chemical recycling for the environment?

[1] U.S. Environmental Protection Agency, "Advancing Sustainable Materials Management: 2018 Tables and Figures," November 2020.

This White Paper finds that the debate over mechanical and chemical recycling should not be "either/or" but instead "both/and." It is not cost effective to collect and recycle all plastic mechanically. Furthermore, the quality of plastics diminishes after each use, diminishing its value and ability to be used in high-performance applications. Consumer packaged goods companies and the plastics industry are committed to the viability of chemical recycling technologies. While mechanical recycling is preferred in general, chemical recycling is the best management option for certain plastics not able to be cost-effectively recycled mechanically.

2. Introduction

What is Chemical Recycling?

Chemical recycling is a broad term that covers a variety of processes and technologies that take plastic scrap and discards and breaks it down into smaller molecules that can be put back into commercial use. The term "chemical recycling" has not been consistently adopted. Some use the terms "advanced recycling," "feedstock recycling," "molecular recycling," or use terms related to a specific technology that a company uses. This White Paper uses the term chemical recycling.

Chemical recycling is differentiated from traditional plastics recycling, referred to as mechanical recycling. Mechanical recycling involves grinding, cleaning, and melting and then using the material to manufacture recycled plastic products without changing the molecular structure of the material. Purification is an emerging technology that is similar to mechanical recycling in that the molecules are not altered; but differs from mechanical recycling in that the plastics are dissolved in a solvent that allows the removal of additives and impurities, yielding a purified plastic that is more like virgin plastics than mechanically recycled plastics. Because the plastic molecules themselves have not been altered, purification, even though it may use chemicals in the recycling process, does not meet the definition of chemical recycling used in this paper.

Decomposition and conversion are categories of chemical recycling. Decomposition, also known as depolymerization, chemically breaks certain types of plastics down into the chemical building blocks that they are made from. Only certain plastic types can be chemically depolymerized, including PET, nylons, polyurethanes, and polylactic acid (PLA). With depolymerization, plastics must be sorted into streams of individual resin types – mixed plastics cannot be depolymerized.

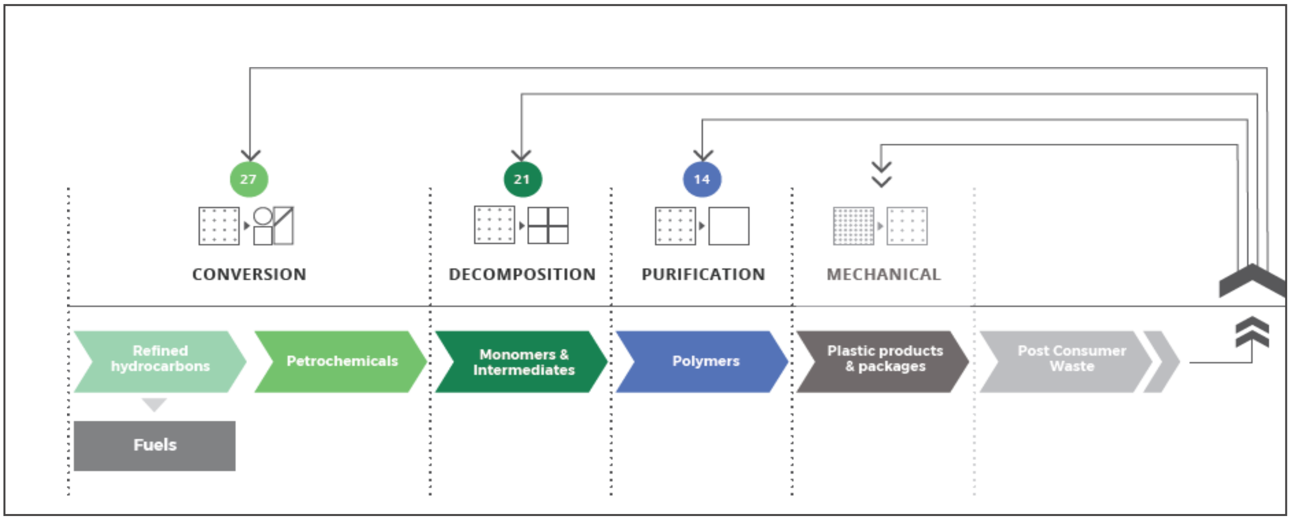
Conversion refers to high-temperature processes where plastics, which can include a mix of resin types, are heated in a low or no-oxygen environment to break them down into oils and gases. Because oxygen is lacking the plastics do not burn; therefore, this type of chemical recycling process should not be confused with waste-to-energy.

There are two primary types of conversion processes – pyrolysis and gasification. In pyrolysis plastics are converted to oil, which can be refined into fuel or sent to chemical plants where the oil can be converted into chemical products and can even be converted back into plastics. The other conversion process is gasification. In gasification mixed plastics are heated with steam and a small and controlled amount of oxygen is introduced to produce carbon monoxide, hydrogen, and methane. These gases are further converted into methanol or ethanol, which can be used to produce chemicals or plastics. Gasification can also be used to process non-plastic organic waste and mixed waste that contains plastic.

Combusting the products resulting from chemical recycling for energy does not meet the definition of recycling by the International Organization for Standardization,[2] and most North American stakeholders also do not consider this to be recycling. Until recently companies operating pyrolysis plants in North America have sold their products strictly as fuels; however, increasingly their products are being sold to the North American petrochemicals industry to be recycled into chemical products and plastics.

Figure 1, by the Closed Loop Partners, illustrates different approaches to recycling plastics.

Figure 1: Differentiating Between Recycling Approaches



Source: Closed Loop Partners, Accelerating Circular Supply Chains for Plastics, 2019.

Current Status and Outlook for Chemical Recycling Capacity in the U.S. and Canada

Although pyrolysis and gasification technologies have existed for decades, companies intending to use those technologies to recycle plastics have historically struggled with profitability. Only recently have they become viewed as an important and necessary part of a circular and sustainable use of plastics. This interest in chemical recycling is being driven by the growth of packaging formats that are not practically recyclable via mechanical recycling, company goals to use recyclable, reusable, or compostable packaging and use recycled content in their packaging, and the need for virgin-equivalent quality in recycled resins, especially when the plastic is used for food and beverage packaging applications.

