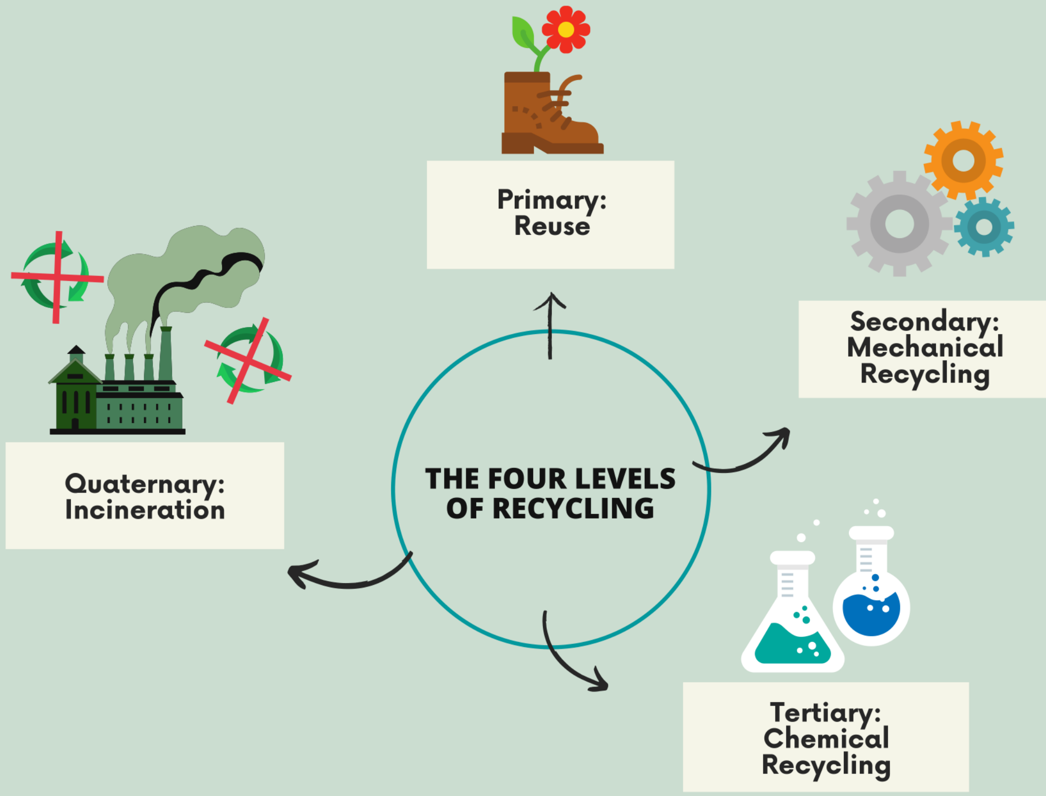
Plastic Recycling - Challenges and Opportunities

A Deep Dive into the Limitations of Chemical Recycling



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The Basics

Effective recycling is the solution to the avalanche of waste plastic humanity generates. The EPA's most recent report on plastic in the US municipal waste stream documented 78 billion lb of plastic in 2017 [i]. Since then, an additional 30 billion lb of plastic production has been added. The alternatives to recycling waste are landfilling, incineration or releasing it into the environment. Minimizing waste is the best tactic, but with the world's population approaching 8 billion people, there will inevitably be waste. Regressing to 1940's packaging and products that rely on glass, metal and paper would skyrocket energy requirements, carbon dioxide production and food waste. No one wants to return to the days of glass syringes, wax paper wrapped meat and heavy steel & wood cars. Plastic is here to stay, and with good reason. The challenge is dealing with the generated waste and putting it back into use through recycling.

Mechanical recycling is the use of mechanical processes that sort, clean, grind and melt plastic for reuse. It does not involve changes to the chemical structure of the plastic itself. Mechanical recycling is the most efficient way to recycle plastic and minimize energy costs and carbon dioxide production. Chemical recycling is being championed by many, but it has serious drawbacks especially regarding curbside PCR processing. This report will compare the two recycling processes and discuss alternatives, citing information from multiple studies.

The following terms are not widely used in the plastics recycling industry but do come up in academic and economic papers. In the interest of a uniform understanding, we define them below.

Primary Recycling has various definitions. The common thread between these definitions is that the recycled material has equivalent properties to the source material. In practice, this means reuse.

Secondary Recycling is mechanical recycling. Post-Consumer Recycled (PCR) and Post-Industrial Recycled (PIR) material can be mechanically recycled. Secondary PCR recycling is what the average consumer considers to be recycling.

Tertiary Recycling or chemical recycling has many names. The term "chemical" has negative connotations, so the plastics industry started using different euphemisms to reference the same process. Articles or podcasts discussing Advanced, Molecular, Tertiary, Feedstock, Depolymerization, Non-Mechanical or Co-Processing Recycling are actually discussing Chemical Recycling. Chemical recycling can process PIR and PCR if it is cleaned and processed adequately.

Quaternary Recycling is incineration or "Waste to Energy" which should not be considered recycling. Unfortunately, some groups refer to incineration as a form of recycling.

Recyclable?

There is debate as to which plastics are recyclable. There is a difference between "recyclable" and "being recycled". By definition, "recyclable" refers to materials or products that are able to be recycled. Based on that definition, almost all plastic is recyclable. The exception is thermosets that can't be remelted like melamine and vulcanized rubber. The key is to isolate the individual types of plastic and clean it so that it may be melted down and reformed into something new. The fact that PET bottles, HDPE containers and PP batteries are the only plastic products being recycled at a rate greater than 15% does not mean that other plastic products cannot be recycled. It means that the value placed on recycled resin is not high enough to cover the costs of the recycler on a consistent basis. Society must place a value on reusing resources and landfill avoidance over cheaper replacements. The alternative is wasted resources until oil and natural gas eventually dwindle in supply and force higher prices for virgin resin. The benefits of lower carbon output and reduced use of oil and natural gas cannot be overstated.

Steps for Chemical and Mechanical Recycling

- **Collected bales of plastic are delivered to the reclaimer**
- **Bales are broken and, often, sorted again**
- **Material is shredded into 50 to 75 mm pieces**
- **Residual metal is removed**
- **Residual paper is removed**
- **Material is ground into 10 mm flakes / regrind**
- **Flake / regrind is washed**
- **Flake / regrind separated via float / sink tank into polymer groupings**
- **Flake / regrind is dried**
- **Flake / regrind is packaged into gaylord boxes, super sacks, or into a silo**

Mechanical Recycling

Mechanical recycling is the use of equipment and processes to physically sort, clean, breakdown and reform plastic. Mechanical recycling of metals has been done for hundreds of years and is better understood by the casual observer. Most people can visualize taking aluminum cans that are cleaned, melted and made into ingots for future processing into new cans. The difference between metal and plastic is the complexity of the material itself. Many social media accounts would have you believe there are only seven types of plastic, because there are only seven chasing arrow symbols with resin identification codes. In fact, there are dozens of types of plastic in routine use every day.

