CHEMICAL RECYCLING: A DANGEROUS DECEPTION

WHY CHEMICAL RECYCLING WON'T SOLVE THE PLASTIC POLLUTION PROBLEM

October 2023

BEYOND PLASTICS
BENNINGTON COLLEGE

IPEN
for a toxics-free future

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October 2023

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ISBN: 978-1-955400-22-0

Beyond Plastics is a national education and advocacy organization that works to end plastic pollution through policy change. Using deep policy and advocacy expertise, Beyond Plastics pursues the institutional, economic, and societal changes needed to save our planet and ourselves from plastic's harmful impacts on health, climate, and the environment.

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IPEN is a network of over 600 non-governmental organizations working in more than 125 countries to reduce and eliminate the harm to human health and the environment from toxic chemicals..

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ACKNOWLEDGMENTS

This publication was made possible through the generous support of **Bloomberg Philanthropies' Beyond Petrochemicals campaign**. Beyond Petrochemicals is turbocharging efforts led by frontline communities to block the rapid expansion of 120+ petrochemical projects concentrated in three target geographies – Louisiana, Texas, and the Ohio River Valley.

IPEN and Beyond Plastics thank Rebekah Creshkoff (Beyond Plastics volunteer), Alexandra Shaykevich (Environmental Integrity Project), and Ronald Steenblik (senior technical advisor at Quaker United Nations Office) for assisting in developing this report.

IPEN would like to acknowledge that this document was produced with financial contributions from the Government of Sweden and other donors. The views herein shall not necessarily be taken to reflect the official opinion of the donors.

Cite this publication as: Bell, L. Chemical recycling: a dangerous deception. Beyond Plastics and International Pollutants Elimination Network (IPEN), October 2023

Cover photo: Braven Environmental facility in Zebulon, N.C.; courtesy of Schuyler Mitchell / The Intercept

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Source: Unsplash

ERRATA

On pages 8 and 87 of the report, we previously reported that even at a reduced production level, Alterra was "nearly reaching the limits of its air emissions permit," and that state air quality officials in Ohio had twice given Alterra permission to temporarily exceed their air emissions limits. Our original analysis of regulatory documents was inaccurate. The language in the Ohio EPA letters was unclear; in fact Ohio EPA was giving Alterra permission to temporarily operate at a higher production level until new stack emissions tests could be conducted at a higher production level. Further review of regulatory documents shows that Alterra is not nearly reaching or exceeding its air emissions limits.

See endnotes 90 and 91 on page 122 for the Ohio EPA documents.

FOREWORD

By Lewis Freeman, former vice president of government affairs for the Society of the Plastics Industry (1979 to 2001)

Plastics have become one of the most common and versatile materials in our society. Indeed, many uses of plastics, particularly in medical applications, are not currently possible with any other material. But, as the use of plastics has grown tenfold over the last 50 years, so have the challenges created for the environment.

In 1980, the first full year in which I was associated with the plastics industry, plastic waste accounted for less than 5% of the municipal solid waste (MSW) stream — 6.8 million tons, according to statistics compiled by the U.S. Environmental Protection Agency (EPA).[1] By 2018, the most recent year for which official EPA statistics are available, plastics were 12% of the 300 million tons of MSW.

As former vice president of government affairs for the Society of the Plastics Industry — a plastics lobbying group now known as the Plastics Industry Association — I remember the conversations that prompted aggressive advertising campaigns around plastic recycling. Plastics executives wanted SPI to advertise its way out of plastic's growing public relations problem as society began realizing the environmental pollution created by the material.

Despite knowing that plastic recycling couldn't realistically manage a significant amount of plastic waste, companies spent millions of dollars convincing the public otherwise. Today, less than 10% of plastic is actually recycled, leading to public confusion and yet another PR issue for the industry.[2]

Public concern over plastics has been particularly heightened by the increasing presence of plastic waste and plastic raw materials (e.g., resin pellets) in the environment, particularly in waterways and the oceans, where it presents a serious danger to aquatic species and birds. This is a waste problem for which recycling is not a suitable response.

More recently, the plastics industry has begun promoting what it calls "advanced recycling," which the industry defines as turning "used solid plastic into its gas or liquid raw materials to be remade into brand new plastic for use in virtually any plastic product or packaging."[3] The industry goes on to state that the "plastics recycling industry is investing heavily in these technologies as part of efforts to meet the goal of reusing, recycling, or recovering 100% of plastic packaging in the U.S. by 2040."

"Chemical Recycling: A Dangerous Deception" reviews the lack of success of the mechanical recycling of plastics waste, but its main focus is an in-depth evaluation of the industry's efforts to implement chemical (so-called "advanced") recycling. The report's meticulous examination in case studies of existing "advanced recycling" facilities does not produce optimism about the industry's potential for success with this approach in addressing its solid waste problems.

It has been 35 years since the plastics industry began prominently responding to public concerns about plastic waste. That's more than a third of a century. In that time, the industry has focused its response to waste issues on promoting recycling. It has taken the industry 35 years to increase the recycling rate of its waste from less than 1% to just under 9%. It now claims that in just half that time — 17 years — the plastics industry will be able to recycle 100% of its waste. This report makes a compelling case for doubting the plastics industry's seriousness and ability to achieve its stated goal.

"Chemical Recycling: A Dangerous Deception" is an important contribution to the public dialogue about plastics waste. It deserves wide attention, particularly from the plastics industry itself.

KEY FINDINGS

Chemical recycling is a false solution to plastic pollution. Chemical recycling has failed for decades, continues to fail, and there is no evidence that it will contribute to resolving the plastics pollution crisis.

Plastics are inherently risky to recycle. Plastics are made with toxic chemicals and when recycled, these chemicals go into the recycled plastic or product. Toxic chemicals can also be created in recycled plastics from cross contamination and heating, resulting in ongoing and often increased chemical threats to our health and the environment.

Chemical recycling is inefficient, energy-intensive, and contributes to climate change. According to U.S. government researchers, the energy needs (derived from plastic waste itself or additional fossil fuels) of chemical recycling can create as much as 100 times more damaging environmental and climate impacts than virgin plastic production.

Chemical recycling creates large amounts of toxic waste. Regardless of what products facilities are attempting to create, chemical recycling — at best — produces small amounts of usable products from large amounts of plastic waste. Typically, most of the plastics going into chemical recycling facilities will become waste (often hazardous waste), be burned as fuel, or be landfilled.

Chemical recycling is dangerous and dirty. Chemical recycling facilities release toxic emissions, create hazardous waste, and are prone to fires and explosions.

Chemical recycling will not supplement conventional (mechanical) recycling. Proponents say chemical recycling is needed for mixed plastics that are difficult to recycle mechanically, but there is no evidence that chemical recycling can economically or effectively recycle mixed plastic waste. To the extent it works at all, chemical recycling uses the same kinds of plastics as conventional recycling. Thus, chemical recycling will likely compete with, not supplement, conventional recycling.

Burning plastic as fuel is dirty and unsustainable from start to finish. These operations can create unacceptable risks to nearby communities, posing threats to environmental justice. Weak regulations will increase these health and environmental risks. Using chemical recycling to turn plastic waste into fuel creates a toxic, dirty fuel that is harmful to human health and disastrous for the climate.

Making plastic into fuel to burn is not recycling. According to internationally accepted definitions, plastic to fuel is not recycling. It is a dirty and dangerous disposal method.

Eliminating or relaxing regulations puts our health at risk. Chemical recycling facilities emit cancer-causing chemicals and substances that have been banned globally because they are among the most toxic chemicals known. Yet in the United States, many states eliminate or relax environmental and health rules to incentivize new plants, and the industry often evades federal clean air rules. Environmental justice communities that already face unequal health risks from toxic pollution will face the highest health risks from expansion of chemical recycling.

Public funds should support sustainable solutions, not chemical recycling. Government subsidies for chemical recycling are risky investments in a dirty, unproven technology. We need to support innovation for safe, clean materials to create sustainable alternatives that can replace plastics.

KEY FINDINGS FROM OUR CASE STUDIES

As of September 2023, 11 chemical recycling facilities have been constructed in the United States. Chapter 2 of this report provides a summary of findings, and a detailed case study of each facility can be found in Appendix 1. Just a few of the key facts include:

- In 2021, a Reuters special report profiled the demise of the Renewlogy chemical recycling project, a collaboration between Dow and Reynolds Consumer Products (the maker of Hefty plastic bags). The 2018 program instructed residents of Boise, Idaho, to place their hard-to-recycle plastics in “Hefty EnergyBags,” which were then trucked 340 miles away to the Renewlogy pyrolysis plant in Salt Lake City, Utah. The program — which benefited from state and city loans totaling more than half a million dollars — failed in part because the plastic waste collected contained “10 times” the amount of contaminated garbage than was expected. Since March 2020, plastics collected in Boise’s recycling program have been sent to a Utah cement plant to be burned.[4]
- In 2012, two companies, Agilyx and Americas Styrenics, opened a chemical recycling plant in Tigard, Oregon. After 12 years, the plant has yet to prove commercially viable and despite its low output, regulators say the operation is a “large quantity generator” of hazardous waste. In 2013, another Oregon chemical recycling plant owned by Agilyx opened to convert plastic to oil, after receiving a $577,255 tax credit from the state. The plant closed in 16 months.
- An Alterra company plant broke ground in 2014 in Akron, Ohio, but has only run as a “demonstration” plant. Despite its low output, regulators say it is a “large quantity generator” of hazardous waste.
- After 10 years of testing, a Braven chemical recycling facility in Zebulon, North Carolina, received a state air permit in 2020, though it remains unclear whether the plant is producing commercially viable amounts of outputs. Regulators say it is a “large quantity generator” of hazardous waste, and on at least two occasions state regulators cited the plant with a notice of violation for its mismanagement of hazardous waste.
- In June 2020, Brightmark Energy facility in Ashley, Indiana claimed its chemical recycling plant in Ashley, Indiana, would reach a yearly plastic waste recycling capacity of 100,000 tons by early 2021. But to date the plant remains at the “test” phase, has processed just 2,000 tons of plastic waste, and has been affected by fires, oil spills, and worker health and safety complaints. Brightmark has received $4 million in federal subsidies for the project. A Brightmark plan to build the nation’s largest chemical recycling plant in Georgia was contingent on the company proving its Indiana plant could produce useful output, but in December 2021, Brightmark admitted it was unable to deliver recycled end-product, and the Georgia project was abandoned. There was strong opposition to the facility.

