Pyrolysis and Circularity White Paper

Decades worth of innovation and technology improvements have enabled plastics to improve and elevate standards of living[1]. Alongside continuous plastics advancement, a tremendous need has been recognized to properly manage plastics at their end-of-life. In recent years, a growing concern in microplastics, plastics ending up in water systems, and the increasing size of landfills has made the public more aware of the dire need to properly recycle plastic waste. In general, plastics comprise less than 13% of the United States municipal solid waste, however, it has been increasingly shown that only a small fraction of plastic waste is recycled each year. The EPA calculated that in 2018 only 8.7% of the total quantity of plastics disposed of are actually recycled[2]. This is a consequence partially driven by the increasing amount of hard-to-recycle (H2R) plastics, such as flexible packaging films, foams, food containers and bottle caps, that cannot be handled through traditional mechanical recycling. Therefore, to continue using these plastics for everyday needs, it is imperative that technology be developed and utilized to manage H2R plastics at their end-of-life.

Traditionally, plastic waste has been from single use applications and is often landfilled, incinerated, or leaked into the environment, which can be described as a linear economy approach. A linear economy involves extracting raw materials, producing products from those raw materials, disposing of the products, and then extracting new virgin material to create the product over again. However, rapid urbanization and industrialization has led to a dramatic increase in plastics production, and a proportional dramatic increase in the use of petroleum-based feedstocks to develop those plastics. In recent years there has been an increasing need to find solutions to the accumulation of plastic waste in our environment and more efficient use of plastic as a resource through a circular economy approach. Under a circular economy approach, instead of disposing the end products, they are recovered or collected and then reenter the production process for use and reuse in a closed looped system. The circular economy approach redirects plastic waste from those traditional disposal methods and generates new plastics, which decreases the demand for virgin raw materials and diverts material being sent to incineration or landfill, mitigating the risk of leakage to the environment. A main focus within circularity is maintaining the intrinsic value of the materials that are being recycled[3]. Advanced recycling *allows* plastics to achieve this circularity.

Recycling processes are generally categorized into two groups: mechanical and advanced recycling. In mechanical recycling, post-consumer plastic waste is recovered via mechanical processes such as sorting, compounding, grinding, granulating, and drying, and is then converted to plastics products. Mechanical recycling does not change the chemical structure of the material, but rather allows reuse and recycling of the same polymeric materials into similar or downcycled

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[1] Collias et al.; Circular Economy of Polymers: Topics in Recycling Technologies. ACS Symposium Series; American Chemical Society: Washington, DC, 2021.
[2] Plastics: Material-Specific Data; United States Environmental Protection Agency; December 3, 2022. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data
[3] The Plastics Pact Network; Ellen MacArthur Foundation; Accessed January 27, 2023. https://ellenmacarthurfoundation.org/the-plastics-pact-network

applications in a closed loop manner. High density polyethylene (*e.g.,* milk cartons, laundry detergent bottles, jugs toys,), polyethene terephthalate (*e.g.,* bottles, jars), and polypropylene (*e.g.,* ropes, carpets, tape) type plastics are typically mechanically recycled. These plastics are commonly abbreviated as follows: HDPE, PET, and PP. However, mechanical recycling has many of its own concerns. Only certain types of plastics can be recycled mechanically, and proper sorting needs to be conducted to ensure that the recycled plastic is a relatively pure stream (>95% HDPE, PET or PP) in order for the material to be usable and to perform in its next application. Household waste that is sent to recycling is often contaminated due to improper cleaning and contains a wide range of other plastics like flexible packaging films, which end up clogging machines and making those plastics unrecyclable. The United States has typically depended on foreign exports to handle a large amount of this country's plastic waste, but with increasing pollution concerns many countries have banned foreign plastic imports. The United States does not have the infrastructure necessary to handle all this plastic waste domestically[4]. These challenges contribute to the low recycling rate in United States.

Advanced recycling is a highly engineered process that entails converting the plastic polymer chain into its original building blocks to be used as the raw material to develop or produce new plastic products or plastic-derived chemicals. It differs from mechanical recycling in that the chemical structure of the plastic is changed at the molecular level. Advanced recycling is beneficial as it complements mechanical recycling and can be utilized to promote circularity by improving the recoverability and retention of plastics materials that cannot be mechanically recycled. Advanced recycling is the last avenue to restore the plastic to productive use versus the alternatives of incineration or landfill.