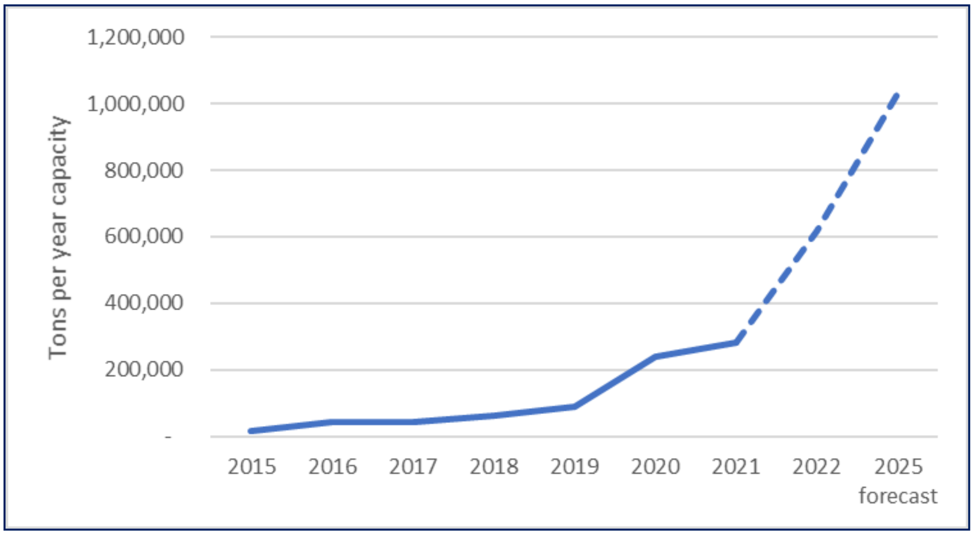
The current capacity for chemical recycling of plastics in the U.S. and Canada is around 0.2 million tons of plastics per year, most of which has been added in the last year. By comparison, 3.3 million tons of postconsumer plastics were mechanically recycled in the U.S. and Canada in 2018, and approximately 30 million tons were landfilled or combusted at waste-to-energy facilities in the two countries. As a result of the growing interest in chemical recycling, including from virgin plastics and chemical companies that are supporting the growth of the industry, another 0.6 million

[2] ISO 15270:2008 (en) Plastics —Guidelines for the recovery and recycling of plastics waste.

tons of additional chemical recycling capacity has been announced. Some of these are plastics-to-fuels plants, some of which may ultimately not be developed; but the capacity to chemically recycle plastics in North America is growing significantly.

Figure 2 shows growth in the capacity to chemically recycle plastics in the U.S. and Canada.

Figure 2: Growth in U.S. and Canadian Chemical Recycling Capacity



Source: Circular Matters

As depicted in Figure 2, the growth rate of chemical recycling accelerated in 2019 and there are several plants currently under construction that are expected to open in 2021 and 2022. Several companies have also announced projects that are forecasted to be operational before 2025.

It is likely that the pace of capacity expansion will continue after 2025. However, chemical recycling will likely not be widely considered proven and economically viable in North America until 2030 or beyond, when collection and sorting of plastics for chemical recycling could expand comprehensively throughout North America. Challenging the pace of expansion is that chemical recycling capacity over the next few years will likely exceed collection of feedstock, especially from residential generators. Consequently, consumer packaged goods companies wishing to meet recyclability goals for their flexible packaging by 2025 (the target date for goals set by the U.S. Plastics Pact, the Canada Plastics Pact, and the New Plastics Economy Global Commitment) recognize the need to focus in the near term on designing packaging to be compatible with mechanical recycling while concurrently working to advance collection and processing systems that can supply increasing amounts of hard-to-recycle plastics to chemical recyclers as well.

Overview of Stakeholder Positions on Chemical Recycling

Some stakeholders have explicitly supported chemical recycling, not as a panacea, but as a strategy that can play a positive role in bringing about the circular economy if implemented properly, while others have explicitly stated concerns with or outright opposition to chemical recycling. Still other stakeholders have not yet weighed in. These positions are summarized in Table 1, and several key ones are expanded upon in the next sections.

Table 1: Summary of Stakeholder Opinions on Chemical Recycling

Stakeholder Category	Support	Concerns
Environmental NGOs	• Some see chemical recycling as a way to reduce ocean plastics (e.g., Trash Free Seas Alliance, Ocean Conservancy)	• Some have concerns about Greenwashing (e.g., GAIA, Greenpeace) • Concerns about chemical recycling being an excuse to continue to use plastics (e.g., GAIA, Greenpeace) • Concern about burning, pollution/toxins, energy use, greenhouse gas emissions and environmental justice (e.g., GAIA, U.S. PIRG) • Lack of ability to commercialize and scale up (e.g., GAIA)
Material Recovery Facilities (MRFs)	• Some supply and others are positioning to supply feedstocks to chemical recycling facilities	• Some are concerned with ability to manage material profitably and without negatively impacting other material streams • The Alliance of Mission-Based Recyclers (includes nonprofit organizations and zero waste organizations that operate MRFs) does not see plastics to chemicals or fuels as recycling and believes it is premature to include plastics-to-plastics processes in the recycling rate
Plastics Reclaimers	• See opportunities to supply non-targeted plastic materials as feedstock to chemical recycling facilities, especially if accepting a broad range of resins such as mixed bales	• See chemical recycling as competition
Virgin Resin Producers	• See chemical recycling as essential to reducing plastics impact on the environment and maintaining consumer acceptance of plastics by keeping plastics from being waste • Shareholder pressures are increasing investment in sustainability measures such as chemical recycling • Many forming partnerships/joint ventures with chemical recyclers	
Consumer Packaged Goods (CPG) Brands	• See as a means to meet sustainability/circularity goals (i.e., recycled content and recyclability) Some have formed partnerships with chemical recycling companies	

Stakeholder Category	Support	Concerns
Industry Groups and Associations	• See as a means to reduce reliance on petroleum (ACC) • See as a potential means to enhance circularity (ACC, The Recycling Partnership) • See as complementary to mechanical recycling (ACC, APR, TRP)	• Some see chemical recycling that is energy recovery or results in production of fuel as not recycling (ACC recognizes plastics to fuel as "advanced recovery")
State and Local Governments	• Some see as a potential means of reducing disposal/bringing about the circular economy • Some states (12) have passed laws to ensure chemical recycling is seen as manufacturing or processing, not disposal, to minimize permitting burdens, thus supporting chemical recycling[3]	• May have permitting/environmental impact concerns • May be uncertain whether all chemical recycling "counts" as recycling – some do not believe it is recycling (see discussion in following sections)

3. In Support of Chemical Recycling

Chemical recycling is supported in varying degrees by many stakeholders. Several recycling industry groups (with some caveats) and consumer packaged goods brands actively support it, whereas some but not all environmental NGOs and certain state and local governments will support it under certain conditions. This section presents reasons to support chemical recycling, with examples of statements and positions by stakeholders.