The mechanical process begins with collection of scrap. Once collected, it must be sorted to remove non-plastic and isolate each type of plastic. Each commodity grade that is being targeted will be baled by a Material Recovery Facility (MRF) for delivery to a processing facility. General collection and sorting levels today deliver 70% of the target material and 30% of undesirables. There are a few sortation facilities that have invested in the newest equipment and are able to deliver 85-90% bales. Even if the bale is all one kind of plastic it still has the variations of that type throughout.

Physical properties like viscosity, impact and stiffness can be varied within each type of plastic. Additives and fillers that impart different characteristics such as flame retardance or static properties can be added. Taking all the variations into account for each commodity, there are hundreds of different types of plastic. Add in color as a differentiator, and there are thousands.

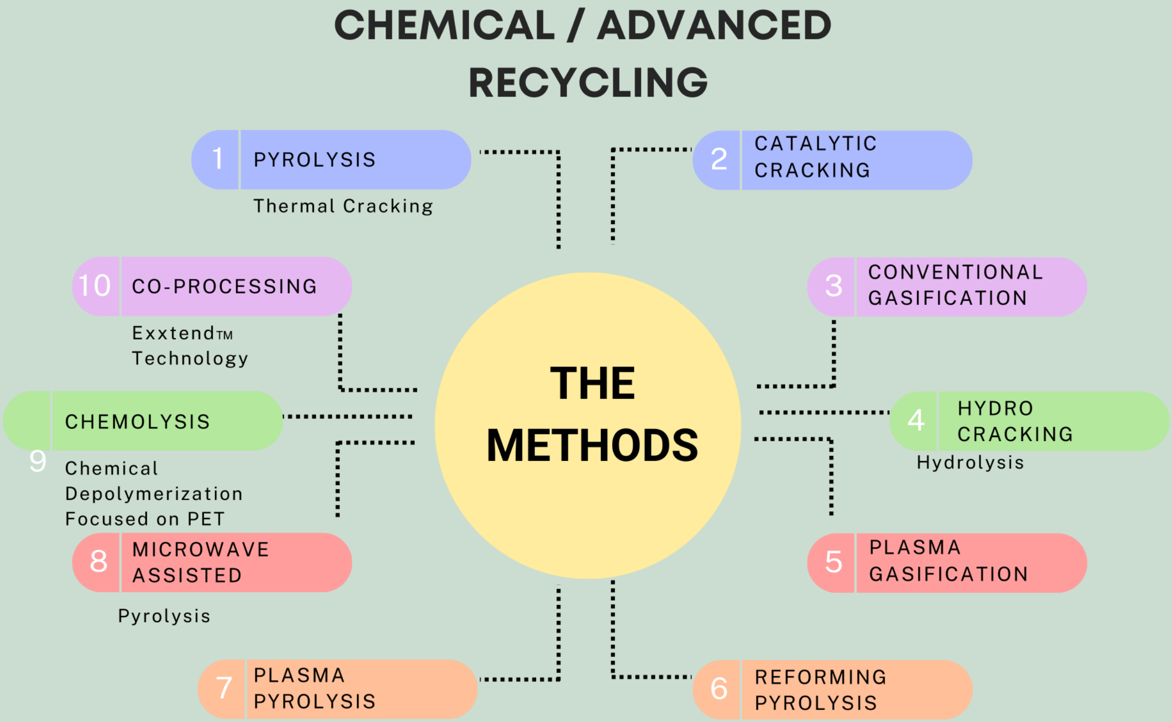
Plastic gets many of its properties depending on the molecular structure. For example, a short molecular chain of propylene and an extremely long chain of propylene are both called polypropylene (PP), but they have radically different properties. Remelting polypropylene shortens the molecules. Making smaller and smaller molecules by reheating the plastic is a process referred to as thermal degradation. Because of the degradation, the physical properties of the plastic will deteriorate after several passes depending on stabilizer levels. Polypropylene specifically can be remelted 4-7 times before it becomes unusable. All polypropylene has stabilizers added to maintain desired properties. The lowest useful amount of stabilizers are added to minimize the cost. Increasing stabilizer levels in the virgin resin would have a beneficial effect on the number of times you could recycle PP.

Introducing stabilizers during the reprocessing step would help for the next time it is melted, but doesn’t correct the degradation that has already occurred. Even with a best case, 50% recycling rate, it will be decades before recycled plastic degradation becomes a problem. Recycling should not be hindered by those worried about how many times it can be recycled. With virgin material continually added to the mix, degradation poses little risk. A process improvement would be to direct recycled materials towards durable goods such as cars and appliances.

A separate technology used to clean plastic is Solvent Based or Dissolution. Crippa [ii], Hann & Connock [iii] and Patel [iv] are incorrect in stating that solvent-based recycling should be included under chemical recycling. This report agrees with Cefic [v], Solis & Silveira [vi] and others that since the chemical structure of the polymers remains unchanged in the solvent dissolution, the process should be considered its own form of technology classification. Solvents utilized for recycling can use either PIR or PCR raw material. The process itself fits into mechanical recycling with an extra solvent purification step and not chemical recycling.

Chemical Recycling

Chemical recycling refers to many different processes. The underlying objective of all the processes is to clean out contaminants and break plastic down into its molecular building blocks converting waste material into something useful. The ideal is to make waste plastic back into first quality plastic, but objectives and reality are difficult to align. There are primarily eight different types of chemical recycling identified by Solis & Silveira [vi], but the most prevalent and semi-commercial is pyrolysis. Add chemolysis and ExxonMobil's new co-processing technology to the list of processes and it grows to ten.