One of the major hurdles in circularity is proper collection of materials. Recycling processes have always struggled with the proper collection and sorting of household recyclable materials. The Hefty® ReNew® program was developed to complement current recycling efforts to help create end-of-life solutions for H2R plastics instead of directing the material to landfill. Common household items are collected in Hefty® ReNew® bags and sent to recycling centers who then send these plastics to facilities that use H2R plastics as energy resources or convert them into new products for different applications, including through advanced recycling technology such as pyrolysis.

One specific type of advanced recycling is pyrolysis, which involves converting plastic waste into its building blocks by heating in a closed system in the absence of oxygen[5]. These waste plastics convert into smaller molecules in the form of a gas (syngas), liquid (oil), and inert solid (char). The ratio of the outputs of pyrolysis primarily depend upon the operating conditions of the manufacturing process and to a much lesser extent, the type of plastic being used[6]. Using

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[4] Cho, Renee; Recycling in the US is Broken. How Do We Fix It?; Columbia Climate School; March 13, 2020. https://news.climate.columbia.edu/2020/03/13/fix-recycling-america/

[5] Papuga et al.; Catalytic Pyrolysis of Plastic Waste and Molecular Symmetry Effects: A Review; Symmetry 2023, 15, 38.https://doi.org/10.3390/sym15010038

[6] What is Pyrolysis?; US Department of Agriculture; September 10, 2021. https://www.ars.usda.gov/northeast-area/wyndmoor-pa/eastern-regional-research-center/docs/biomass-pyrolysis-research-1/what-is-pyrolysis/

pyrolysis to convert waste plastics into feedstocks that generate virgin-quality plastics or other products, results in greenhouse gas emissions (GHG) reduction versus fossil-based plastic production along with the benefit of waste diversion from landfill. This technology can utilize a mixed plastics stream comprised of HDPE, LDPE, PP, and PS as plastic feedstocks, which makes up around 60% of plastics produced, much of which is sent to landfill[7].

A recent study on the quantitative comparison of life cycle assessments (LCAs) on the current state of advanced recycling technologies has been published by the Earth Engineering Center of the City University of New York[8]. This study details the findings of 13 LCA reports that analyzed the global warming potential (GWP) associated with thermal or depolymerization recycling of post-use plastics. This report details the process in which plastics that are well suited for advanced recycling are turned into new products though thermal or chemical depolymerization. The efficiency of chemical depolymerization is highlighted, ranging between 79% to 84%, indicating that a majority of the recycled plastic material can be reutilized and can contribute to circularity. The study concludes that in some scenarios, implementing advanced recycling practices can emit less GHG emissions than using virgin feedstock or landfilling post-consumer plastic. However, a wide range of results are shown among different studies, and the most appropriate technology should be implemented depending on the specific recycling scenario. The study did show that GHG emissions, circularity, and fossil fuel depletion were areas where advanced recycling technologies performed favorably.

While landfills are currently more cost effective, they have many disadvantages. As waste breaks down, it generates leachates and GHGs that can contaminate soil and groundwater or the atmosphere[9]. Another issue is that land is a limited resource, and by creating landfills, we are trading off other potential uses, driving a need for more land development. As plastic waste continues to grow in this linear system, more space will be needed for landfills from an ever-decreasing stock of available land. Therefore, it is imperative that we find alternative ways to deal with plastic, and pyrolysis*, a form of advanced recycling,* offers an opportunity to infinitely extend the lifecycle of a valuable resource.