Enhanced Circularity

Chemical recycling can be used to recycle plastics that would otherwise be disposed today, and in some cases enables them to be recycled endlessly. This is the epitome of circularity. Using mechanical recycling processes, plastic molecules change structurally when subjected to thermal and mechanical stress during melting and extrusion, causing plastic to degrade after each use, resulting in quality and performance limitations. Considering the vast amounts of plastic waste that have not been able to be recycled mechanically, chemical recycling is critical to shifting toward circularity.

Consumer packaged goods (CPG) companies largely support chemical recycling because it is seen as a means to help them achieve their circularity goals for their packaging (both recyclability and recycled content), without sacrificing the product protection and consumer convenience attributes of their packaging. Some brands, like Unilever, PepsiCo, Sealed Air, and L'Oréal, have engaged in partnerships with chemical recycling companies to help bring about the circular economy and help ensure they can achieve their packaging sustainability goals.[4]

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[3] These states include Arizona, Florida, Wisconsin, Georgia, Iowa, Tennessee, Texas, Illinois, Ohio, Pennsylvania, Virginia, and Oklahoma.

[4] Plasticsinpackaging.com, "Partnership aims to Convert Waste into Virgin Grade Material," April 4, 2018

Many virgin resin producers are also in support of chemical recycling, as they are becoming involved in developing or have developed their own chemical recycling processes or have formed partnerships or joint ventures for chemical recycling, so that they, too, are able to achieve sustainability goals through chemical recycling processes. Examples of virgin resin companies investing in chemical recycling include American Styrenics, Braskem, Chevron Phillips Chemical Company, Dow, Eastman, ExxonMobil, Indorama, Nova Chemicals, and Shell.

The American Chemistry Council (ACC), an industry organization representing companies engaged in the business of chemistry, actively supports chemical recycling as one tool to help achieve the circular economy. The ACC sees chemical recycling as complementary to mechanical recycling. The Advanced Recycling Alliance for Plastics (ARAP) is a self-funded group of the American Chemistry Council's Plastics Division that works go grow chemical recycling for plastics.

The Association of Plastics Recyclers (APR) sees chemical recycling as having the potential to greatly enhance the sustainability of plastic, if it is implemented properly, and sees chemical recycling as a complementary process to mechanical recycling as long as the products of chemical recycling go back into plastics.[5]

The Alliance to End Plastic Waste is an organization with over 80 members and supporters, including founding signatories Dow, BASF, ExxonMobil, Chevron Phillips, DSM, Henkel, and Procter & Gamble. The organization's position is that "Ending plastic waste is achievable through ***innovative and impactful solutions, deployed at-scale*** whilst partnering with communities around the world. All this is further bolstered by catalysing investment capital."[6] The organization is working globally to end plastic pollution and is focusing their attention on communities where the risk of leaking plastic into the environment is highest. The organization recently solicited proposals for chemical recycling projects to be funded by grants for $1-$20 million.[7,8]

The Ellen MacArthur Foundation (EMF), which promoted the concept of the circular economy and whose mission is to accelerate the transition to a circular economy, appears to accept chemical recycling as one tool to help achieve the circular economy. The Foundation envisions the path to plastics circularity as eliminating unnecessary plastics, reusing some plastics, and ensuring the remainder of plastics are recyclable, reusable or compostable. The Foundation created The New Plastics Economy, a collaborative uniting more than 1,000 organizations to help bring about circularity in plastics. The vision is supported by three key actions: eliminate, innovate, circulate. Led by EMF, CPG companies and other supporters have made commitments to engage in those three key actions and strive to achieve certain goals (the key one being to have all plastic packaging in use be recyclable, reusable, or compostable by 2025) through various Plastics Pacts (including the U.S. Plastics Pact and the Canada Plastics Pact) and the New Plastics Economy Global Commitment. While EMF has not explicitly stated that the organization supports chemical recycling, their published documents imply that they are supportive of plastic-to-plastic chemical recycling when mechanical recycling is not feasible and see it as a means of keeping the molecule in play. Additionally, members of the EMF network published a document about the mass balance

[5] APR, "Position Statement on Chemical Recycling," May 2021

[6] The Alliance to End Plastic Waste, "Our Mission"

[7] The Alliance to End Plastic Waste, "The Alliance to End Plastic Waste Calls for Submissions for Recycling Technologies," February 10, 2021.

[8] Recycling Today, "The Alliance to End Plastic Waste to Fund Chemical Recycling Projects," February 12k, 2021.

approach (described later in this Paper), stating “A mass balance approach to enable the sale of certified recycled products at virgin-grade quality could be very valuable to all users of materials and chemicals in the value chain.”[9]

The EMF and other environmental NGOs concerned with ocean plastics see chemical recycling as a potential means of adding value to plastics, thereby incentivizing their recycling and reducing the amount ending up in the environment as litter or poorly managed waste.

The Ocean Conservancy’s Trash Free Seas Alliance® includes in its Roadmap and Call to Action to “Explore emerging recycling technologies (e.g., chemical recycling) to make non-recyclable plastics recyclable.[10]”

May Include Multiple Resins

One benefit of chemical recycling is that some technologies (e.g., pyrolysis and gasification) enable multiple resin types to be processed together, which reduces the need for additional sorting, thereby enhancing economic viability for low-value plastics. Eastman, for example, has developed a carbon renewal gasification technology that can transform hard-to-recycle mixed plastics into chemicals to be used to manufacture new plastic products as well as potentially other products for which those chemicals are ingredients. Most pyrolysis companies process mixtures of non-bottle polyethylene, polypropylene, and polystyrene.