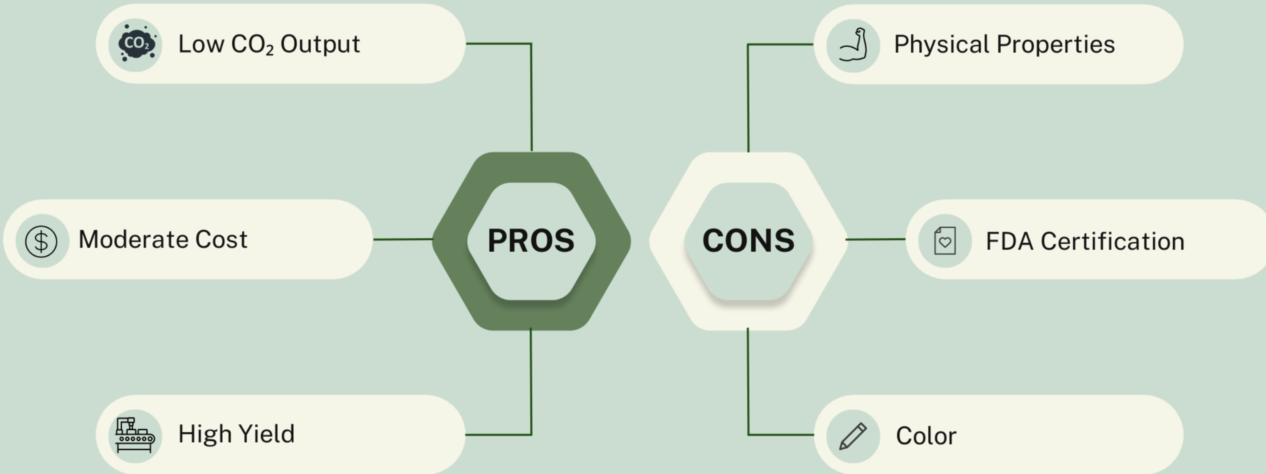


The goal for all the chemical processes is to break plastic waste down to its basic building blocks or monomers to be used again to make "good as new" resin. This will limit the demand for virgin resin and eliminate the need to landfill or incinerate it. A benefit is that if the processed plastic makes it all the way back into plastic again, it can be used in FDA food contact applications. Chemically recycled resin is truly virgin resin once again if it is taken to completion. The yield loss, energy consumption and CO_2 generation required will be explored.

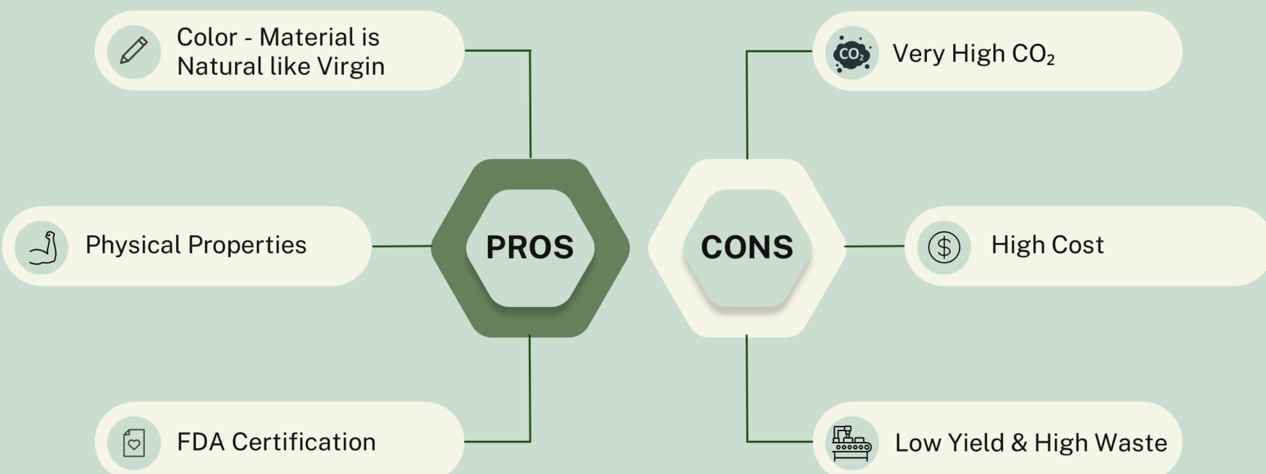
The enthusiastically used but rarely defined comment about chemical recycling is that it can handle "difficult to process plastic". It is inferred, if not stated, that chemical recycling can reprocess material that mechanical processing cannot. The ideal that one envisions for chemical recycling is to drop mixed bales of waste plastic into the front of the process to produce ready to use monomer out the back for new plastic production. At the very least, it would produce oil that can be sent directly to one of the existing oil refineries. This is not how it works in practice.

Pyrolysis or thermal cracking is the oldest and most common form of chemical recycling. Operating temperatures between 300° and 700° C are required depending on the specific technology used although, typical temperatures in a commercial operation are 400° - 500° C. The energy required to process material makes this an expensive alternative

Mechanical



Chemical



Mechanical recycling is the most efficient way to reprocess plastic. From a resource and cost perspective it will always be better than chemical recycling. There are some road blocks that chemical recycling is better situated to address. When plastics are mechanically recycled the colors blend like pigments. Without color sortation, the output is a gray to black color. Similarly, high levels of sortation are required to isolate physical properties within resin types. The most common way to achieve this is through reverse logistics. Curbside PCR will have physical property limitations when mechanically recycled because of cross contaminants.

To get FDA certification, a process with extreme levels of sortation that can consistently remove impurities and contaminants back to virgin quality must be in place. This can be achieved in mechanical processes but is inherently part of the chemical recycling process.

Technical Hurdles of Chemical Recycling - Pyrolysis

Polyvinyl Chloride is a non-starter

All PVC needs to be removed from the plastic waste stream before being processed. During pyrolysis the chlorine leaves the PVC and forms Hydrochloric Acid. There is a large amount of carbon steel throughout the process that hydrochloric acid immediately corrodes.

Polyethylene Terephthalate must be removed

The word pyrolysis comes from two root words meaning "fire" and "dissolution". Pyrolysis must be done in a no oxygen environment otherwise the material will combust instead of dissolve. Therefore, the material that is being dissolved cannot have oxygen either. The chemical formula for PET is $(C_{10}H_8O_4)_n$ where the O is oxygen. This is fine for bottles because PET bottles are easily identified, sorted and mechanically recycled already. PET thermoforms are another matter. These clamshell containers used by bakeries, restaurants and grocery stores are largely not sorted.

Polystyrene can be handled in small doses

PS is comprised of a benzene ring with other carbon and hydrogen atoms. The additional double bonds in the benzene ring present different challenges. There are some processes designed specifically for just PS but isolating enough PCR of strictly PS is challenging. The default source for PS processes is typically PIR.

ABS, Acetal, Acrylic, Nylon, Polycarbonate, PBT, PEEK, etc.

These have oxygen, benzene or nitrogen which are all problematic. Nitrogen poisons the catalysts for downstream FCC processes that refine the oil. ABS and Nylon both have nitrogen, PC has oxygen so the top three most common of "other" are all undesirable. Very little of these materials get collected other than by reverse logistics collection systems focused on electronic recycling, so they typically don't pose much of a problem in curbside streams.