Brightmark Energy facility in Ashley, Indiana. Source: The Last Beach Cleanup

- A 2020 statement by New Hope Energy company claimed its chemical recycling plant would process 50,000 tons of plastic waste annually, but in June 2022, a company official optimistically noted the plant was "on track" to process about one-third of this amount by the year's end. No company data was found to confirm whether the plant reached even this low goal.
- A Nexus Circular company recycling plant in Atlanta, Georgia, has been operating since 2011 at "pilot" capacity, with latest figures showing the plant operating at between 6% and 13% of capacity. The plant sells oil from plastics certified as "sustainable" by ISCC. In 2020, Shell agreed to purchase 66,000 tons of Nexus' plastic waste oil over four years, but as of January 2023, the plant had processed just 4,000 tons of plastic waste.
- In 2010, a Prima America chemical recycling plant applied for a permit to make diesel fuel from plastic waste in Northumberland, New Hampshire. In March 2023, a plant manager admitted the facility was still in its "test" phase and noted its diesel fuel was too expensive to be sold economically. The plant shut down for about a year in 2019/2020 due to multiple issues with state environmental rules.
- In March 2023, PureCycle defaulted on its agreement with the Southern Ohio Port Authority and UMB Bank by failing to complete construction of its chemical recycling project before December 1, 2022, as called for in its financing agreement. UMB Bank and Southern Ohio Port Authority waived the default in exchange for a number of financial and performance-based conditions. In September 2023, the Ironton facility experienced a mechanical failure and its operations were halted. In filings to its bondholders and the Securities and Exchange Commission Purecycle claims that the mechanical failures were due to a power outage on August 7, 2023, caused by inclement weather affecting a third-party power supplier. After repairs and replacement of a faulty seal, restart procedures were initiated at the facility on September 11, 2023, but PureCycle could not guarantee that the restart would be successful or whether further mechanical failures would occur as the result of the August 7, 2023, power outage. Recognizing that the facility would not meet a key milestone as required in its default waiver, PureCycle filed a Notice of Force Majeure to release itself and its bondholders from their contractual obligations.

10 RECOMMENDATIONS

1. **Declare** a national moratorium on new chemical recycling plants.
2. **Require** extensive analyses and testing of existing chemical recycling plants' toxic emissions, releases, waste residues, wastewater, output contamination levels, and fire and explosion risks.
3. **Deny** approval or permitting of chemical recycling plants if risks from their emissions or products (for example, fuels) exceed a one in 1 million excess public cancer risk.
4. **Mandate** testing of oils and other outputs from chemical recycling before they can be used as fuel or plastic feedstock to prevent widespread contamination of products and human exposure to unacceptable toxic risks.
5. **End** all federal, state, and local incentives for establishing chemical recycling plants, including public funds, subsidies, tax breaks, investment bonds, carbon credits, landfill diversion credits, and other schemes.
6. **End** siting of chemical recycling plants in environmental justice communities.
7. **Prohibit** plastic-to-fuel projects, which recreate (rather than displace) fossil fuels that pose dangers to the climate and the environment.
8. **Implement** the "polluter pays" principle and ensure that the petrochemical industry bears all financial risks of chemical recycling and the manufacture, use, and disposal of plastics.
9. **Prohibit** chemical recycling of any form to count toward recycling targets or recycled content goals in any public policy or program, including but not limited to extended producer responsibility (EPR) programs.
10. **Prohibit** use of free-allocation mass balance accounting in determining recycled content of products that incorporate chemical recycling outputs.

EXECUTIVE SUMMARY

This report has been prepared to address the plastic industry's claims that chemical recycling, also known as "advanced recycling," can play a significant role in reducing global plastic pollution. The science and data currently available do not support this claim and actually point to the conclusion that chemical recycling would support expansion of plastic production, while potentially causing unacceptable levels of environmental and social harm — as well as impacts on human health — through emissions, waste generation, energy consumption, and contaminated outputs.

Highly informed and experienced delegates at the 2023 Conference of the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Waste and Their Disposal (hereafter the Basel Convention) did not agree to include chemical recycling in the global technical guidance on the management of plastic waste. The delegates overwhelmingly rejected its inclusion because it could not be demonstrated that chemical recycling met the threshold of environmentally sound management (ESM). This report identifies many of the technical and economic reasons why chemical recycling is not considered environmentally sound, will not effectively address plastic pollution in any meaningful way, and should not be supported with public funds, subsidies, tax breaks, or similar instruments. Chemical recycling is not anticipated to be commercially viable, and any economic risks associated with its investment should be borne by those responsible for plastic production, not the public.

Chemical recycling is not new or advanced, as it is based primarily on technologies such as pyrolysis and gasification that have struggled technically and commercially to process such wastes for decades. The majority of the output is not feedstock for new "circular" or "green" plastic but petrochemical fuels that will be burned, creating toxic emissions and emitting greenhouse gases. Every step of these technologies is expensive, polluting, and energy-intensive, from pretreatment and thermal processes to output cleanup.

Many chemical recycling companies use fossil fuel energy to turn petrochemical-based plastics back into fossil-derived fuels to burn, creating a polluting, carbon-intensive merry-go-round. U.S. government researchers have concluded that the economic and environmental impacts of pyrolysis and gasification are likely to be 10 to 100 times higher than those of virgin polymer production, casting serious doubt on the environmental credentials of the sector (see Appendix 1: U.S. Case Studies on page 80).

Chapter 1 briefly summarizes the state of the global plastic pollution crisis and how that pollution has exceeded the Earth's limits for its ecosystems to function in a stable manner. Then it explores the reasons why conventional, mechanical recycling has failed to process more than 9% of all plastic ever produced. It includes the technical, economic, and policy limitations that prevent effective recycling and explains the plastic industry's awareness of this as it launched its recycling campaigns to head off plastic product bans in the 1980s.

Chapter 2 summarizes the 11 chemical recycling plants that were constructed, operating, or partially operating in the U.S. as of September 2023. It is supplemented by "Appendix 1: U.S. Case Studies," which details these plants' financing, investment and public subsidy status, outputs, if any, and whether they are situated in environmental justice communities. Environmental justice communities are communities where a high percentage of residents are low income or people of color. These communities often bear a disproportionate impact from heavy industries and are further burdened by the establishment of polluting chemical recycling plants.

Chapter 3 explores current attempts spearheaded by chemical industry lobbyists to deregulate the chemical recycling sector in the U.S. and reclassify its operations as manufacturing facilities, not solid-waste operations, in an attempt to reduce emissions monitoring and regulatory controls needed to protect workers and communities. Technical data on chemical recycling emissions, yield, and waste streams is generally not made public. That which is available, combined with research data, suggests that chemical recycling represents a significant threat to nearby communities and must be regulated at least as strictly as other incineration facilities. The issue of toxic plastic feedstock and its relation to toxic outputs and emissions from chemical recycling is also discussed.

Chapter 4 describes the international linkages to chemical recycling technology and policy, how it is regarded outside the U.S., and rejection of these technologies as environmentally sound management of plastic waste by the leading global hazardous waste decision-making body, the Basel Convention. It also examines the relevance of the Stockholm Convention on Persistent Organic Pollutants to chemical recycling in relation to toxic compounds contaminating feedstock, formed in the process, released in emissions, and contaminating outputs.

Chapter 5 establishes conclusions that can be drawn from the report research and recommendations with respect to chemical recycling and plastic pollution.

The Technical Addendum Part 1 details the myriad terms, definitions, and technologies that currently fall under the umbrella of chemical, or advanced, recycling. Many of these terms also have marketing synonyms that bear little resemblance to technical processes being proposed or used. The addendum also addresses the technical processes, principles underlying the processes, and feedstock types. Part 2 elaborates on the long history of chemical recycling and why its application to post-consumer waste has not been successful or viable, especially in relation to plastic waste. It addresses the problems encountered in the scaling-up processes from lab or pilot stage to commercial operations. It also explains that for regulatory purposes, pyrolysis and gasification are regarded as incineration technologies, requiring strict monitoring for and regulation of toxic emissions and releases. Finally, it refutes the claims that chemical recycling is suitable for mixed plastic waste recycling and that the process does not compete with conventional mechanical recycling for clean feedstock.

Ultimately, policymakers worldwide must decide whether they will engage in years of further delay, distracted by the promise of a technology "solution" that has failed before and will fail again, while the global plastic pollution crisis spirals out of control. Planetary toxic plastic waste pollution requires immediate action. The answer lies in producing a lot less plastic, making it significantly less toxic, and substituting other reusable or more sustainable materials for plastics wherever possible.

The cost of inaction, distraction, and delay will be terrible, and it will be paid by us all: by future generations, the environment, and especially by environmental justice communities. The myth of chemical recycling as a solution to plastic waste should be seen for what it is: a public relations distraction to prevent plastic regulation and prop up the profits of the petrochemical/plastics industry. We have lost nearly 40 years waiting for conventional plastic recycling to "work." We have waited decades for chemical recycling to work. We can no longer afford to waste more time waiting for mythical solutions. Plastic recycling simply does not work.

INTRODUCTION

As the planet is swamped with visible plastic pollution, and microplastics have been found in the human placenta and in breast milk, the global community is finally preparing to act. Many world leaders now recognize that any international plan to control plastic pollution will require major cuts in production and prohibition of toxic components. In response, the global petrochemical industry and oil-dependent governments are making a last-ditch effort to convince the world they can recycle their way out of the mess. This time, they say, the savior is chemical recycling, and its advocates claim it will create a circular economy for plastics without resorting to production cuts.

Chemical recycling is an umbrella term for a variety of technical ideas that promise a backend fix to the plastic waste crisis. Collectively, these technologies target plastic at the end of its life cycle, after it has been used and thrown away. The stated objective is to make chemical ingredients for more plastic or for burning as fuel. In this report, "chemical recycling" includes all methods that either involve the use of chemicals in the plastic waste treatment stage or produce chemicals from plastic waste.

The hyperbole surrounding these technologies is frantic, and the stakes are high. Big Oil and Big Plastic have wagered heavily on plastic production due to the low cost of the fossil gas feedstock from fracking operations and the potential for high profits. Now, as people raise the alarm about plastic pollution and negotiators begin drafting a global treaty, the industry is making a desperate Hail Mary pass in an attempt to fight off regulation of its toxic and polluting products.

The relentless publicity machines of the fast-moving consumer goods (FMCG) industry, petrochemical companies, and chemical industry associations churn out projections on the success of chemical recycling and claim significant investments in the sector. But they omit facts about chemically recycled plastic outputs because the only thing actually being recycled is the myth that recycling will solve the plastic pollution crisis.