Can Often Include Materials Not Widely Recycled

Chemical recycling processes can help catalyze the circular economy by broadening the array of materials that can be recycled via these new pathways, versus landfilling or processing them in waste-to-energy facilities, which is largely their destiny today.

Chemical recycling processes such as gasification, and to a lesser extent pyrolysis, can be used to process multi-layer materials, including multi-material packaging such as flexible packaging with paper and/or metallic layers. Additionally, chemical recycling can be used to process textiles and bulky items that are often challenging to manage at the end of their useful life, including carpet. For example, chemical depolymerization processes using glycolysis and hydrolysis variations can process PET/polyester, including carpet and textiles, with claims of yields of upwards of 90 percent, and resulting in pure monomer feedstocks.

Some food packaging, such as condiment sachets, are convenient and preserve food quality and safety, but do not always allow full evacuation of product and thus have low recycling yields. Therefore, they are not desired by mechanical recyclers. Chemical recycling processes such as pyrolysis and gasification are more tolerant of these streams of material.

As is mentioned above, CPGs in general support chemical recycling because the processes may enable the companies to achieve their recycled content and recyclability goals. Recycled content goals may be met through direct recycled content, or by using the mass balance approach.

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[9] Members of the Ellen MacArthur Foundation Network, “Mass Balance White Paper,” 2020.

[10] Ocean Conservancy/Trash Free Seas Alliance®, “Plastics Policy Playbook: Strategies for a Plastic Free Ocean.”

Reduces Use of Oil and Gas

By making products from recycled plastic, including plastic goods but also fuels and other chemicals, manufacturers of those products rely less on virgin natural gas and petroleum-based inputs, which is a goal of nearly all stakeholders.

4. Concerns about Chemical Recycling

Some stakeholders, in particular certain environmental NGOs, have been outspoken regarding their concerns about chemical recycling. Examples include GAIA (Global Alliance for Incinerator Alternatives), whose vision is a "just, toxic-free world without incineration"[11] and Greenpeace.

Energy Use/Greenhouse Gas Emissions

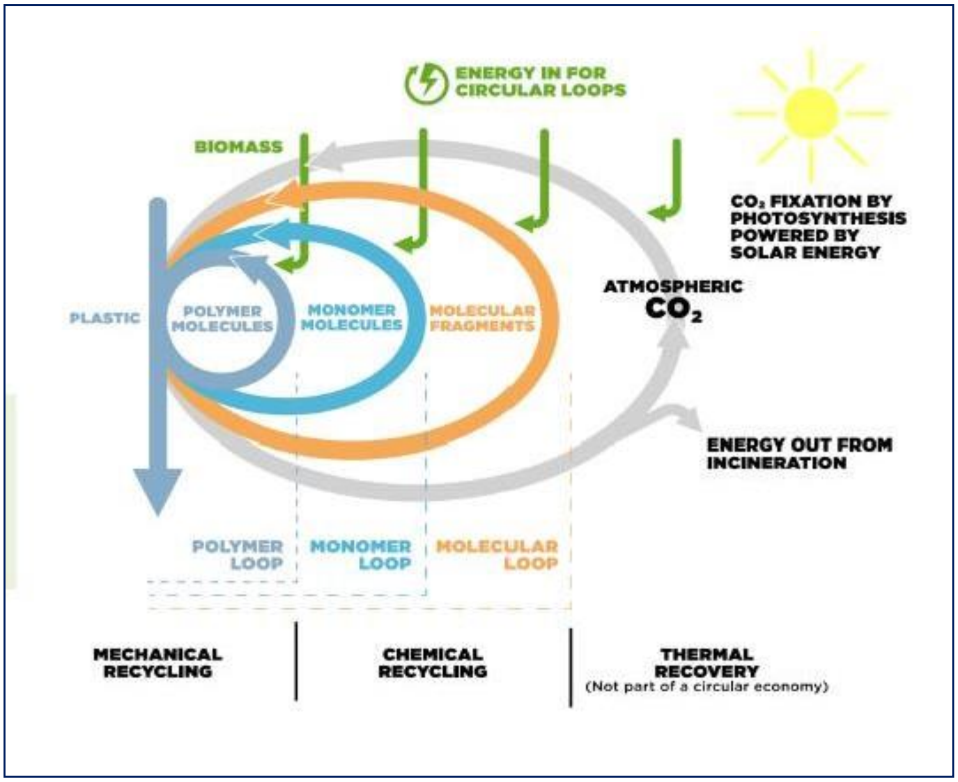
The major concern with chemical recycling processes is the relatively high use of energy required by them, which is the major factor impacting greenhouse gas (GHG) emissions, which contributes to global warming. How different technologies perform relative to each other is challenging to discern, as all processes have their unique aspects, and not all companies are willing to share their data. Another important factor to consider is the source of energy where the processes take place. Some in the industry have committed to use renewable energy in order to offset impacts. Examples include BASF and Dow. Eastman has committed to achieving carbon neutrality by 2050, with an interim goal of reducing absolute scope 1 and scope 2 greenhouse gas emissions by one third by 2030.[12]

A presentation regarding a lifecycle assessment (LCA) study conducted for BASF includes a graphic (Figure 3Figure 3) illustrating how more energy is needed when plastics molecules are altered. Therefore, moving from a polymer "loop" to a monomer "loop" to a molecular "loop" requires increasingly more energy, and mechanical recycling is therefore preferred, all else being equal.

[11] GAIA, "About GAIA."

[12] https://www.eastman.com/Company/Sustainability/Pages/Introduction.aspx

Figure 3: Recycling and Incineration "Circular Loops"



Source: Dr. Christian Krüger, Corporate Sustainability, BASF, "LCA ChemCycling™" October, 2020.

It is generally agreed upon that chemical recycling processes use more energy than mechanical recycling, and that chemical recycling is preferred over virgin resin production.

Will Divert Material from Mechanical Recycling

Some stakeholders (such as reclaimers and some environmental groups) are concerned that chemical recycling will pull material from mechanical recycling. PET and HDPE bottles and jugs are material types that have robust mechanical recycling infrastructure in the U.S. and Canada, for example. Because chemical recycling processes require more energy and are relatively costly, it is unlikely that chemical recycling processes would be able to profitably purchase relatively high value plastics such as these as a feedstock.