PLA deserves its own mention

PLA is bad for chemical recycling because it has oxygen and bad for mechanical recycling because it must be reprocessed 100% on its own. It is not great for composting because it has to reach 136ºF to decompose which doesn't happen unless it is in an industrial composting facility. Search out PHA, polyhydroxyalkanoates, if you want biodegradability and are not focused on recycling.

Organic contaminants need to be removed

Char is the number one reason that pyrolysis units do not run continuously. The frequency of shutdowns depends on the levels of contamination. Organics, like sugar and food, turn directly into carbonized char and shut the line down. A pre-wash system is required just like it is required for mechanical recycling. Very few chemical recyclers have their own wash systems. The majority rely on off-site processors to preclean any curbside material they receive. The favored way around this hurdle is to use PIR which does not require washing.

Moisture cannot be above 5-7%

The higher the moisture content of the material the more energy is required to process it into pyoil. The more energy required, the more it costs and the higher the CO_2 output. Therefore, curbside material must go through a drying system just like mechanical recycling of PCR.

HDPE & LDPE

HDPE is already being sorted and baled by MRFs to be mechanically recycled. HDPE bales are far too expensive for chemical recyclers. LDPE film is not accepted at MRFs but is a feed stream of which chemical recyclers can make better use. However, a separate collection system is required.

The least sorted and collected of the large volume commodity resins

The problem for chemical recyclers becomes value. If you sort the rigid plastic waste all the way down to polypropylene, it can just as easily be converted by mechanical reprocessors at a fraction of the cost and carbon dioxide footprint as chemical recycling. The physical properties of mechanical PCR PP reprocessed material are poor compared to virgin resin, but additives or more robust sorting can address that problem. Another problem that applies to both chemical and solvent recyclers is that a large portion of collected PP comes from restaurant takeout containers. For cost and heat stability reasons most PP takeout containers have 20-40% talc or calcium carbonate fillers.

Filler & Color

During chemical recycling, fillers become char in the system and accelerate shutdowns. Solvent recycling removes fillers from the plastic as a waste component. The most common fillers are talc, calcium carbonate and glass. Colors are also contaminants that become char for chemical processes and waste for solvent processes. Mechanical recycling reprocesses the plastic with fillers and color kept in place.

Recycling Yield

Chemical recycling of curbside PCR requires the same type of preprocessing as mechanical recycling. Sorting out PVC and non-bottle PET and minimizing PS in the raw material stream is a baseline requirement for both. HDPE and PET bottles already get sorted because of the value proposition for MRFs. LDPE (and LLDPE) either gets scooped up in the HDPE sort mainly as lids or is collected in a completely different way because it is in the form of film. The "Other" resins are not generally collected through curbside. Where these materials can be collected is through separate electronic collection efforts. Unfortunately, the bulk of electronic scrap tends to be processed solely for metals and the plastic is ignored. PLA is its own "Other" that is a detriment to all forms of recycling. After all the sorting is done, what resin is left of PCR curbside collections? Polypropylene. If the only material left is polypropylene with some LDPE and HDPE contamination it can be mechanically recycled.

Just like mechanical recycling, chemical recycling requires washed and dried curbside PCR material. Without washing, char and additional energy consumption are detriments to chemical recycling where clogged screens and poor physical properties of the end-product inhibit mechanical recycling. According to the Eunomia [vii] report, (commissioned by the AEPW) for pyrolisis to work, the feedstock must contain a minimum of 85% PE / PP and a maximum of 1% PVC. The headwinds against curbside PCR for chemical recycling leave few raw materials left to use other than PP for pyoil production. Directly comparing the yield of chemically versus mechanically recycled PP all the way to polypropylene pellets is instructive.

The first step of any curbside recycling process is for the MRF to collect, sort and bale the specified material. Focusing on polypropylene, the mechanical, solvent and chemical recycling processes start with 1,000 lb bales. The current best practices of MRFs collecting PP bales is to achieve a 70% yield of PP per bale or 700 lb. The mechanical recycler may or may not further sort the PP by color or properties, and it may or may not incorporate additives and fillers and pelletize the PP. The 700 lb of reprocessed polypropylene pellets can be sold to a converter or a compounder.

The solvent reprocessor takes the 700 lb yield and puts it through the solvent cleaning process. If the curbside bale has parts with filler in them then a reasonable yield for the solvent process would be 80%. Removing color, additives, talc, calcium carbonate, and the unremoved polyethylene fraction as a waste stream leaves 560 lb of polypropylene pellets.

The chemical recycler has many additional steps that not only require energy but further reduces the yield of all usable products, especially polypropylene. Starting with the same 700 lb as the mechanical and solvent recyclers, the scrap material is then processed into pyoil with a typical 70% yield of oil taking the total amount of material to 490 lb of pyoil. The pyoil needs to be hydrotreated to remove excess O_2. Otherwise, it is unusable by the oil refinery. Hydrotreatment has an average yield of 89% [viii] taking the total yield to 436 lb of oil. At this point in the process, you can call it a day and sell the oil into low end fuel applications. This is where all existing pyrolysis plants stop and mass balance calculations begin. If you want to go full circle to polypropylene there are a few steps to go. The oil needs to go through an oil refinery that will be utilizing a Fluid Cracking Catalytic (FCC) Unit [ix] and yield about 38% propylene. That is 166 lb of chemical grade propylene (CGP = 95% propylene and 5% propane and other light ends). To make polypropylene the propylene must be polymer grade (PGP) or 99.5% propylene. The CGP is put through a splitter with a yield of 95% producing 157.7 lb of PGP. The PGP is then delivered to a polypropylene plant with a 99.5% yield of PP or 156.9 lb of prime polypropylene for sale.

SOLVENT RECYCLING

1. PP Sorted, Collected and Baled — 1,000 LB
2. Reprocessor Sorts and Cleans PP — 700 LB
3. Solvent Used to Remove Impurities — 560 LB

Final Results

560 lb of PP

MECHANICAL RECYCLING

1. PP Sorted, Collected and Baled
2. Reprocessor Sorts and Cleans PP — 700 LB

Final Results

700 lb of PP

CHEMICAL RECYCLING

1. PP Sorted, Collected and Baled — 1,000 LB
2. Reprocessor Sorts and Cleans PP — 700 LB
3. Pyrolysis of PP – Pyoil Produced — 490 LB
4. Hydrotreatment of Pyoil to Remove O2 — 436 LB
5. Treated Oil Cracked to Propylene — 166 LB
6. CGP Converted to PGP — 158 LB
7. PGP converted to polypropylene — 157 LB

Final Results

- 157 lb of PP
- 8.3 lb of Propane & other Hydrocarbons
- 270 lb of Fuel & Other Byproducts

RECYCLING PP YIELD

Mechanical	70%
Solvent	56%
Chemical	16%

MASS BALANCE

Corporations like the idea of chemical recycling because it can be incorporated into some of their existing infrastructure. They also buy into the theory that there is a readily available raw material source that they can process in large volumes. A quick review of the hurdles chart shows that curbside post-consumer plastic waste is not a good source for chemical recyclers. It is virtually impossible to trace from beginning to end chemically recycled plastic. Chemical companies are responding by employing a mass balance approach [x]. The basic idea is that recycled raw materials can be intermingled with virgin material during processing and specific portions of the output can be identified as having recycled content. It is a bookkeeping exercise. International Sustainability & Carbon Certification (ISCC) [xi] along with the American Chemistry Council (ACC) and all its industrial members and the Ellen MacArthur Foundation [xii] are championing the idea of mass balance. If mass balance is not accepted, then chemical recycling is all but impossible to accomplish. The use of mass balance requires a third party to confirm the validity of the claims.