> ***The only thing actually being recycled is the myth that recycling will solve the plastic pollution crisis.***

Chemical recycling is not new. Pyrolysis, gasification, and other techniques have been around for decades without making a dent in plastic pollution — and without making much money. Startup companies now abound with trials, pilot plants, and project announcements, but with very little commercial output. The plastics industry, desperate for green credentials, is heavily promoting these projects, despite little real-world performance to show for it. Many projects revert to selling their output oil as fuels. At its core, this is petrochemicals turned into plastic and then turned back into petrochemicals to burn — a dead-end, carbon-intensive waste of resources.

Most chemical recycling produces very little product, such as clean polymer feedstock, and generates hazardous waste. It requires an enormous amount of energy to heat the processes while releasing toxic air pollution and toxic waste. The outputs of oil, gas, and waxes are typically contaminated with toxic chemicals. This is no surprise, as all plastics contain thousands of chemical additives, many of them hazardous, that are carried through the chemical recycling process into the outputs. These have to be cleaned and upgraded at great expense, further undermining the commercial viability of the operation. Even the few niche processes that have less-contaminated polymer outputs create significant hazardous waste streams.

A September 2023 report by the Nordic Council of Ministers[5] casts further doubt on the relevance and contribution of chemical recycling to the management of plastic waste into the future. The report models the impact of 15 potential global policy interventions on plastic pollution through 2040. It concludes that, at best, chemical recycling will only recycle 15.4 million tons of plastic waste in 2040 — a mere 3% of all plastic waste generated. The report raises significant concerns about the risks and uncertainty associated with chemical recycling, including impacts on human health; greenhouse gas and toxic emissions; and discharges containing hazardous chemicals. It also raises concerns about substances of concern from chemical recycling feedstock being reintroduced into its outputs.

The 2023 Conference of the Parties of the Basel Convention, the leading global body on hazardous waste management and regulation, adopted guidance on how the world should manage plastic waste. The world's leading experts on the subject declined to include chemical recycling in the guidance, as no evidence demonstrated it is environmentally sound management (ESM).

We agree with those findings, and this report provides details as to why chemical recycling fails the test of environmentally sound management. These include the emissions, the toxic waste generated in the process, the energy consumption, the inability to process contaminated mixed plastic waste, and its competition with mechanical recycling for clean plastic waste. The chemical recycling industry is neither transparent nor accountable, and is not releasing data on its operations — especially in regard to product yields, emissions, and hazardous waste.

In the current market, the price of most recycled plastic cannot compete with that of virgin plastic due to cheap and abundant oil, cheap fracked gas, and the enormous economies of scale of the petrochemical industry. The majority of recycled plastic — that which is generated by residential curbside recycling programs — is of low quality and low value, and is often downcycled into products that cannot themselves be recycled.

Overshadowing all of this is the plastics industry's massive increase in production that is projected through 2050 (Ryan 2015). Increased plastic production will vastly outstrip any attempts to boost plastic recycling, and the world's ability to assimilate plastic pollution has already been passed. We simply can not catch up with unfettered plastic production that ultimately leads to plastic waste.

The petrochemical industry is working hard to convince policymakers that production cuts are not needed and that we can catch up with plastic pollution by throwing massive public and private resources behind technologies with a long history of underperformance, failures, and bankruptcies.

Some major waste management industry players have already seen the writing on the wall. As Markus Binding, managing director at Veolia Umweltservice GmbH, said about chemical recycling: "And this is precisely the risk for our industry: Without proof of safe, reliable, and sustainable mode of operation on an industrial scale, without a transparent database for life cycle analyses from sources that are as neutral sources as possible, without critical consideration of the proven and the new, we run the risk of being used as a stirrup holder for a vision of the petrochemical industry."[6]

Decision-makers should take note, look past the distraction tactics, and not let the petrochemical industry use its recycling-myth playbook again. It's time to take real action and limit plastic production, eliminate the use of toxic chemical additives, ban unnecessary single-use plastic items, and require polluters to pay to clean up the mess.

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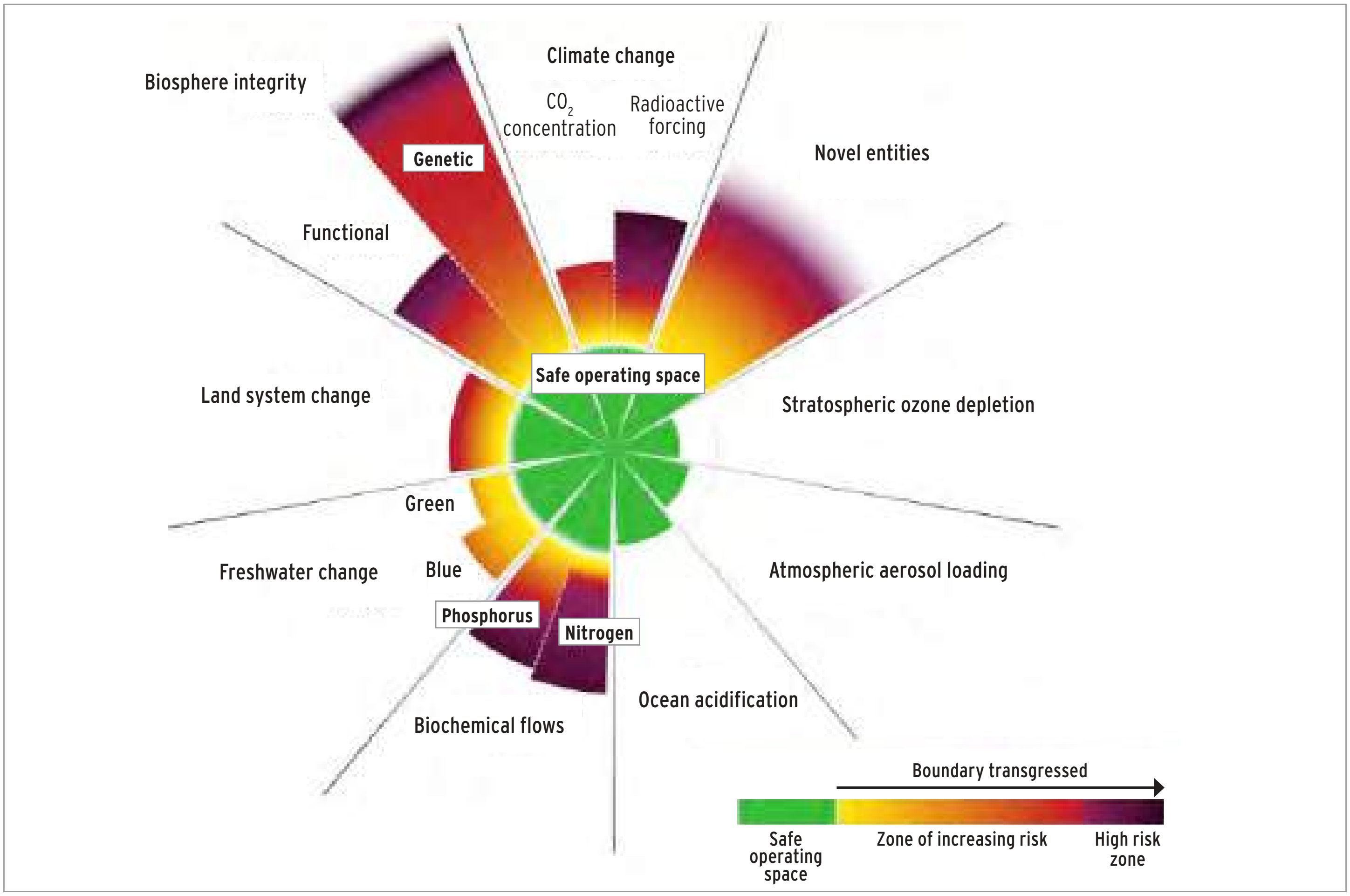
CHAPTER 1

THE GROWING PROBLEM OF PLASTIC POLLUTION AND THE FAILURE OF CONVENTIONAL RECYCLING

Source: pexels-fatima-yusuf-14688593

Plastic pollution is now a problem of such enormous proportions that it amounts to a global environmental crisis. Plastic waste joins climate change, biosphere integrity (which includes biodiversity), freshwater availability, land use, and nutrient pollution (see Figure 1) as one of six of the nine planetary boundaries that have been exceeded (Richardson et al. 2023). Plastic falls into the "novel entities" planetary boundary, as this category refers to human-made pollution, such as plastic and industrial chemicals. The nine planetary boundaries have been identified by scientists as those that demarcate the stable state Earth has remained in since the last ice age 10,000 years ago (Rockström et al. 2009). Breaching these boundaries risks destabilization of the Earth and its ability to support human life.

Figure 1 Novel Entities Exceeding Global Assimilative Boundaries*



* Novel entities are entities that are novel in a geological sense and that could have large-scale impacts that threaten the integrity of Earth system processes. This includes pollution from plastic, synthetic chemicals like PFAS, and nanomaterials. Source: Katherine Richardson et al., 2023

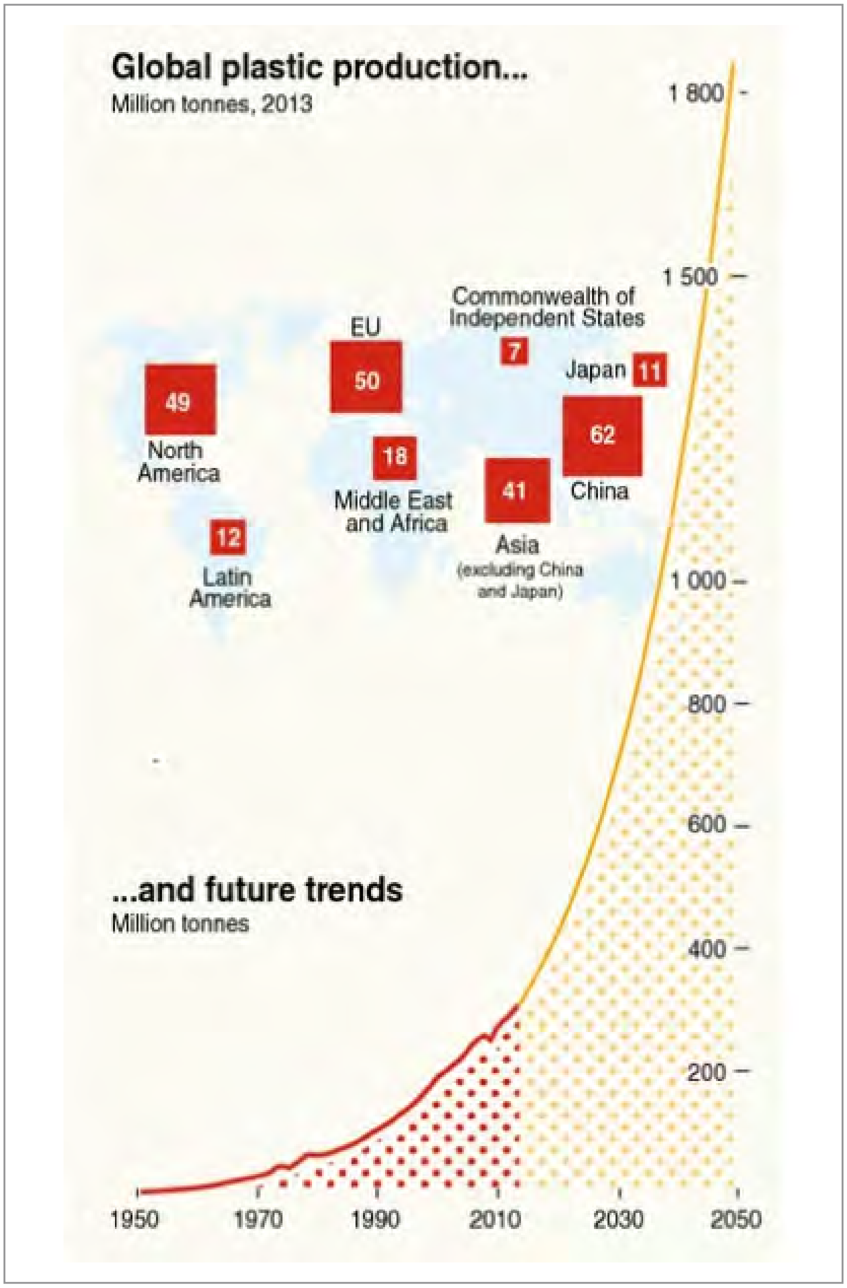
Across the globe, hundreds of millions of tons of plastic waste end up in landfills each year, and tens of millions of tons of plastic are fed into incinerators or leaked into rivers and oceans. In countries where waste infrastructure is rudimentary, plastic is dumped and burned in the open, causing soil and food-chain contamination and human exposure to toxic residues (Petrlik et al. 2020).