Another option to deal with H2R plastics is by using them as fuel in cement kilns. Cement is produced by heating limestone, shells, check or marl, shale, clay, slate, blast furnace slag, silica sand, and iron ore in kilns that reach temperatures as high as 2700 degrees Fahrenheit. These components melt and combine to form cement "clinker," which is a rock-like substance. Once this stage has been reached, the clinker is grinded until it turns into the fine powder known as Portland cement[10]. Cement has been an essential part of our infrastructure for decades, and as

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[7] Used Plastic Feedstock; Nexus Circular; Accessed January 27, 2023. https://nexuscircular.com/our-technology/

[8] Creadore, Lauren and Castaldi, Marco; Quantitative Comparison of LCAs on the Current State of Advanced Recycling Technologies; Earth Engineering Center, City College of New York; October 2022. https://ccnyeec.org/wp-content/uploads/2022/10/comparisonOfAdvRecyclingLCAs.pdf

[9] Basic Information about Landfill Gas; United States Environmental Protection Agency; September 6, 2022. https://www.epa.gov/lmop/basic-information-about-landfill-gas

[10] How Cement is Made; Portland Cement Association; Accessed January 27, 2023. https://www.cement.org/cement-concrete/how-cement-is-made

population and urbanization grows, so does its demand and production. With the increased demand, the industry is incentivized to reduce production costs and environmental impacts. One way of doing this is by changing the fuels used in the kilns.

Typically, kilns use coal as fuel to reach the high temperatures needed to produce cement, but coal can be substituted by alternative fuels made of non-recycled plastics and paper. The properties of these fuels, such as moisture and ash content, chlorine concentrations, or heating values, must be similar to that of traditional fuels. While these alternative fuels are sometimes viewed negatively because they release chlorine, form dioxins, and furans during combustion, in reality these effects are negligible because they are usually stabilized in the clinker or entrapped by Air Pollution Control systems. Overall, using H2R plastics as alternative fuels in cement kilns is one way to decrease coal usage, which enables lower GHG emissions while diverting plastic waste from landfills[11].

There are still some challenges with using H2R plastics as alternative fuels in cement kilns. Using alternative fuels can negatively impact clinker properties, as alternative fuels differ in particle size, material density, and transport characteristics. This can affect clinker characteristics such as clinker burning grade, granule porosity, clinker phase crystal sizes, and general reactivity. Additionally, many times components such as phosphorus get added to the kiln, which can lower early strength or lead to longer setting times for cement performance.

Pyrolysis converts H2R plastics into their original molecular hydrocarbon building blocks which can enter the market as valuable resources. H2R plastics can then be recycled an infinite number of times through pyrolysis, extending their life and maintaining a circular system. In contrast, once plastics are burned as fuel in a cement kiln, the plastic resource is consumed and is no longer can be used to make any other useful items and *reduces the availability of plastics waste that can be used as feedstock for mechanical or advanced recycling options*. And although pyrolysis is a *technologically sound* process, the pyrolysis of H2R plastics into their building blocks is a nascent technology that is still in its early stages, while cement has been used for thousands of years and, thus, has had more time to develop. As such, while cement kilns still have potential for scalability and efficiency improvements, pyrolysis is likely to advance at a faster rate and obtain higher efficiency gains in the near future.

Today, most pyrolysis-based advanced recycling processes are at a small pilot or early-commercial scale with small production lines that are energy intensive per unit of output. As Pyrolysis technology progress to industrial scale in the coming years, the energy efficiency, cost effectiveness will increase which will subsequently lessen the overall environmental impact. This will occur as a result of cleaner energy sources and technology innovations. Electricity is the main driver of environmental impacts for pyrolysis technology, especially GWP. However, renewable energy is growing at a rapid pace to achieve the carbon reduction goals stated in the Paris Agreement. Within recent years, there has been a bigger push to diversify energy and

[11] Sustainable Solutions Corporation; Hefty EnergyBag Program Life Cycle Assessment; Reynolds Consumer Products; July 27, 2022. https://www.hefty.com/sites/default/files/2022-11/Hefty-EnergyBag-Program-2022-Life-Cycle-Assessment.pdf

achieve energy independence from fossil fuels. This has led several countries around the world to further increase their already ambitious clean energy targets. As renewable energy continues to grow and replace fossil fuels, the environmental performance of pyrolysis will improve significantly.

Overall, pyrolysis is an effective recycling technology for H2R plastics such as PE, PP, and PS that would normally accumulate in a landfill and/or pollute the environment, water, and air. While it does have some challenges, pyrolysis is a relatively new technology with great potential to manage plastic waste and it will complement other advanced recycling technologies to create a more circular plastics economy.

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