The use of mass balance to define which end products have recycled content and which ones do not are a form of bookkeeping referred to as “free attribution” by ISCC. In their example, there is an even distribution of recycled content in all products but only one is certified as having recycled material. This approach is further endorsed by the Ellen Macarthur Foundation. In practice, there will rarely be pyrolysis oil made into plastic. Fuel products are more practical.

CO_2 Generation

Greenhouse gas (GHG) is the most important measure of how "green" a product is, but it is infinitely more difficult to monetize than plastic that is bought and sold. Carbon dioxide (CO_2) is formed during every step of production, but when heat and pressure are required, the amount produced increases markedly. The size of each processing bubble depicted in the chart below represents its contribution of CO_2 into the atmosphere for each kilogram of plastic produced. The individual concentric circles represent the different steps required to accomplish each process but are not representative of the CO_2 load that each step contributes. It is difficult to isolate every single step, but several Life Cycle Analysis (LCA) studies have been conducted with the output being published in whole. Common sense instructs that when more steps are required, more carbon dioxide is produced. Also, the more energy required in the step the higher the CO_2 output. All three of the represented processes share transportation as a contributor even though they differ in form. Pyrolysis shares all the steps of mechanical and virgin production minus the drilling required for virgin resin. Pyrolysis has a multiplier effect due to heating up the plastic to convert it to pyoil and cleaning the pyoil. These comparisons are going from original raw material to final pellet ready for conversion.

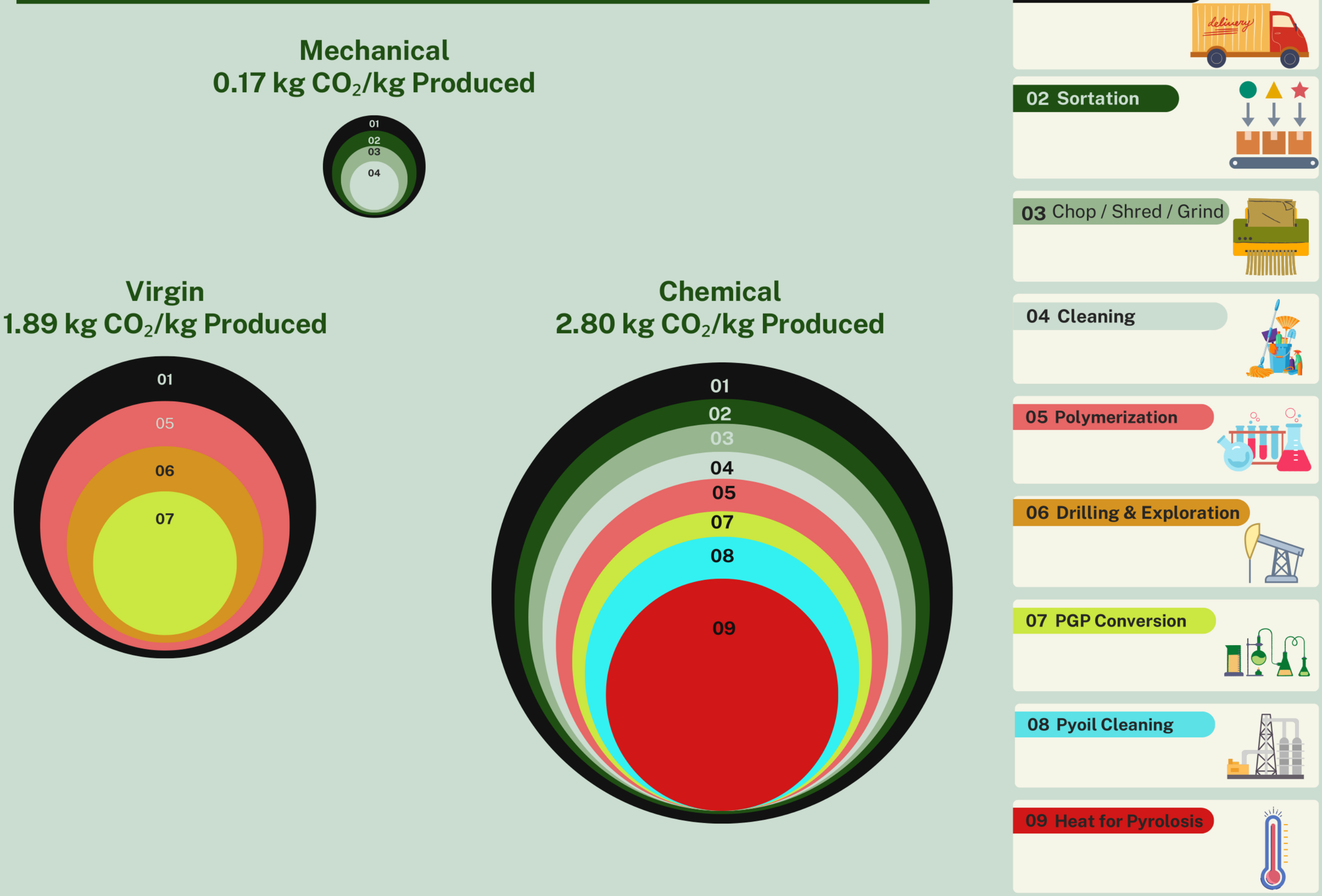
Some studies comparing pyrolysis to mechanical recycling divide the amount of carbon dioxide produced by the amount of waste put into the process to arrive at kg CO_2 produced per kg of waste processed. A much better measurement would be kg CO_2 produced per kg of plastic produced. Mechanical recycling has a 70% yield where pyrolysis has a 16% yield when looking specifically at finished polypropylene pellets. As an example, if a 1,000 lb bale of PP waste is introduced to each process and you follow it all the way to finished pellets, mechanical recycling delivers 700 lb of PP and chemical recycling delivers 157 lb of PP. Fuel and other by-products are produced by pyrolysis but plastic pellets are the end goal. It takes a substantial amount of energy to bring the process to completion.