The rate of pollution is staggering, with estimates of global plastic waste discharges to the aquatic environment at about 10 to 25 million tons per year and to the terrestrial environment at 16 million to 32 million tons per year as of 2016. Emission rates are set to double by 2025 (MacLeod et al. 2021).

Plastic recycling has failed, with only 9% of all plastic produced having been recycled (Geyer et al. 2017). Millions of tons of plastic waste enter the oceans every year, and increased plastic production rates suggest that ocean contamination will only grow (Jambeck et al. 2015, Geyer et al. 2017, Lebreton and Andrady 2019). In 2050, the global annual rate of plastic production is estimated to increase from the 2016 production level of more than 360 million tons to almost 2 billion tons annually (Ryan 2015) (see Figure 2).

ENVIRONMENTAL IMPACTS

Figure 2 Projected Plastic Production Through 2050



Source: Ryan 2015

Visible plastic pollution is common and causes many environmental and human health problems, but the damage inflicted on the planet and people by plastic goes far beyond this visible destruction.

Plastic production plants are typically located in fenceline (also known as frontline) communities, which are typically low-income communities and communities of color. Toxic emissions from producing plastic contaminates the air in these neighborhoods, threatening the health of nearby residents. Plastic producers often tout the cheap cost of plastic, but its low costs are enabled precisely because the fossil fuel and petrochemical companies externalize so many of their costs onto frontline communities.

Microplastics may be an even greater threat to human health and the environment. Microplastics are particles of plastic less than 5 millimeters in diameter and are created by the breakup of plastic waste, or they are intentionally added to products. They can also, for example, be generated by tires wearing down, by polymer paints flaking, and from textiles releasing them as fibers when they are laundered in washing machines and dryers (UNEP 2021).

Much smaller particles known as nanoplastics (less than 1 micrometer in diameter) are also emerging in the literature as a problematic byproduct of plastic use and pollution (Gigault et al. 2018). Nanoplastics are the tiny pieces of plastic created from the fragmentation of macro- and microplastics. However, they behave in fundamentally different ways than both of these, and they are regarded as a separate material due to the properties associated with their size, which may have implications for the health of wildlife and humans. These include transport properties, interactions with light, analytical challenges to detect them, bioavailability, potential toxicity, and different leaching behavior for additives (Gigault et al. 2018).

Plastic pollution, particularly microplastics, is found in virtually every part of the planet, from the highest mountains[1] and the snow falling on them (Paolo et al. 2022, Parolini et al. 2021) to the bottom of the oceans (Kane and Fildani 2021, Zhang et al. 2020, Harris et al. 2023). Microplastics are also increasingly found in rainfall (Fan et al., Brahney et al., 2020), lakes (Fuschi et al. 2022, Baldwin et al. 2020), and rivers (Gad et al. 2023, Rowenczyk et al. 2022).

Plastic waste and microplastics are now ubiquitous in the environment, and the health implications for humans and animals are emerging. The first confirmed microplastic-related disease, plasticosis, was recently identified in seabirds that ingest significant quantities of plastic waste. It is defined as the inflammation, fibrosis, and scarring of gut tissue in the presence of plastics (Charlton-Howard et al. 2023). Impacts on ocean life have been broadly studied, and widespread adverse effects caused by plastic waste include entanglement, smothering, rafting of pathogenic organisms, ingestion of fragments and subsequent starvation, and exposure to chemicals associated with plastic waste (UNEP 2021).

HUMAN HEALTH

Concerns about impacts of plastic pollution on human health are also rising as recent studies have now confirmed that microplastics are present in placentas (Ragusa et al. 2021) and meconium samples, indicating exposure of pregnant women and infants (Liu et al. 2022). Plastic particles were once thought to be inert, but laboratory observations on animal exposures are linking microplastic ingestion to various forms of inflammation, immunological response, endocrine disruption, alteration of metabolism, and other disorders (MacLeod et al. 2021).

Tests using human cell lines exposed to plastic additives — such as phthalates, bisphenols, and organotins — suggest adverse effects leading to oxidative stress, cytotoxicity, immunotoxicity, and thyroid hormone disruption, and evidence suggests that microplastic exposure may play a part in human obesity (Kannan, K., and Vimalkumar 2021).

Hazardous chemical additives may be released and leach from plastic during their use, as well as their waste phases, in a multitude of ways (Hahladakis et al. 2018). These chemicals can disrupt endocrine function and increase risk for male reproductive birth defects, infertility, obesity, cardiovascular disease, renal disease, and cancers (Landrigan et al. 2023).

Fetuses and young children are particularly sensitive to chemicals in plastics that are associated with increased risks of prematurity, stillbirth, low birth weight, birth defects of the reproductive organs, neurodevelopmental impairment, impaired lung growth, and childhood cancer. Early exposure may also increase the risk of multiple non-communicable diseases later in life (Landrigan et al. 2023).

In many developing countries (and often elsewhere), plastic waste is dumped and burned, causing toxic emissions and contamination of the soil with persistent organic pollutants (POPs), such as brominated and chlorinated dioxins, polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), and short-chained chlorinated paraffins (SCCPs) (Petrlik et al. 2020, Petrlik et al. 2022). The contamination of the soil leads to contamination of the food chain with POPs, as indicated by the analysis of chicken eggs taken from impacted areas. In many cases, the eggs exceed the tolerable intake guidelines for contamination established by the European Union by many times, exposing the local population to consumption of contaminated food (Petrlik et al. 2019).

Other research into human health, plastic, and plastic waste has found that impacts occur throughout the life cycle of plastic. According to Landrigan et al. (2023), both plastic textile workers and plastic recycling workers die of bladder cancer, lung cancer, mesothelioma, and interstitial lung disease at increased rates. Waste pickers are among the most exposed and least protected of all plastic waste workers (Gutberlet and Uddin 2017).

TOXICITY OF PLASTIC WASTE MANAGEMENT AND RECYCLING

In 2016, the U.S. created more plastic waste than any country in the world, generating 46.2 million tons (Law et al. 2020). When U.S. plastic waste exports to countries that had inadequate waste management (0.16 million to 1.09 million tons) and illegal dumping in the U.S. (0.15 million to 0.45 million tons) were taken into account, the amount of plastic waste generated in the U.S. and entering the coastline was among the highest in the world (Law et al. 2020).

Even where adequate waste management systems exist in developed countries, plastic pollution is common, and landfills are full of plastic waste. Stockpiles of unrecyclable plastic are growing, and many are hazardous fire risks.[2] In the United States, there are estimates of up to 2,400 such fires[3] since 2016, leaving a trail of contamination and toxic smoke in many communities (see Section 3.5).

In countries where waste incinerators burn plastic, millions of tons of ash are generated every year, contaminated with persistent organic pollutants, such as dioxins, dioxin-like PCBs, PFAS (Du et al. 2013, Liu et al. 2021), heavy metals, and microplastics (Yang et al. 2021). The ash is either landfilled, where it leaches into groundwater, or used for building blocks or construction of roads, allowing eventual re-entry of the toxic compounds and microplastics into the environment (Petrlik and Bell 2017).

The most common methods of plastic waste management — landfill, incineration, and recycling — all have toxic impacts associated with them because plastic contains many hazardous additives or polymers — recently estimated at more than 3,200 hazardous chemicals (UNEP 2023). In turn, they contaminate the plastic waste management processes (Takada and Bell 2021) and outputs while possibly exposing waste and recycling workers, as well as nearby communities.

As noted by Landrigan et al. (2023), "plastic recycling workers have increased rates of cardiovascular disease, toxic metal poisoning, neuropathy, and lung cancer. Residents of 'fenceline' communities adjacent to plastic production and waste disposal sites experience increased risks of premature birth, low birth weight, asthma, childhood leukemia, cardiovascular disease, chronic obstructive pulmonary disease, and lung cancer."

This is fundamentally caused by the toxicity of plastics, and the contamination created by their recycling, including:

- The transfer of toxic chemical additives used in virgin plastic manufacture and products into the recycled plastics;
- Adsorption of toxic substances onto plastic waste, such as pesticides and POPs, during use and waste collection, which then transfers toxic chemicals into the recycled products; and
- New toxic chemicals created by the recycling process. (Greenpeace 2023, Rung et al. 2023)

At best, waste management systems shift the plastic pollution problem from one environmental medium to another, buying time before the limits of environmental assimilation are breached. At worst, they amplify and accelerate the toxic and ubiquitous impacts of plastic waste. The toxicity of plastic means little of it is recycled and makes it incompatible with a circular economy, as well as a barrier to both mechanical and chemical recycling.

The incompatibility of many polymers when melted in the recycling process and then pumped through an extruder as well as their contamination with hazardous additives are two key technical reasons why conventional recycling has failed, and why chemical recycling will struggle to be more than a marginal exercise in plastic waste recovery. However, there are many other barriers, both technical and economic, that have prevented 91% of all plastics ever made from being recycled. These are discussed in the following section.