Chemical recycling companies generally focus on lower value plastics for their feedstock needs, as well as materials that are currently not commonly recycled. Eastman is an example of a chemical recycling company that acknowledges that mechanical recycling "is a very effective, environmentally friendly process that should be used whenever possible,"[13] but acknowledges its limitations. The U.S., for example, only manages to achieve a recycling rate of about 30 percent for PET and HDPE containers – and these are materials with the most robust recycling systems in the U.S. and Canada. Other types of plastic including PS, PET films, thermoforms, carpet and

[13] Eastman, "Some Things are Better Together," Accessed March 23, 2021.

textiles, LDPE and PP have much lower recycling rates and far less robust recycling systems.

Will Cause Pollution with Toxic Chemicals

GAIA states concerns about the toxins that are in plastics (e.g., antioxidants, flame retardants, plasticizers, lubricants and heat stabilizers), and how the chemical recycling processes of these plastics reportedly create toxic gases such as hydrogen cyanide and carbon monoxide, among others, as well as toxins in the resulting gas, oil or char. GAIA claims that pyrolysis oil, in particular, is far more contaminated with solid residue, dioxins, and PAHs than regular diesel, requires substantial post-treatment cleaning to be used as a fuel, and that cleaning the fuel is extremely difficult, expensive, and creates additional toxic waste streams.[14]

Most plastics-to-fuel pyrolysis companies exclude non-packaging plastics that contains problematic additives, and certain plastic packaging that can contaminate their product streams (e.g., PVC, metalized plastics), in order to reduce the need for post-process treatment of the oil to meet fuel purity standards.

Greenwashing/Used to Justify Continued Use of Plastics

One document by GAIA states that chemical recycling is "an industry greenwash term used to lump together various plastic-to-fuel and plastic-to-plastic technologies."[15] A report by the same organization states that the petrochemical industry is latching onto chemical recycling as a way to save itself as "the future of the fossil fuel industry becomes more and more precarious."[16] GAIA supports "upstream, zero waste strategies which focus on reducing the production and consumption of plastic."[17] Greenpeace, too, claims that "the industry has often attempted to conflate waste-to-fuel/plastic-to-fuel and plastic-to-plastic under the respective umbrellas of 'chemical recycling' and 'advanced recycling.'"[18]

Industry Has a Poor Track Record

Another report by GAIA attempts to present the industry as full of "empty promises" with "a track record of high-profile failures across the globe."[19] The same report states that of the 37 projects that have been initiated in the U.S.:

- Fourteen are "mere announcements;"
- Eleven are at a pilot stage or under construction;
- Twelve projects claim to have developed a plastic-to-plastic (PTP) process, none of which are yet at commercial stage;
- Twenty are plastics-to-fuel (PTF) projects, and thus do not qualify as recycling; and

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[14] GAIA, "Chemical Recycling Distraction, Not Solution," 2020.

[15] GAIA, "Questions and Answers: Chemical Recycling," 2019.

[16] Patel, D., Moon, D., Tangri, N., Wilson, M. for Global Alliance for Incinerator Alternatives, "All Talk and No Recycling: An Investigation of the U.S. "Chemical Recycling" Industry," 2020.

[17] Ibid.

[18] Schlegel, Ivy, for Greenpeace, "Deception by the Numbers," September 9, 2020.

[19] Ibid.

- Only three projects – Agilyx (claims to be PTP but authors see no evidence, as they have observed that material goes to cement kilns), Brightmark (PTF), and New Hope Energy (PTF) – are currently commercially operational.[20]

While chemical recycling processes have taken some time to become commercialized, several are now operating at full scale commercially, and an array of situational factors (e.g., advancements in technology, focus on supportive policies, changing virgin feedstock prices, and increased focus on the recyclability and recycled content of packaging) are likely to result in accelerated commercialization of these processes by other companies. Furthermore, at least two pyrolysis companies operating at commercial scale, New Hope Energy and Nexus Fuels, are selling increasing amounts of their production to chemicals companies for conversion into chemicals or plastics, rather than selling primarily into fuel markets.

5. Making Sense of the Arguments

The various pro and con arguments introduced above can leave one uncertain about whether or not to support chemical recycling. This section provides an assessment of key concepts to consider in forming a position.

Many Criticisms Lump All Processes in One Basket. Several opponents of chemical recycling lump all chemical recycling approaches and specific technologies together without acknowledging the differences in processing approaches used or products produced. For example, opponents often conflate pyrolysis to fuel with (1) pyrolysis followed by cracking and refining to chemicals, (2) gasification, and (3) depolymerization. Past failures of plastics-to-fuel projects then are put forward to say that all varieties of chemical recycling will not be financially viable today or in the future, or that they will all have the same environmental footprint as plastics to fuel. This line of reasoning fails to acknowledge that plastics to fuel has a much different environmental impact and value in the marketplace than plastics chemically recycled back into plastics or other chemicals.

The Marketplace and Technologies Have Evolved. With respect to value in the marketplace, CPGs have made commitments to their customers to increase their use of recycled plastic in their branded packaging. As they do so, the value of recycled plastic in the marketplace has increased, even exceeding that of prime virgin resin due to the "recycled" pedigree.[21] The same is not the case for plastics recycled to fuel, which generally is a commodity in the marketplace without strong brand-to-customer connections, so that "recycled" fuel typically does not obtain similar premium prices.[22] Failures of plastic-to-fuel companies therefore cannot be used to discount the financial viability of pyrolysis companies in a chemical recycling value chain, or other chemical recycling approaches for that matter. Similarly, technologies continue to evolve to become more efficient and, when scaled, economics are expected to be more favorable. It is not beneficial to judge today's scenario based on yesterday's circumstances.

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[20] Ibid.

[21] According to the April 19, 2021 edition of Plastic News, the sales price of recycled natural HDPE resin from milk jugs was 108-112 cents per pound whereas virgin milk jug resin was 75-78 cents per pound.

[22] Circular Matters estimates the value of diesel fuel to be U.S. 45 cents per pound at the time this White Paper was produced. This is based on a diesel fuel product with a density of 6.9 pounds per gallon and the national average on-road diesel retail price of $3.13 per gallon as of April 2021 as reported by the U.S. Energy Information Administration, "Gasoline and Diesel Fuel Update."