Another way that CO_2 production can be made to look similar between mechanical and chemical recycling is to assume that all waste residuals from the mechanical process are incinerated. Obviously, incineration will vastly increase the amount of carbon dioxide produced for the mechanical process if that is the preferred way to dispose of the waste. Europe may have systems that work in this manner, but in the United States, the preferred method is landfilling. Landfilling residual waste is how we will measure the CO_2 produced by mechanical recycling.

Using assumptions of landfilling mechanical waste and making the finished output as the denominator vastly changes the carbon dioxide comparison for mechanical and chemical recycling. It is always a good idea to step back and give your answer the common sense test. Look at the number of steps with required pressure and heat. These require the consumption of large amounts of energy and appear in chemical not in mechanical recycling. There is no way that pyrolysis's CO_2 output can be anywhere near the low CO_2 output for mechanical recycling. The only heat component for mechanical polypropylene recycling requires a temperature of 200 °C to make pellets. Pelletization is required at the end of the chemical process as well.

The charts below illustrate the major steps for their respective processes. The greenhouse gas effect is represented by kg of CO_2 produced per kg of finished product made. For the analysis of mechanical recycling [xiii] CO_2 production, for every 500 kg of material fed into the system 330 kg of finished product is created. This is a fairly conservative estimate as additional sortation and cleaning could lower the waste residuals leaving the system. The remaining 170 kg are landfilled. This yields .17 kg CO_2 / kg of production. Virgin plastic production varies from 1.89 [xiii] to 2.6 [xiv] kg CO_2 / kg of production. The largest contributor of CO_2 per kg of plastic is pyrolysis. For a best case scenario, the theoretical numbers from BASF were used to show for every 500 kg fed into the system, 270 kg of LDPE can be produced. This far exceeds the yield achieved from PP in a pyrolysis system. With this assumption pyrolysis achieves a value of 2.80 kg CO_2 / kg of production. Using the best-case scenario for chemical recycling shows it has a 16.5 times higher output of carbon dioxide than mechanical recycling.

CO_2 Generation from Plastic Production



All chemical recyclers start their presentations or reports with statements that mechanical recycling “wins” over chemical recycling in one way or another. The most frequently used term is “complements” as used by the American Chemistry Council when they state that chemical recycling “complement(s) mechanical recycling methods currently in use” [xv]. Dow Chemical [xvi], Shell Chemical [xvii], Eastman Chemical [xviii] and Borealis [xix] all have made similar comments. These statements beg the question as to why there is not more investment in mechanical recycling by the big producers. Mechanical recycling is done in 10 and 20 million lb increments where chemical recycling will theoretically produce 100 million lb per line at a minimum. Big corporations install new lines that produce 1 billion lb per year of virgin plastic, so they have a hard time thinking in terms of the relatively small output from a mechanical recycling extruder.

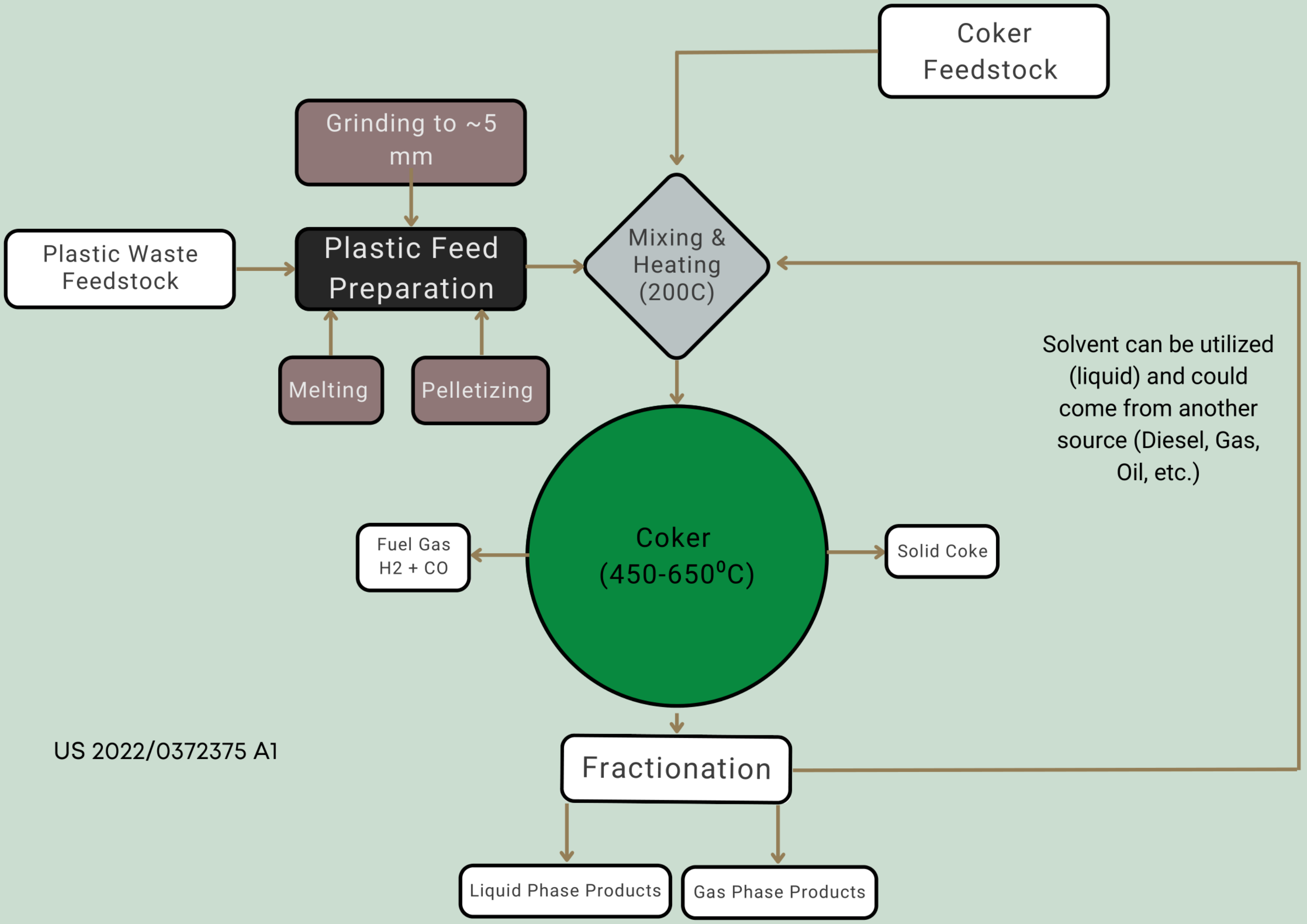
Braskem partnered with Valoren and inaugurated its first mechanical recycling facility in São Paulo, Brazil in 2022 [xx]. This facility only has a 30 million lb capacity, but is currently operational which is more than most of the other producers can say. LyondellBassell signed a memorandum of understanding (MOU) to form a JV with Genox Recycling [xxi] in Guangdong Province, China to start a mechanical recycling facility in 2023. As of today, there are no announcements by plastic corporations for mechanical recycling facilities located in the US.