1.1 THE FAILURE OF CONVENTIONAL PLASTIC RECYCLING

1.1.1 WHAT IS CONVENTIONAL RECYCLING AND WHY HAS IT FAILED?

Conventional recycling of plastic, also known as mechanical recycling, uses physical — as opposed to chemical — processes to recover polymers from plastic waste for use in new plastic products. Typically, the waste plastics are shredded and washed before being melted for new plastics production.

The failure of conventional plastic waste recycling is due to a range of technical, and interlinked, economic and policy reasons. But it is also largely due to the limitations imposed by the physical composition of many plastics, such as the polymer itself, different colorants, and their chemical additives. This section examines the technical and economic barriers that have led to the failure of mechanical recycling, the plastics industry's awareness of these barriers, and its misleading campaign to promote a system doomed to failure.

That mechanical recycling has failed is undeniable. The current U.S. plastic recycling rate is only 5% to 6%[4] — well below materials such as paper and metal (see Figure 3). Globally, only 9% of all the more than 9 billion tons of plastic ever produced (up to 2015) had been recycled (Geyer et al. 2017), with the rest landfilled, incinerated, or discarded into the environment, often entering rivers and eventually the ocean. Since then, industry has added more than 2 billion tons to that production total at a rate of around 420 million tons per year. At the current growth rate, annual global plastic production is expected to quadruple to almost 2 billion tons by 2050 (Ryan 2015).

Conventional recycling typically involves collection, grinding, washing, separating, drying, regranulating, and compounding (Delva et al. 2019). Compounding is another term for melt blending of different polymers with additives before extrusion. The recycled materials from these processes can sometimes be used to replace virgin polymers in the production of new plastics, but they rarely meet the same quality. Even with the addition of new chemical additives and stabilizers, the quality of recycled plastic struggles to meet that of virgin plastic. This is mainly due to the polymer chain becoming shorter with each cycle, due to thermal degradation and mechanical shear during melting and extrusion, while mixing of polymer types and additive contamination also reduces quality (Ragaert et al. 2017).

In basic terms, mechanical recycling preserves the molecular structure of polymers and breaks plastic waste into smaller fragments through physical processes, such as shredding and grinding — whereas chemical recycling uses heat and pressure or chemical solvents to either split polymer chains or strip them out from the wider plastic matrix that includes additives, fillers, and sometimes reinforcements (see Technical Addendum, Part 2).

Monomers are single molecules that become polymers when arranged in long-chain sequences — the backbone structure of plastics. But to make a functional plastic product, chemical additives must be used to give the plastic product desirable attributes like color, flame retardance, flexibility, UV stability, and fillers that reduce costs. Plastics are divided into two categories: thermoplastics and thermoset plastics.

For thermoplastics, after mechanical processing and remelting, the recycled material can be formed into functional objects by several processes, including injection or rotational molding, extrusion, and heat pressing (Lettieri and Baeyens 2009). Thermoplastics include polymers such as polypropylene, polystyrene, and polyvinyl chloride and account for 80% of plastic production (Kazemi et al. 2021). Thermoset plastics will not re-melt, are not suitable for mechanical recycling, and include polymers such as epoxy resin, polyester, and polyurethane. They account for around 20% of all plastic production. Chemical recycling has also struggled to successfully treat thermoset plastics like epoxy resins — a process described as “exceedingly challenging” by research scientists (Türel et al. 2023).

Source: UNEP/Adriane Ohanesian

1.1.2 TECHNICAL BARRIERS TO SUCCESSFUL MECHANICAL RECYCLING

Conventional, mechanical recycling of plastic waste has failed to make any serious inroads into plastic pollution because of a combination of interrelated technical and economic factors that limit its growth. One of the most critical issues is the loss of performance properties of recycled polymers via degradation through reprocessing cycles. This compromises the economic viability of the recycled material output when competing with virgin plastic containing new additives and which has optimum performance characteristics. The cost involved in attempting to bring recycled plastic output closer to the quality of virgin plastic is one of the most significant economic issues for the industry and continues to defy resolution.

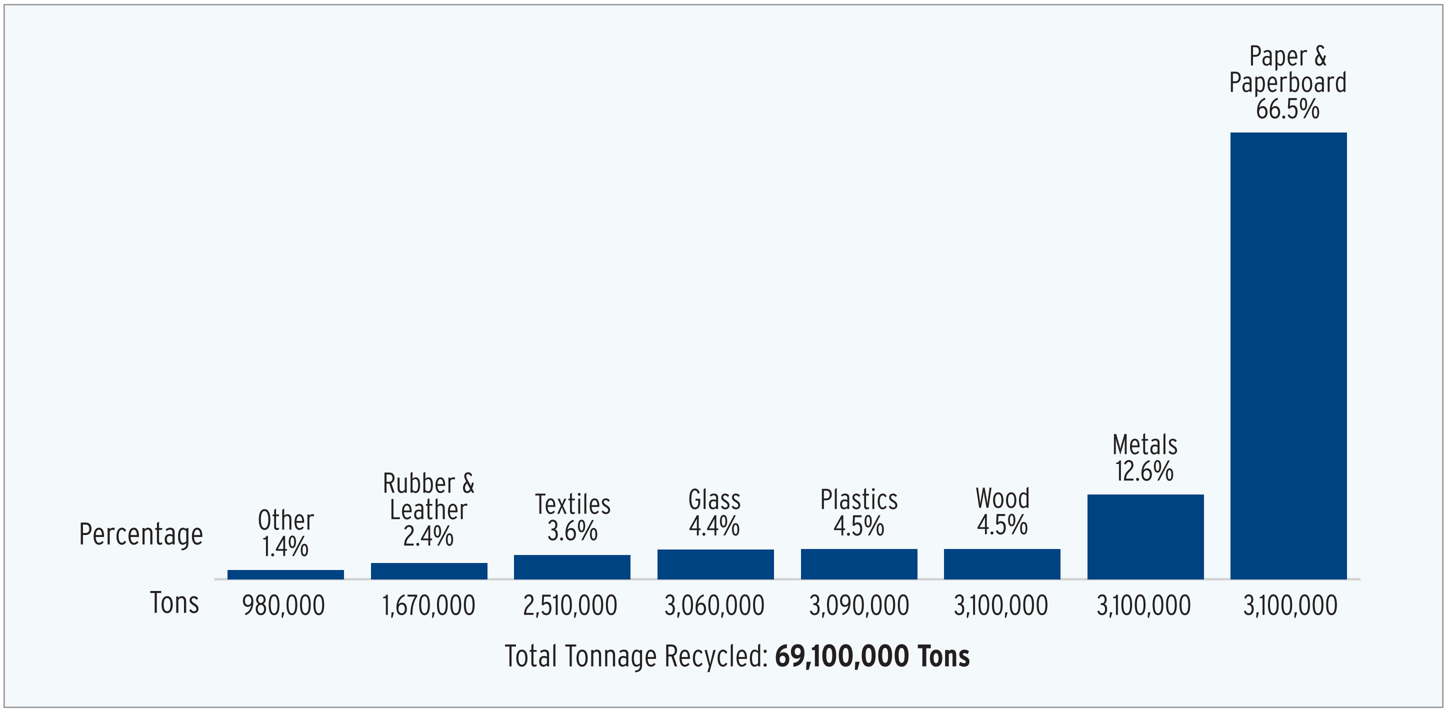
Some polymers, such as PET (polyethylene terephthalate) and HDPE (high-density polyethylene), have been recycled in commercial volumes, but the recycling processes are subject to similar limitations for other polymers caused by contamination and additives. This means they are subject to degradation and quality loss with each pass through the recycling system until they can no longer be recycled successfully.

Technical limitations include manufacturers designing plastics to be reliant on chemical additives that inhibit recycling and contaminate recycled material (DiGangi and Strakova 2017, Milios et al. 2018); immiscibility, or failure to combine, with other polymers in the recycling process (Ragaert et al. 2017); contamination in the consumer/post-consumer phase (Hahladakis and Iacovidou 2018); and property degradation through the recycling process (Eriksen et al. 2019, Schyns and Shaver 2021, Manias and Utracki 2014), leading to lower-value uses and eventually the need for disposal (Hahladakis and Iacovidou 2019). The increasing use of multilayer packaging with foils, plastics, and paper combined into a single laminate further complicates or precludes recycling, as the complexity of the mix often makes it too difficult to process (Ignatyev et al. 2014).

DEGRADATION

Degradation of virgin plastic begins as it passes through its use and waste phase via photodegradation, heat, oxygen, moisture, and pollution exposure (Hahladakis et al. 2018) and as it passes through the mechanical recycling process. It degrades further as it is melted and during the extrusion phase (da Costa et al. 2007, Schweighuber et al. 2021).

Figure 3 U.S. Materials Recycled by Waste Type



Source: 2018 U.S. EPA data

Thermal degradation of polymers in the recycling process due to heat and mechanical shear is a significant problem affecting the quality of the output (Chapell et al. 2022). This form of degradation often consigns the material to downcycling into low-value products, such as park benches, flowerpots, and plastic bags. This degradation increases with each pass through the extruder and after a brief detour as a low-value product, the plastic becomes unrecyclable waste.

Thermal mechanical degradation is caused by the heating and mechanical shearing of the polymer during the melt processing. This can lead to changes in the polymer chain backbone, such as chain scission (breaking and shortening of the polymer chains) and subsequent reductions in molecular weight and functional properties (Ragaert et al. 2017).

Alternatively, it can lead to chain branching of the polymer backbone (also known as "crosslinking"), increases in the molecular weight of the polymer and the release of some volatile components (Beyler and Hirschler 2002). Chain branching causes the molecular polymer backbones to join with each other, changing their physical properties and making them harder to recycle. These changes can adversely affect the deformation and viscosity behavior of polymers in the recycling process, particularly in the extrusion phase.

The "downcycling" of high-performance plastics to lower-value products is sometimes described as "cascading," whereby a plastic product may be recycled from a high-quality but short-lived plastic product into a more durable but lower-quality product, extending the time the plastic is kept out of final waste disposal (Crippa et al. 2019). Yet ultimately, even when producing longer-lived recycled plastic products, the detour is simply extended, and the plastic is finally so degraded it can no longer be recycled.