Lifecycle Assessments are Used – But They are Complex and Situationally Specific. There has been reluctance from some governmental policymakers and certain environmental NGOs to support chemical recycling out of concern that plastics that can be mechanically recycled will go to chemical recycling. They also express concern that LCAs conducted by companies in support of chemical recycling are biased and have been conducted to ensure favorable outcomes for chemical recycling. The energy use/greenhouse gas emissions, pollution from toxic chemicals, and competition with mechanical recycling arguments introduced above flow from the distrust opponents of chemical recycling have of the results of existing LCAs.

LCAs are intended to be used to compare one alternative to another across a product's complete lifecycle. LCAs are complex to conduct, include many assumptions, and assess multiple criteria. Sometimes one option provides a better outcome for one criterion, but a worse outcome for a different criterion, which can make it difficult to conclude whether one approach is preferable over another. Caveats to be considered when reviewing chemical recycling LCA data include:

- The results of a plant-specific LCA only applies to that plant at that site. An identical plant constructed elsewhere will have different LCA results. This is because energy produced in one region (or facility) may be made primarily from renewable energy but energy in a different region (or facility) may be made primarily from fossil fuels. Energy produced from fossil fuels has greater impacts.
- An LCA for a specific chemical recycling technology in a specific location going to specific end uses is not necessarily representative of what an LCA would be for other chemical recycling technologies with different end uses. For example, an LCA for a plastics-to-fuel pyrolysis plant will provide different results than an LCA for a different chemical recycling technology (e.g., depolymerization or gasification), or even the same pyrolysis plant if it were to send its products to chemical recycling rather than fuel use. A single plant-specific LCA should not be considered representative of the family of chemical recycling technologies in general.
- One needs to ask: "what alternative option is the specific chemical recycling approach being compared to?"
    - Virgin plastic resin made from petrochemicals?
    - Recycled plastic from mechanical recycling?
    - Plastic to fuel vs. fossil-derived fuel?
    - Disposal through waste-to-energy plants or landfills?

The more precise an LCA is the more reliable its data will be, at least for the specific location and technology covered by the analysis. An LCA assessing whether mixed resins of small-sized packaging in Atlanta, Georgia, should be collected and sent to chemical recycling versus whether they should be further sorted and sent to mechanical recycling can provide the data needed for a local decision, for example, although the outcome of the analysis might change if the analysis were conducted for a different location.

Comparing generalized LCAs of mechanical recycling to chemical recycling of plastics is based on an assumption that a post-consumer milk jug, for example, could just as likely be purchased by a chemical recycler as a mechanical recycler, or that multi-material flexible packaging can be just as feasibly recycled mechanically as chemically. The reality for many plastic products is that mechanical and chemical recyclers are generally not competing for the same material, although it is acknowledged that there are some exceptions (e.g., loose film plastic collected in residential curbside recycling collection systems and PET thermoforms have low market value and could be sourced by either mechanical or chemical recyclers). By and large, chemical recyclers are seeking to source material that is either being disposed or has weak mechanical recycling or end user demand because mechanical recycling does not produce material of sufficient quality to elicit strong demand.

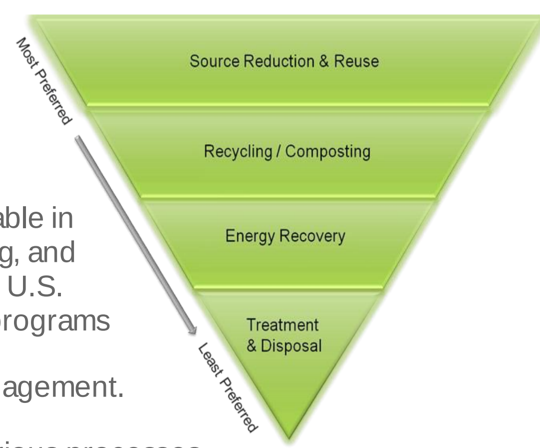
Circular Matters reviewed several LCAs, nearly all from Europe because few are available for North America, where chemical recycling was compared to alternatives. Assuming that climate change is the overarching criterion of concern, and that the results from elsewhere generally are transferrable to North America, which has not yet been established, the studies show:

- From an end product standpoint, all forms of chemical recycling into non-fuel products are preferred to virgin plastics production from petrochemicals.[23]
- Mechanical recycling may be preferred, but not greatly so, over chemical recycling, at least for mixed streams of plastics.
- From a waste perspective, chemically recycling plastics is generally preferable to incinerating them.

The bottom line on LCAs is that they can be a valuable tool for data-based decision-making and establishing policies regarding materials management hierarchies once consensus regarding priorities and objectives is established. More LCAs specific to North America are needed to clearly demonstrate the extent to which specific end-of-life plastic streams should be prioritized for recycling through mechanical or chemical means.

6. Where Chemical Recycling Can Fit in a Sustainable Materials Management Hierarchy

Figure 4: U.S. EPA Waste Management Hierarchy



The U.S. EPA developed the “non-hazardous materials waste management hierarchy” provided in Figure 4 in recognition that no single waste management approach is suitable for managing all materials and waste streams in all circumstances, but that some approaches are clearly preferable in general. The hierarchy places emphasis on reducing, reusing, and recycling as key to sustainable materials management. Most U.S. states follow EPA guidance and have developed plans and programs supporting this hierarchical approach to waste/materials management.

In the current EPA hierarchy, there is no differentiation of various processes for recycling/composting or for energy recovery. In other words, the hierarchy

[23] Eastman’s comments on U.S. EPA’s Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021, stated that it has two polyester renewal technologies – glycolysis ad methanolysis – which recycle a broad array of polyesters that are not currently recycled to a significant degree down into monomers, to be used in manufacturing new polyester materials of virgin quality. Eastman asserts that glycolysis, which has been at operating commercially at full scale since 2020, results in an estimated 20 to 30 percent reduction in greenhouse gas emissions based on lifecycle assessment vs. fossil-fuels based processes and expects a similar GHG reduction for their methanolysis facility, which will be commercially operational in 2023.

regards all forms of recycling and composting as equally preferable, and likewise, for all forms of energy recovery to be equally preferable. Some stakeholders, including environmental, and zero waste proponents, advocate for revision of the hierarchy to place greater emphasis on lifecycle assessment and resource conservation impacts of various waste management methods. Some of the proposed hierarchy revisions describe mechanical recycling as more preferable than chemical recycling (e.g., Zero Waste Europe). The U.S. EPA is considering options for revising the waste management hierarchy to include where the various chemical recycling technologies may fit, including which pathways should be considered recycling, and what should be measured as being recycled. It recently solicited input from stakeholders and received the following responses. Those in support of including chemical recycling to varying degrees include:

- American Chemistry Council (ACC) – "Advanced plastics processes that produce feedstocks for plastics, chemical products, waxes and lubricants should be counted as recycling…. [conversion to] fuels should be considered "advanced recovery."[24] [Making a distinction between waste-to-energy/consumption in a cement kiln vs. production of a fuel.]
- American Institute for Packaging and the Environment (AMERIPEN) – Believes all forms of chemical recycling should be a pathway for recycling. Further believes that 'including chemical recycling technologies within the realm of recycling rates …sends a strong message to early scale innovators and their investors who are seeking reduced risk to advance these technologies."[25]
- Consumer Brands Association (CBA) – Believes all pathways that reduce the demand for virgin material streams should be considered recycling. In order to meet demand for recycled plastics, "the U.S. needs to be open to advanced recycling methods that can provide the high quality and quantity of recycled material necessary."[26]
- Florida DEP (FL DEP) – "Pyrolysis, solvolysis, depolymerization and gasification processes are considered recycling in Florida, if the recycled materials are processed and then shipped as a feedstock. Often, it is difficult to quantify certain material management pathways; such as, pyrolysis, solvolysis, depolymerization and gasification. For recycling credit to be received in Florida, it must be quantifiable."[27]
- Indiana Department of Environmental Management (IDEM) – "Consideration should be given to include sorted plastics for chemical recycling applications (pyrolysis, solvolysis, depolymerization, and gasification) without limitations to specific end products such as purified polymers or fuels & chemicals."[28]
- Household & Commercial Products Association (HCPA) – Believes recycling should include all pathways in which waste can be "sustainably processed into new materials to be used in

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[24] ACC's comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[25] AMERIPEN comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[26] CBA's comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[27] FL DEP comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 1, 2021.

[28] IDEM comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

manufacturing new products."[29]

- NAPCOR – Believes that chemical recycling should be included in measuring recycling.[30]
- National Recycling Coalition (NRC) – Believes all processes that result in recycling as they define it should be considered recycling. "Recycling is a series of activities by which material that has reached the end of its current use is processed into material utilized in the production of new products."[31]
- National Waste and Recycling Association (NWRA) – Believes that chemical recycling processes should be considered recycling if used as a feedstock to make a new product.[32]
- The Recycling Partnership (TRP) – Has not specifically stated that they support chemical recycling or consider it to be recycling, but recommended EPA "focus on measuring material circularity and keeping molecules in motion."[33]
- Waste Management (WM) – Believes chemical recycling processes should be considered recycling if used to make new products, but not if used to make a fuel.[34]

Organizations against including chemical recycling in recycling data include:

- GAIA – "EPA lists various forms of incineration, including pyrolysis, solvolysis, depolymerization, gasification, and combustion with energy recovery; all of which not only fall short of tackling the waste crisis at the source but also have negative environmental, climate, and financial impacts. [35]Burning things is not recycling them at all, regardless of what technology is used and whether it generates energy or a byproduct. EPA must in no way count these methods toward national recycling goals…"
- U.S. Public Interest Research Group (U.S. PIRG) – Believes chemical recycling processes should not be counted as recycling.[36]
- State of Washington Department of Ecology (WA DEC) – Chemical recycling processes should count as diversion, not recycling.[37]
- Wisconsin Department of Natural Resources (WDNR) – Believes chemical recycling could

[29] HCPA comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[30] NAPCOR comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 4, 2021.

[31] NRC comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[32] NWRA comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[33] TRP comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 4, 2021.

[34] WM comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[35] GAIA comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[36] U.S. PIRG comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[37] WA DEC comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 1, 2021.

count as diversion but should not count as recycling.[38]

Sustainable materials management advocates believe that the waste management hierarchy should not be used rigidly as it does not take into consideration the variability of real-world circumstances and the need to account for impacts such as greenhouse gas production. The U.S. EPA also offers a simple-to-use tool called the Waste Reduction Model (WARM) to help solid waste planners and organizations calculate greenhouse gas (GHG) emissions reductions when considering various end-of-life waste management options. Inputs into WARM include the amount of waste handled by material type for PET, HDPE, PP, and mixed plastics, the associated waste management practice currently used (recycling, composting, combustion, anaerobic digestion, or landfilling) and the alternative practice, which could include source reduction. Like the waste management hierarchy, WARM lacks the ability to specifically include chemical recycling in end-of-life management. WARM is not a substitute for LCAs, and it was never intended by EPA that the waste management hierarchy or WARM be used by governments for packaging/product restrictions or ban decisions.

There are some recycling advocates who say that all materials must be mechanically recycled into equivalent products regardless of the cost, that there should be no local decision-making, and that materials whose only cost-effective option is chemical recycling or disposal should be phased out. LCAs have demonstrated that packaging with recycling challenges can be preferable to other packaging that has a moderately high recycling rate but otherwise has greater global warming impacts.[39] General hierarchies and governmental policies should recognize that chemical recycling technologies are complementary to mechanical recycling and chemical recycling can have a beneficial role in achieving greater circularity.

Most stakeholders regard mechanical recycling to be the preferred approach to recycling, all else being equal. However, some plastic packaging and other items, for many reasons (contamination, multi-material, and others), cannot currently be mechanically recycled effectively or cost-effectively. Furthermore, mechanically recycled plastics' quality deteriorates over time and at some point, must either be downcycled into less demanding applications or upgraded through chemical recycling to restore them to virgin-equivalent properties. These are the materials that most in the industry deem to be most suitable for chemical recycling.

Figure 5 illustrates how mechanical and chemical recycling can be complementary and together contribute to circularity for plastics while minimizing environmental footprints, considering costs to society, and respecting the quality of packaging materials needed to minimize packaged material waste and otherwise meet performance requirements. The example presented in this case is for PET, but conceptually it can apply to any plastic packaging material.