There are several announcements for chemical recycling to commence but little output. LBI announced a decision to make a decision (another MOU) at the end of 2023 to potentially JV with Source One Plastics. The JV would build a “commercial scale advanced recycling plant” [xxii] that would source multilayered food packaging in Germany. There are multiple failed attempts at chemical recycling as documented in the Reuters article “The Recycling Myth” [xxiii]. Among the false starts are Renewlogy, Enerkem, CreaSolv and a joint effort between Agilyx and Delta.

ExxonMobil has a functioning chemical recycling process that is trade marked as Exxtend™ technology [xxiv]. The patent behind the technology is titled “Co-Processing of Waste Plastic in Cokers” [xxv]. ExxonMobil’s pilot facility processed 2 million lb of waste plastic by Oct. 11, 2021 [xxvi]. As of June 2022, the facility had processed 11 million lbs of waste plastic at the Baytown, TX site [xxvii]. In an article published by Baytown West Chamber County [xxviii], on September 30, 2022, Exxon’s vice president of new market development, Dave Andrew, is quoted as saying, “Literally we get bales of plastic waste with a bicycle or lead-acid battery stuck in the middle of it. So, we’ve got to work through all of those issues, which means consumer education and sorting. It's creating a whole new value chain.” ExxonMobil started a slightly larger scale facility with 80 million lb per year capacity as of December 14, 2022 [xxix].

ExxonMobil's chemical recycling process relies on feeding a clean and size reduced stream of waste plastic into their existing coker process. They have two advantages with this approach. First, they are adding onto existing facilities, so the capital expenditures are minimal compared to green-field pyrolysis plants. Second, according to their patent, they can feed in 1% to 30% plastic waste. This range of feed gives them the theoretical ability to change on the fly as the feed stream changes. The particle size for Exxon's process at a median size of 5mm is about half the size that other mechanical and chemical processors will accept. This could be a burden to supply, so they have proposed pellets for the system as well. Discussions with ExxonMobil personnel indicate that their expectations are to initially keep the plastic waste stream at 1-2% of the coker's total feed. The mantra of mechanical recyclers has always been, "the solution is dilution". When mechanical recyclers encounter high contamination levels or poor properties persist, the recycled material content will go from 50% to 20% to 10% to 5% until the problem is diluted away. The blend component is virgin resin of known properties. Typical pyrolysis does not allow for this type of solution, but Exxon's version of pyrolysis through co-processing in a coker does. Compounders can feed in 1% dirt from their parking lot and still make acceptable products, so 1-2% waste plastic should all but disappear in the coking process. Documenting the output of this process and whether it produces additional monomers over the normal coking process will be important. From a CO_2 production and energy requirements perspective, co-processing is in the same basket as pyrolysis.

Co-processing Plastic Waste Feedstock During Coking



Chemical recycling is not the optimum answer given its inefficiency, cost and carbon footprint. Curbside collections are a poor source of raw materials for any chemical recycler. Chemical recycling does have a viable alternative to curbside PCR. Alternatively sourced PCR film, especially metallized film used in sachets, chip bags and other food packaging is a great area for chemical recyclers to tackle. This multilayer PP/PE material is not being recycled today. This type of material is commonly refered to as "film & flex". Washing and drying would still be required, but mechanical recyclers do not want multilayer film constructs that have been metallized. Running metallized film through an extruder cuts throughput by as much as 50%. The metal content will increase char in a chemical process, but it would be predictable. Exxon's process already removes solids in the form of coke, so it has an advantage using metalized film over traditional pyrolysis practitioners. Because the coker runs at 450-650 °C which is even hotter than most pyrolysis units, this is certainly not the low CO_2 option.

Final Thoughts

Mechanical recycling is a time-tested method to recycle plastic. It involves facilities that are typically installed in 10 to 20 million lb increments and require multiple pieces of equipment. It requires less energy, produces much less carbon dioxide and is cheaper than chemical recycling. The better and more robust sortation at the beginning of the process, the better quality of the end product. It isn't flashy and does not require any scientific advancement to make it work. If the traditional single stream collection process in the US were modified to a plastic and everything-else stream, the quality of the recycled plastic material would increase by leaps and bounds. To paraphrase Mr. Andrew at Exxon, the collected waste stream needs to improve. All forms of recycling benefit from greater sortation. If every PP bale yielded 90% instead of 70% PP from the MRF, all players would benefit.

Chemical recycling has so many limitations regarding curbside PCR that most projects are now focused on collected film streams outside of the curbside system or PIR. The high carbon dioxide output along with the relatively low amount of plastic produced leaves a large carbon footprint. If chemical recycling could take "hard to recycle" plastics that didn't involve a > 85% PE/PP content as advertised, it could be a winner. Perhaps new technology with new catalysts and systems will clear this hurdle in the future. There are no discernable prospects for this today.

The advantage of producing natural virgin resin from chemically recycled plastic must be weighed against the drawbacks. All recycled resin producers need commitments / contracts from buyers, converters and brand owners to maintain a minimum sales price to develop a strong business. To quote a recycling insider, "sales contracts have to be written with a hard floor and a soft ceiling to make this work." The cycle of boom-and-bust when recycled resin is dropped for wide-spec resin during times of depressed prices is not sustainable for recyclers. It also makes hitting those big brand 2025 and 2030 sustainability goals impossible. Recycled resins won't magically spring out of the ground in 2025 if commitments aren't made today to build a healthy recycling industry. Betting on chemical recycling without investing heavily in mechanical recycling is a poor decision that will have repercussions for years to come. Investment in mechanical recycling facilities is the fastest and most effective way to increase recycling rates with the least amount of damage to the environment.

[i] United States Environmental Protection Agency. *Advancing Sustainable Materials Management: 2016 and 2017 Tables and Figures*, EPA.

[ii] "Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C. & Wagner, M. *A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions*, 2019 (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium."

[iii] Hann, Simon, and Toby Connock. Eunomia - For CHEM Trust, 2020, Chemical Recycling: State of Play.