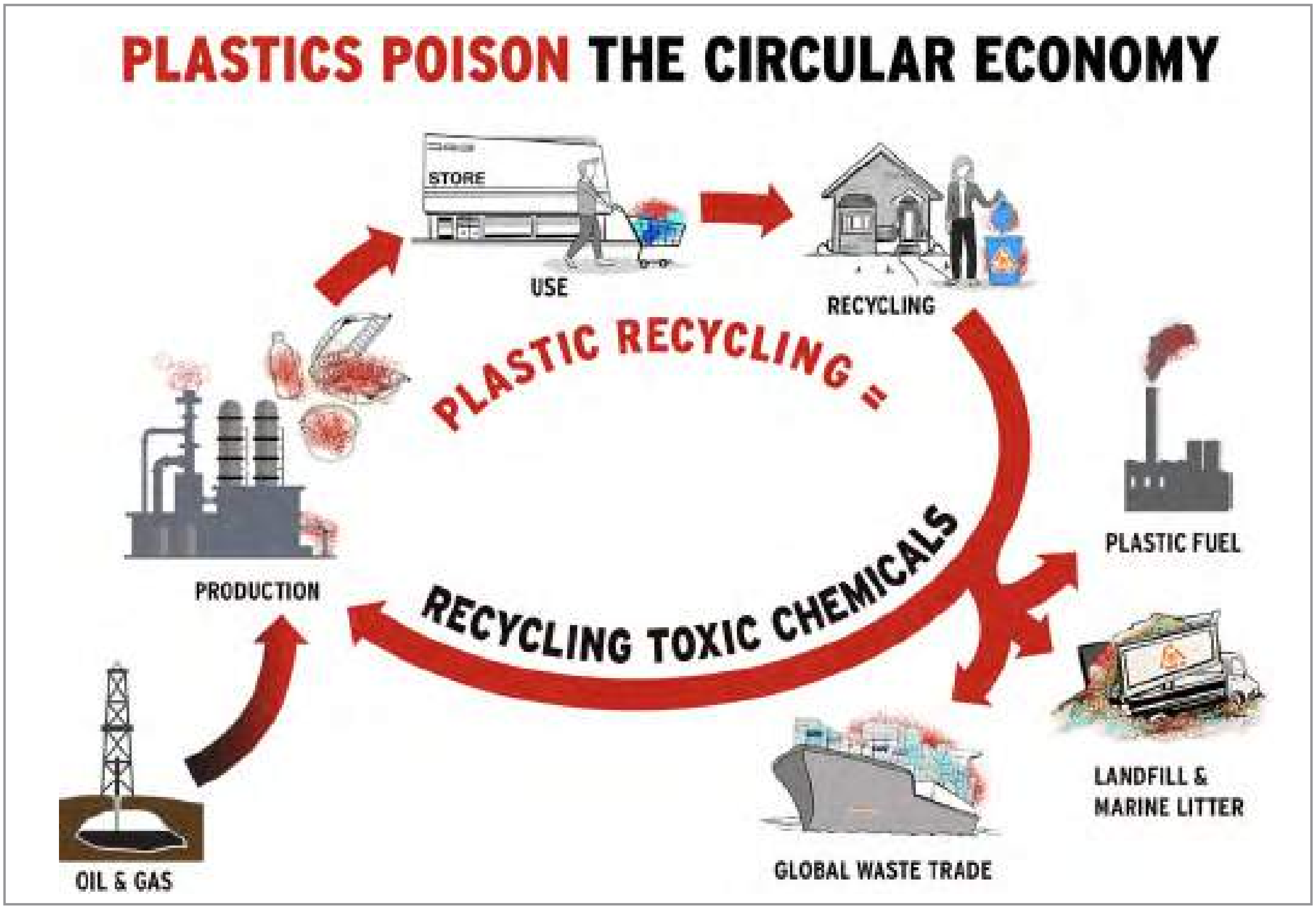
ADDITIVES

Additives are chemicals that plastic producers add during plastic compounding, whereby the polymers and additives are blended in a molten state to create functional properties during production and/or for the final product (Hansen et al. 2013). They are broadly divided into the categories of functional additives, colorants, fillers, and reinforcements (UNEP 2023). Some are used as processing aids that make extrusions run faster or thinner or make molding times shorter. According to UNEP (2023), functional additives "influence specific properties, such as stability against UV light and heat, resistance to microbes, flame retardancy, durability, softness, hardness, aesthetics, etc.," whereas "reinforcements are used to enhance mechanical properties, such as the strength and elasticity of plastics."

Many additives have hazardous properties and can adversely impact human health when released from plastic through processes such as migration, leaching, emissions, and degradation of the plastic to which they are added (Hahladakis et al. 2018). It has been estimated there are around 13,000 chemicals used in plastic production. There is no hazard data for 6,000 of them, meaning many of these could be chemicals of potential concern. Of those with data, 3,200 have been identified as substances of potential concern based on their hazardous properties, including carcinogenicity, mutagenicity, reproductive toxicity, endocrine disruption, and ecotoxicity to aquatic organisms (UNEP 2023).

Several chemical additives for polymers have been assessed as so hazardous and persistent that they have been listed in the Stockholm Convention on Persistent Organic Pollutants (POPs) annexes.[5] This either severely restricts or prohibits their use and manufacture at a global level. POPs that have been additives in plastic before their listing include plasticizer group's short-chain chlorinated paraffins (SCCPs); flame-retardants, such as polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCD); and phenolic benzotriazole UV 328, a light stabilizer. Some countries are not parties to the convention and continue to use and manufacture these chemicals in plastics. Currently, the United States is not a ratified party to either the Stockholm Convention on POPs or the Basel Convention on hazardous waste.

Enormous stockpiles of plastic waste, especially from electronic equipment, still contain these chemicals. Other additive groups of high concern include PFAS, phthalates, flame retardants, bisphenols, polycyclic aromatic hydrocarbons, biocides, UV stabilizers, metals and metalloids, and non-intentionally added substances (NIAS), which are described below (UNEP 2023). Degraded additives can also remain in the recycled polymer resin and may be released during secondary use or cause the recycled material to be rejected by plastic producers, as they exceed allowable contamination levels.



Both intentionally added chemicals and their breakdown products can reduce the quality and marketability of recycled plastics in a number of ways. Used to promote the breakup of plastic in the environment, pro-oxidant additives can promote oxidation in the recycling process, breaking down the polymer matrix, or resin, and reducing the quality of the recycled material (European Commission 2016). These additives include polymer categories such as “oxo-degradable” plastics and “oxo-biodegradable” plastics (Sciscione et al. 2023). Mixing of different additives and pigments may result in darker coloring for the recycled resin, reducing its aesthetic appeal (Schiller 2022).

Non-intentionally added substances (NIAS) are chemical compounds that have not been intentionally added to polymers during their production. They include impurities in the substances that were used to make the polymer, reaction intermediaries, and decomposition or reaction products formed during polymer production (European Commission 2011). These can be particularly problematic in products with high human exposure potential, such as toys, cooking implements (Budin et al. 2020, Brosche et al. 2021), and food packaging (Kato and Conte-Junior 2021).

As an example, brominated flame retardants may convert into highly toxic brominated dioxins and furans at specific recycling temperatures and may be transferred to the recycled material, exposing end users of plastic products (Budin et al. 2020). Brominated dioxins and furans have similar toxicity to chlorinated dioxins and furans — the most toxic chemicals ever studied. These cancer-causing chemicals are highly toxic at extremely low levels and are measured in parts per billion. Studies have found they can be carried through the plastic recycling process into new products like plastic toys. Children are particularly vulnerable to the developmental impacts of these toxic chemicals.

MIXTURES OF ADDITIVES

Mixtures of additives can reduce the compatibility of different waste streams, even with the same polymer type (Wang and Praetorius 2022). In many cases, the same polymer type, such as HDPE, will have a very different range of chemical additives applied during its initial manufacture, depending on its intended use. An outdoor application may require more UV stabilizer additives, whereas an underground pipe system may require more additives that resist moisture degradation.

Even with those plastics considered most suited to mechanical recycling, such as PET, additives can reduce the compatibility of identical resin types in the recycling process. For this reason, PET bottles and PET trays cannot be mixed in the recycling process — their different additive composition means the trays tend to produce smaller scraps, more heterogeneous parts, and more dust (Wang and Praetorius 2022).

This inability to “mix” certain polymers in the recycling process is referred to as immiscibility. This is when two substances are not capable of combining to form a homogeneous mixture. In the case of plastic waste, this refers to the incompatibility of certain polymers with others in the melt and extrusion process. The immiscibility can produce fracture points in the extruded material, significantly reducing its quality (Schyns and Shaver 2020). Immiscibility of polymers is another major technical barrier to mechanical recycling of mixed plastic waste.

Attempts have been made to improve miscibility, or successful mixing of polymers, by adding chemical compatibilizers (Koning et al. 1998, Maris et al. 2018) which can improve interfacial tension between polymer mixes and help them to blend better (Ragaert et al. 2017). While they have been found to improve the recycling qualities of many immiscible polymers, the problems of immiscibility have not been resolved. The increasing use of “bioplastics” has also raised concerns in the recycling industry about increased contamination rates and immiscibility in the waste stream polymers. The entry of polylactic acid (PLA) based biopolymers in the waste stream has led to problems with PET recycling due to the severe incompatibility of PLA with PET (Alaerts et al. 2018).

1.1.3 ECONOMIC AND POLICY IMPEDIMENTS TO CONVENTIONAL RECYCLING

Economic and policy barriers to the success of mechanically recycled plastic are particularly evident in the difficulty in competing in the market with virgin plastic prices, especially when the price of oil is low (Selmi et al. 2022).

Source: Unsplash

These factors have been intensified by the tendency of many wealthier countries to export plastic waste to less developed countries, ostensibly for recycling but often ending in poor management and more plastic pollution (Petrlik et al. 2019). The plastic waste export model of wealthy countries, combined with their poor domestic commercial opportunities for plastic recycling, has historically also resulted in low levels of development of mechanical recycling infrastructure.[6] In the U.S., a heavy reliance on waste plastic exports left the domestic recycling market with outdated and inadequate infrastructure, exacerbated by China's restrictions on plastic waste imports. As a result, the U.S. Environmental Protection Agency (EPA) notes that[7] "America's recycling infrastructure has not kept pace with today's waste stream."

Researchers such as Heiges and O'Neill (2022) have noted that the U.S. export-reliant recycling system failed to introduce sound, methodical recycling practices and technologies, and therefore "the institutional complexity of this system meant that in recent decades it became subject to neglect and stasis. Little new recycling infrastructure had been built since the early 2000s, and that which existed received little maintenance."

Even in European countries that have a relatively high level of incentivization for plastic recycling, systemic economic challenges remain for the mechanical recycling sector, including high operational costs (Lin et al. 2023). For recyclers who want to access plastic waste for recycling, there is an insufficient volume of low-cost, high-quality recyclable plastic. Collection and processing costs are high, and sorting operations often have low capacity and low efficiency (Milios et al. 2018).