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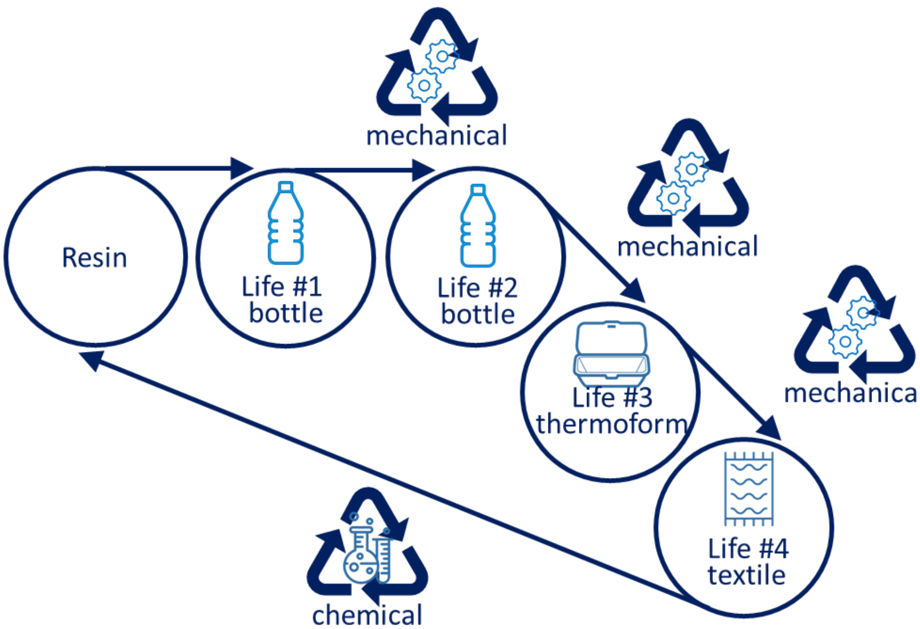
[38] WDNR comments on U.S. EPA's Recycling Rate Measurement Methodology, Docket ID: EPA-HQ-OLEM-2020-0443, March 8, 2021.

[39] Trucost PLC, "Plastics and Sustainability: A Valuation of Environmental Benefits, Costs and Opportunities for Continuous Improvement," July 2016, and the Flexible Packaging Association, "Sustain the World: The Case for Flexible Packaging," 2018.

Figure 5: Example of Complementary Relationship of Mechanical and Chemical Recycling



Recognizing that local governments and waste generators still need to choose between sending specific discard streams to either chemical recycling or mechanical recycling options, we crafted the questions in the text box to the right to assist in that local decision-making process. As the questions indicate, it is possible that a chemical recycling option, if located nearby so that transportation costs and environmental impacts are minimized, could be the better recycling option for some materials. Chemical recycling should also be preferred over disposal. Such an analysis would likely always indicate a preference for HDPE and PET rigid packaging to be sent to mechanical recycling, with perhaps the exception of some harder to recycle materials such as PET thermoforms.

Questions to Guide Chemical vs. Mechanical Recycling Decisions

- Is it more costly to recycle the plastic type mechanically than chemically (including collection, sorting, and transportation costs and material value received)?
- Will the end use result in a "downcycled" product that is also recyclable, or will the end use be the final use of this resource?
- If not recycled chemically or mechanically, will the material be disposed?

7. What Else is Needed Going Forward?

Acceptance of the family of chemical recycling approaches and plant-specific technologies is under debate. We hope this White Paper clearly describes the role these approaches and technologies can play in reducing the impact of plastic packing on the environment and lead to a more circular use of plastics. To ensure that chemical recycling in general is accepted as a complementary part of plastic materials management in the future, certain actions are needed, and interested stakeholders can engage in the debate and advocate for these actions as they see fit. These actions include:

- Design packaging and products for mechanical recycling, including eliminating toxins, so that reliance on chemical recycling is minimized.

- Identification of plastic material streams generally suited to chemical recycling.
- Development and sustainable funding of a cost-effective and robust collection, consolidation, sorting, and transportation system to collect and supply materials from residential, commercial, and industrial generators to both mechanical and chemical recyclers.
  - Dale Gubbels, CEO of Firstar Fiber, who was interviewed for this White Paper when asked what will be essential in building a chemical recycling infrastructure said: "MRFs are the first line of defense in converting recovered materials into valuable feedstock for further use. Brands that ultimately want to use recycled content in their packaging and/or products, therefore, should support investment in MRFs so that they can take the material they receive to the next level, from a value standpoint, and create marketable commodities of value to the brands and their customers."
- Collaboration among generators, recycling/waste management program managers, haulers and MRFs to recover materials for both mechanical and chemical recycling.
- Ongoing commitments and agreements to purchase recycled material by brand owners and to use recycled content, with legislation from policy makers where there is a need to level the playing field and ensure all packaging suppliers are held to the same standards.
- Acceptance of mass balance accounting for meeting recycled content goals (see the text box below).
- Acceptance of recycled content credits where recycled content is legislated.
- Continued innovation to improve yield, cost effectiveness, and reduce environmental impacts of chemical recycling.
- Policies that support the growth of chemical recycling technologies (definitions of recycling, recycled content, regulatory status, etc.) while still protecting the environment.

Acceptance of Mass Balance Accounting for Meeting Recycled Content Goals

CPG companies have committed to use increasing amounts of recycled content in their packaging. North American companies that make plastics want to meet this demand with chemically recycled plastics. These large chemical plants typically have not been designed to keep inputs from different suppliers segregated. Raw materials from chemical recycling are normally combined with virgin raw materials in these plants, and as a result the recycled material is distributed into all of the products produced.

The "recycled" attribute is valued by CPGs and they may be willing to pay more for it than virgin commodity resin. If resin producers are able to account for and credit the recycled content to specific CPG buyers (even though in actuality it is distributed in all products and buyers) then CPGs can pay more for material and financially support chemical recycling. This concept of crediting to specific buyers is called mass balance accounting.

Mass balance accounting is used in a variety of industries, including renewable energy and the trading of carbon credits. Without acceptance of mass balance accounting for recycled content and third-party auditing and certifications, the recycled attribute will not be able to economically support chemical recycling of plastics. It should be noted that the Ellen MacArthur Foundation is supportive of mass balance accounting and has stated that "a mass balance approach to enable the sale of certified recycled products at virgin-grade quality could be very valuable to all users of materials and chemicals in the value chain." [40]

[40] Members of the Ellen MacArthur Foundation Network, "Mass Balance White Paper," 2020.