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

[v] Belliard, Rue. European Chemical Industry Council - Cefic, 2022, *Chemical Recycling: Enabling Plastic Waste to Become a Valuable Resource.*

[vi] Solis, Martyna, and Semida Silveira. "Technologies for Chemical Recycling of Household Plastics – a Technical Review and TRL Assessment." *ELSEVIER*, vol. 105, 29 Jan. 2020, pp. 128–138., https://doi.org/10.1016/j.wasman.2020.01.038.

[vii] Gendell, Adam, and Vera Lahme. Eunomia, *Feedstock Quality Guidelines for Pyrolysis of Plastic Waste*.

[viii] Wang, Jia, et al. "Catalytic Cascade Vapor-Phase Hydrotreatment of Plastic Waste into Fuels and Its Sustainability Assessment." *Green Chemistry*, The Royal Society of Chemistry, 3 Oct. 2022, https://pubs.rsc.org/en/content/articlelanding/2022/gc/d2gc02538h.

[ix] Radcliffe, Charles, and Johnson Matthey. "The FCC Unit as a Propylene Source." *Digital Refining*, Digital Refining, July 2007, http://www.digitalrefining.com/article/1000312.

[x] "The Mass Balance Approach." ISCC System, ISCC, https://www.iscc-system.org/about/circular-economy/mass-balance-approach/.

[xi] "The Mass Balance Approach." *ISCC*, International Sustainability & Carbon Certification, https://www.iscc-system.org/about/circular-economy/mass-balance-approach/.

[xii] Dittrich-Kramer, Brigitte, et al. ELLEN MACARTHUR FOUNDATION / CO.Project, *Enabling A Circular Economy For Chemicals With The Mass Balance Approach.*

[xiii] Krüger Christian. Sphera Solutions GmbH*, Evaluation of Pyrolysis with LCA –3 Case Studies*, https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainablesolutions/ circular-economy/mass-balanceapproach/ chemcycling/lca-forchemcycling/download-study.html.

[xiv] Tonini, Davide, et al. "Carbon Footprint of Plastic from Biomass and Recycled Feedstock: Methodological Insights." *The International Journal of Life Cycle Assessment*, vol. 26, no. 2, 2021, pp. 221–237., https://doi.org/10.1007/s11367-020-01853-2.

[xv] "Advanced Recycling." *American Chemistry Council*, ACC, https://www.americanchemistry.com/better-policy-regulation/plastics/advanced-recycling.

[xvi] "Dow and Mura Technology Announce Largest Commitment of Its Kind to Scale Advanced Recycling of Plastics." *Dow Corporate*, Dow, https://corporate.dow.com/en-us/news/press-releases/dow-and-mura-technology-announce-largest-commitment-of-its-kind-.html.

[xvii] "Chemical Recycling: Tackling Plastic Waste." *Shell Global*, Shell, https://www.shell.com/business-customers/chemicals/chemical-recycling-tackling-plastic-waste.html#iframe=L3dlYmFwcHMvU2hlbGxfQ2hlbWljYWxzX1JlY3ljbGluZy8.

[xviii] "Mechanical and Molecular Recycling-Some Things Are Just Better Together." *Eastman*, Eastman Chemical Company, https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Mechanical-Molecular.aspx.

[xix] "True to Its EVERMINDS™ Mind-Set, Borealis Drives Collaborative Project in Sweden to Increase Supply of Chemically Recycled Feedstock for the Manufacture of More Circular Base Chemicals and Plastic Products - Borealis." *Borealis Group*, Borealis AG., 15 Apr. 2021, https://www.borealisgroup.com/news/true-to-its-everminds-mind-set-borealis-drives-collaborative-project-in-sweden-to-increase-supply-of-chemically-recycled-feedstock-for-the-manufacture-of-more-circular-base-chemicals-and-plastic-products.

[xx] “Braskem Inaugurates Its First Mechanical Recycling Plant in Partnership with Valoren.” *Carbon Neutral Circular Economy*, Braskem, https://www.braskem.com/newsletter-carbon-neutral-detalhe-en/braskem-inaugurates-its-first-mechanical-recycling-plant-in-partnership-with-valoren.

[xxi] “LyondellBasell and Genox Recycling Plan to Establish Plastics Recycling Joint Venture.” *LyondellBasell*, LyondellBasell, 10 Oct. 2022, https://www.lyondellbasell.com/en/news-events/corporate--financial-news/lyondellbasell-and-genox-recycling-plan-to-establish-plastics-recycling-joint-venture/.

[xxii] “LyondellBasell Makes Decision to Progress Advanced Recycling Plant in Wesseling, Germany.” *LyondellBasell*, LyondellBasell, 18 Nov. 2022, https://www.lyondellbasell.com/en/news-events/products--technology-news/lyondellbasell-makes-decision-to-progress-advanced-recycling-plant-in-wesseling-germany/.

[xxiii] Brock, Joe, et al. “The Recycling Myth: A Plastic Waste Solution Littered with Failure.” *Reuters*, Thomson Reuters, 29 July 2021, https://www.reuters.com/investigates/special-report/environment-plastic-oil-recycling.

[xxiv] “Exxtend™ Technology for Advanced Recycling.” *ExxonMobil Chemical*, ExxonMobil, https://www.exxonmobilchemical.com/en/exxonmobil-chemical/sustainability/advanced-recycling-technology.

[xxv] Patel, Bryan A, et al. *CO-PROCESSING OF WASTE PLASTIC IN COKERS*. 24 Nov. 2022.

[xxvi] “ExxonMobil to Build Its First Large-Scale Plastic Waste Advanced Recycling Facility.” *Corporate ExxonMobil*, ExxonMobil, 11 Oct. 2021, https://corporate.exxonmobil.com/News/Newsroom/News-releases/2021/1011_ExxonMobil-to-build-its-first-large-scale-plastic-waste-advanced-recycling-facility.

[xxvii] “Exxtend™ Technology for Advanced Recycling.” *ExxonMobil Chemical*, ExxonMobil, https://www.exxonmobilchemical.com/en/exxonmobil-chemical/sustainability/advanced-recycling-technology.

[xxviii] Drane, Amanda. “Exxon's Baytown Facility Finds New Ways to Break down Plastic as Consumers Demand Better Recycling.” *Baytown West Chambers County*, Houston Chronicle, 30 Sept. 2022, https://baytownedf.org/news-media/article/exxons-baytown-facility-finds-new-ways-to-break-down-plastic-as-consumers-d.

[xxix] “ExxonMobil Starts Operations at Large-Scale Advanced Recycling Facility.” *Corporate ExxonMobil*, ExxonMobil, 14 Dec. 2022, https://corporate.exxonmobil.com/news/newsroom/news-releases/2022/1214_exxonmobil-starts-operations-at-large-scale-advanced-recycling-facility.