Mechanical recycling, with its high operational and sourcing costs, also faces competition from relatively inexpensive landfill and incineration disposal operations. More plastic waste is also being directed to refuse-derived fuels[8] (RDF) and similar "fuel" products destined for burning in cement kilns and waste-to-energy incinerators. While the quality of waste plastics destined for fuel is not always high, some regions — especially the EU, Japan, and Scandinavian countries — have developed excess incineration capacity and have an elevated demand for high-calorific-value wastes, such as plastics, to ensure they can maintain the operation of the incineration plants.

This demand has led to the repression of recycling rates in some regions, such as Southeast Asia and Europe, as they compete with mechanical recycling for waste to burn (Yamamoto and Kinnaman 2022). The construction of new incinerators exacerbates competition with mechanical recyclers and leads to long-term infrastructure lock-in, as has been the case in Sweden, where incinerators must maintain a waste supply to burn for up to 30 years of operational life (Corvellec et al 2013).

COMPETITION WITH VIRGIN POLYMERS

Competition with virgin polymers and the sheer volume and scale of virgin polymer production are major economic barriers to the profitable recycling of plastic waste. High costs associated with each stage of mechanical recycling limit the ability of plastic recyclers to compete with the low price of virgin plastics, which benefit from economies of scale generated by the petrochemical industry and its refineries. When the oil price is relatively high, the market for some recycled plastics is viable, but when the crude oil price drops, as happened in the recent pandemic, the recycled plastic market slumps both in price for output and demand.[9]

As Selmi et al. (2022) noted, "Plummeting oil prices resulted in a sharp decline in virgin plastic prices (causing positive dependence), while it has shrunk the plastics-recycling industry (leading to negative dependence). Moreover, we find that the COVID-19-induced oil price crash generated a marked increase in the systematic risk for the recycled plastics industry."

The same dynamic occurred during previous significant or sustained oil price drops, with reports[10] of the U.S. plastic recycling market hit hard by dropping oil prices in 2016. This resulted in some core recycled product dropping by 50% in value within a year, recycling plant closures, and the loss of jobs. Profitability of the plants is strongly linked to the price of oil; the profitability limit is currently between $50 and $60 per barrel (Maisels et al. 2022).

However, more recently in the U.S. context, virgin plastic production has become less dependent on U.S. crude oil-derived naphtha (which underpins plastic production in Europe and Asia[11]) and is driven by ethane production that has resulted from the proliferation of gas fracking operations. Ethane is cheaper and more efficient chemically for the production of plastics than naphtha (National Academies Press 2016) and is used for the majority[12] of plastic production in the United States.

Domestically produced fracked gas is abundant and relatively inexpensive, and the United States has become the world's top producer and exporter of ethane, significantly increasing cheap virgin plastic production (Sicotte, 2020). This ongoing cheap and abundant gas supply in the United States means that conventional recycling will continue to struggle for viability when competing with virgin plastic in the U.S. domestic market.

COST

The cost of collecting, sorting, and pretreatment of plastic waste is a major challenge for most mechanical plastic recycling operators (Schyns and Shaver 2021) when competing with virgin plastic prices. Collection and transport of plastic waste can be costly, especially for materials like polystyrene waste, which has a high volume-to-weight ratio and requires size reduction before transport (Seo and Hwang 2006).

As most curbside recycling collection, if available, results in a mix of plastics being delivered to recyclers, sorting by polymer is important to maintain the quality of the recycled material, which can be significantly degraded and/or of very low value if immiscible plastics are combined in the extrusion process. Sorting and pretreatment are labor-, energy-, and resource-intensive, requiring significant amounts of water for multiple washing/cleaning stages and flake flotation separation processes (Wang et al. 2015). The processed water may also become a significant source of microplastic contamination that requires further expensive filtration before release (Brown et al. 2023).

Sorting and pretreatment include:

- Sorting and separation by shape, density, size, color, or chemical composition;
- Baling, especially if sorting occurs at a separate location from subsequent processing steps;
- Washing for removal of organic and other contaminants, labels, etc.;
- Grinding into flakes; and
- Compounding and pelletizing, an optional operation whose output can be easier for converters/extruders to use than flakes (Ragaert et al. 2017).

Many recyclers use a combination of manual and automated processes for sorting and separation. Manual separation can be relatively expensive in countries with high labor costs. The alternative is automated electronic sorting equipment, such as near infrared (NIR) optical sorting technologies, which can be used to determine polymer type and separate clear and colored plastics, but cannot detect black plastics (Maris et al. 2012).

Many other electronic methods of sorting have been developed, including X-ray fluorescence-based sorters to separate PVC from PET and to separate PVC and plastics containing brominated flame retardants (BFRs) (Vrancken et al 2017) and VIS (color analysis by camera or spectrocolorimeter). However, only NIR, XRF, and VIS are used at scale in materials recovery facilities (MRFs), particularly in the United States.

Despite the use of automated sorting technology in MRFs to segregate polyethylene terephthalate (PET) No. 1; high-density polyethylene (HDPE) No. 2; polyvinyl chloride (PVC) No. 3; low-density polyethylene (LDPE) No. 4; polypropylene (PP) No. 5; polystyrene (PS) No. 6; and No. 7, "other,"(1) most have little to no market value except PET and HDPE (Lubongo and Alexandridis 2022). Ultimately, the processing costs for poorly sorted or contaminated mixed plastic is much higher and can outweigh any potential profit from recycled materials, leading to facility operators avoiding processing of low-value plastics.

Contamination of waste plastic — whether from additives, organic materials, other polymers, or NIAS — is one of the key factors affecting the economic viability of recyclers. This is why they seek the cleanest and purest form of polymers, which are post-industrial (PI) plastic scrap. This type of clean scrap can include runners from injection molding, waste generated when production runs are changed, and various scraps when products are trimmed or cut from larger pieces (Ragaert et al. 2017).

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(1) Numbers after polymers indicate resin codes.

Ignatyev et al. (2014) conclude it is advantageous for recyclers to use PI plastic scrap, as they are cleaner than post-consumer waste and their polymer composition can be determined. This translates to lower cost via less pretreatment and higher profit from higher-quality recycled materials. If chemical recycling continues to expand through misguided investment, the demand for clean PI plastic waste will increase, as most plastic-to-plastic chemical recycling also requires high-quality, low-contamination inputs (see Technical Addendum, Section 2.4). This will create yet further obstacles to mechanical recycling, as chemical recycling will directly compete for the best-quality inputs.

COMPETITION FROM INCINERATION AND CEMENT KILNS

Competition from incineration and cement kilns burning plastic waste as waste-derived fuels (also known as refuse-derived fuels, or RDF) or municipal solid waste is also increasing globally, particularly if policy settings claim such fuel is "renewable" or attracts some form of carbon credits or landfill diversion benefits. The cement industry regards the use of "alternative fuels" and "waste co-processing" as a key pillar in its claimed decarbonizing strategies and is expanding their use globally. Holcim Group, the biggest cement producer in the world, plans to double[13] its waste-derived fuel use by 2030 with a target of 50%[14] substitution for traditional fossil fuels across its global plants. Meanwhile, the United States still has 75 municipal waste incinerators that continue to burn plastic waste.

The high calorific value of plastic makes it a target for such fuel uses and increases competition for plastic waste that could otherwise supply mechanical recyclers. Landfill also remains a relatively inexpensive disposal option for plastic waste, particularly if the generation source is distant from recycling operations and transport cost becomes a factor. Higher-quality plastics that recyclers rely on for better-quality output are still being buried in large quantities.

POOR POLICY SUPPORT

Poor policies around plastic recycling have also significantly contributed to the failure of conventional plastic waste recycling in the United States. While Germany first introduced packaging extended producer responsibility (EPR) schemes in the early 1990s, and 26 of the 28 EU member states currently have EPR schemes in place for packaging waste, only four U.S. states have passed EPR packaging laws, which are currently in the rulemaking stage. Other states have introduced or enacted various packaging recycling or recycled content bills, with varying objectives. Nonprofit environmental organizations have also proposed progressive EPR policies that would significantly improve plastic packaging recycling rates.

Based on the polluter-pays principle, EPR attempts to make producers of plastic waste financially and operationally responsible for managing their products at end of life. The benefits of the well-established EU EPR scheme for plastic waste are noted by Watkins et al. (2017):

> *"[EPR laws] have helped to create more efficient separate collection schemes, reduce disposal, and increase recycling. In many cases they reduce the burden on public budgets for municipal waste management and increase the cost efficiency of collection and recycling processes. They also contribute to the generation of separated, high-quality secondary raw materials, supporting the development of markets and contributing to resource security."*

Perhaps not surprisingly, the plastics industry associations that first hyped conventional recycling and are now hyping chemical recycling have also sought to avoid paying directly for recycling via EPR programs and instead want to subsidize these operations with public funds. While consumer brand companies may have to contribute some funds toward EPR schemes, plastic producers and the petrochemical industry avoid financial involvement. They quickly found out that funding conventional recycling of plastic did not add up economically, and they bankroll it only as a public relations exercise.

Laura Sullivan reported in a 2020 NPR exposé that "NPR tracked down almost a dozen projects the industry publicized starting in 1989. All of them shuttered or failed by the mid-1990s. Mobil's Massachusetts recycling facility lasted three years, for example. Amoco's project to recycle plastic in New York schools lasted two. Dow and Huntsman's highly publicized plan to recycle plastic in national parks made it to seven out of 419 parks before the companies cut funding."[15]

There are similarities in chemical recycling's trajectory. In 2020, a Greenpeace[16] investigation found that for over 50 U.S. chemical recycling projects promoted on the American Chemistry Council (ACC) website, at least $506 million of public funds was committed to the projects and that "almost 90% of the taxpayer funding identified for projects on the ACC list went to waste- and plastic-to-fuel projects, meaning public money is being used to produce fuels, waxes, and chemicals for the petrochemical industry."

Notably, the ACC has reduced the number of chemical recycling projects promoted on its website from 62 in September 2020[17] to "40-plus" in July 2023. This raises questions about the fate of investments in the companies no longer highlighted on the website.

Additional policies, such as recycled content regulations and government procurement policies mandating recycled content in their departmental purchasing arrangements, have also lagged in the United States compared to European initiatives. While all of the EU has adopted recycled content laws under the 2019 Single-Use Plastics Directive,[18] which requires 25% post-consumer recycled content rates for PET beverage bottles by 2025 and expands to 30% for all plastic beverage bottles by 2030, the United States has similar laws in only three states.[19]

The U.S. is also lagging when it comes to laws known as bottle bills, which require refundable deposits on beverage containers. These have effectively prevented pollution and generated cleaner, source-separated bottles with recycling rates that are two to three times[20] higher than those for non-deposit plastic bottles collected by curbside recycling programs. However, only 10 states have passed these mandatory container deposit laws and no national bottle bill has been adopted.[21]

1.2 CONVENTIONAL PLASTIC RECYCLING AS A PUBLIC RELATIONS DEFENSE AGAINST REGULATION

The concept of plastic recycling began to emerge in the 1980s as the first indications of plastic pollution began to become self-evident — especially in the U.S., where public pressure on the issue was growing. Suffolk County, Long Island, in New York state had already voted to ban certain plastic types used in packaging; and the city council of Saint Paul, Minnesota, voted to outlaw polystyrene plastics.[22] This was overturned when

Source: Flickr/Ted McGrath

a plastics industry body called the Council for Solid Waste Solutions agreed to set up a recycling pilot plant, which it wanted to be funded by the public.[23] The council[24] comprised the main petrochemical corporations behind plastic production at the time, including Amoco Chemical Co., Chevron Chemical Co., the Dow Chemical Co., Exxon Chemical Co., DuPont, Occidental Chemical Corp., and Mobil Chemical Co.

The pivot from plastic-reduction policies coincides with the 1988 launch of the triangular symbol with a polymer-specific number (resin code) on the bottom or center of most plastic products (see Figure 4). The Society of the Plastics Industry (now the Plastics Industry Association) promoted this “chasing arrows” symbol to assist recyclers in distinguishing different kinds of plastic waste.

Oil and plastics executives lobbied in nearly 40 states to mandate the application of the chasing arrows symbol with resin codes onto plastic products, and many agreed.[25] The resin code number and symbol was misleadingly similar to the original recycling symbol[26] created in 1970 as part of a nationwide design contest by Gary Anderson, then a student at the University of Southern California. Though unrelated, the plastic resin code was positioned at the center of a symbol that closely resembled the 1970 design, implying that the plastic product on which it appeared was indeed recyclable. The reality was quite different.

Virtually all plastic products would now be labeled with the resin code number. However, aside from Nos. 1 and 2 (PET and HDPE), most of the polymers were impossible, impractical, or unviable to recycle. In general terms, the higher the resin code, the less likely it is to be commercially recyclable. For example, No. 7 includes styrene acrylonitrile (SAN), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), and nylon, which are rarely recycled using mechanical processes (Takada and Bell 2021) (see Figure 4).

According to a PBS Frontline/NPR investigative report,[27] the use of plastic recycling symbols in the United States very quickly led to problems for recycling operations that had previously only accepted relatively easily recycled plastic packaging like soda bottles and milk jugs. Shortly after the triangular symbols with the resin codes were introduced, recyclers were inundated with plastic wastes from consumers that were labeled with the symbols but had no value and could not be recycled.

Recycling operators fought against the introduction of the symbol, claiming it had cost them credibility with consumers and caused operational problems. They were not successful but top officials at SPI were aware of the issue, with an internal 1993 report telling them “the code is being misused,” “companies are using it as

Figure 4 Plastic Resin Identification Codes

1	2	3	4	5	6	7
PET **Polyethylene Terephthalate**	**HDPE** **High-Density Polyethylene**	**PVC** **Polyvinyl Chloride**	**LDPE** **Low-Density Polyethylene**	**PP** **Polypropylene**	**PS** **Polystyrene**	**Other**
Common Products: • water bottles • soda bottles • peanut butter jars	Common Products: • milk jugs • 5 gal buckets • shampoo bottles • laundry detergent containers	Common Products: • vinyl • tubing/pipe • siding • auto product bottles	Common Products: • laundry baskets • bread bags • squeeze bottles • plastic film	Common Products: • yogurt containers • amber-colored pill bottles • coffee cup lids • straws • kitty litter buckets	Common Products: • styrofoam cups • solo cups • egg cartons • to-go containers	Common Products: • toys • sippy cups • cd/dvds • lenses

Source: Department of Sanitation, City of Conway, Arkansas a ‘green’ marketing tool,” and that it was creating unrealistic expectations about how much plastic could be recycled.[28]

In April 2023 in written comments to the U.S. Federal Trade Commission, the U.S. Environmental Protection Agency[29] recommended that the iconic chasing arrows symbol no longer be used for most plastics.

The objective of the public relations campaign around plastic recycling was not to create a closed loop for plastic production. Instead, it was designed to distract the attention of the public and lawmakers from rising plastic pollution with the promise that plastic waste could mostly be recycled, negating the need for legislation to restrict plastic production or use.

However, within the plastics industry, recycling was not considered viable, and research suggests SPI did not believe that recycling could be economically viable in the future. Geyer (2017) estimated that no plastic waste was recycled until 1988, when only 0.6% of global production was recycled. In 1990, only 2% of U.S. plastic waste was recycled. This outcome reflected internal SPI documents at the time that noted[30] “there is serious doubt that it can ever be made viable on an economic basis.”

So what did the Society of the Plastics Industry know that it was not sharing with legislators and the general public?

It understood that most plastics were not designed to be recycled, and that the collection, separation, pretreatment, and processing costs of recycling are expensive and would heavily disadvantage recycled material in any economic comparison with virgin plastic. Potential buyers of recycled plastic would also understand that the material was generally inferior to virgin plastic in terms of performance. This meant that recycled plastic would be unlikely to be anything other than a marginal economic activity but would have enormous potential as a public relations exercise to prevent legislative restrictions against plastic production and use.

It should also be recognized that massive plastic production growth is matched by unprecedented consumption of plastic products, many of them single-use and of poor quality. While rampant consumption has certainly created strong demand for plastic products, the ubiquitous and inexpensive nature of plastic has driven materials that are reusable, recyclable, sustainable, and less toxic — such as wood, paper, metal, and glass — off the product shelves. This substitution process has limited the options for consumers to buy more sustainable products, whose production has waned under the onslaught of cheap plastic substitutes. Keenly aware of the failure of conventional recycling, plastic producers are anxious to maintain the status quo of plastic consumerism via the myth of chemical recycling as the “solution” to the plastic waste crisis.

When considered collectively, the economic and technical limitations of conventional recycling of plastic waste have not changed since the first cynical attempts by the plastics industry to use recycling as a distraction from production and use prohibitions in the 1980s. The problems of polymer contamination, immiscibility, and degradation have not been solved. The tsunami of virgin polymer production continues to swamp recycled material at such a scale that the latter cannot compete on price or quality. And much needed policies to boost the sector, such as designing polymers for mechanical recycling, prohibiting toxic plastics, curtailing virgin production, and making polluters responsible for waste, remain largely dormant. The inevitable failure of conventional plastic recycling, foreseen 50 years ago by plastics industry executives, has come to pass.

1.3 HOW IS CHEMICAL RECYCLING DIFFERENT THAN CONVENTIONAL RECYCLING?

While there is no legal definition of chemical recycling, it is broadly accepted as an umbrella term for a range of technologies that use heat or chemicals (or both) to break down the polymer chains in plastic waste to create “output.” This output can be either a mix of hydrocarbons, monomers or, in a few cases, polymers. Aside from polymers, this material cannot be directly used to make new plastics, but must undergo expensive procedures to be stripped of contaminants, further refined, dosed with chemical additives, and/or blended with virgin polymers before it might possibly be converted to new plastics.

Industry claims the objective of chemical recycling is to produce "feedstock" chemicals for making new plastics. However, the high energy use of the technologies and cleanup costs for the output often result in the hydrocarbon output being burned as fuel, either to power the on-site facility itself or be sold to third parties as fuel oils.

Conventional, mechanical recycling does not break down the polymer chains in plastic waste. While the shredding, flaking, and extrusion of plastic waste does degrade polymer characteristics on each pass through the recycling process, they do not break down polymers at a molecular level. In contrast with chemical recycling, conventional recyclers try to segregate and keep individual polymer types intact and avoid their degradation as much as possible, since degradation lowers the quality and value of their recycled output.

The use of the term "advanced recycling" has no technical basis and is a public relations and marketing term for chemical recycling intended to make it sound as if there has been a technological breakthrough above and beyond conventional recycling. This is misleading, as the technologies under the chemical recycling umbrella have been used for plastic recycling for decades without commercial success.

The majority of proposals in the United States for chemical recycling are based on pyrolysis technologies. The technological cousin of pyrolysis, known as gasification, is occasionally proposed, but no facilities are operating that exclusively process plastic waste. One facility in Japan is reported to gasify plastic waste mixed with coal and sewage sludge (Quicker et al. 2022), and a U.S. facility claims to gasify plastic waste with coal (see Eastman section on page 95 of Appendix 1: U.S. Case Studies). Pyrolysis relies on treating plastic waste under heat and pressure to generate hydrocarbon-rich oils, waxes, and gas (or, in the case of gasification, just gas) as potentially useful outputs.

The other category of technologies that falls within chemical recycling is solvent-based methods of breaking down polymers into monomers or other intermediaries (depolymerization) that may be used as plastic production feedstock. This group of solvent-based depolymerization methods are collectively referred to as "solvolysis." These techniques have a range of titles usually associated with the solvent they use. For instance, "glycolysis" uses glycols to achieve molecular degradation of the PET polymer, while "hydrolysis" uses water molecules under varying pH conditions at high temperatures and pressure to produce PET intermediaries. "Methanolysis" uses methanol to treat waste PET at high temperatures and pressure to produce dimethyl terephthalate and ethylene glycol, which can then be used for PET manufacture.

Source: UNEP/Ollivier Girard

However, some companies attempting chemical recycling come up with novel names for established processes for publicity purposes. Eastman, which refers to itself as a “global specialty materials company,” makes many plastic products for consumers and is developing its own chemical recycling facility in Texas (see Eastman section on page 95 of Appendix 1: U.S. Case Studies) for polyester and PET waste.[31] The company refers to its process as “molecular recycling.”[32] No other companies or research literature appear to use this term for what is simply a variation of the methanolysis method of depolymerization.

Solvolysis should not be confused with a process known as “solvent-based purification” which is neither conventional nor chemical recycling. This is a unique process that uses solvent to separate target polymers from all the contaminants in plastic waste, yielding a clean, reusable polymer. The process has limited application and is typically used only with polystyrene. The main difference between solvolysis and solvent-based purification is that the latter separates polymers from contaminants but does not break down the polymers, as occurs in solvolysis.

Each of these chemical recycling technology types, their applications, limitations, and pseudonyms are described in detail in Part 1 of the Technical Addendum of this report. Part 2 of the Technical Addendum details the long and troubled history of these technologies, especially pyrolysis and gasification, and the myths around their ability to treat post-consumer plastics waste. Combined, these sections debunk industry claims that chemical recycling can resolve the plastic pollution crisis through end-of-pipe treatment methods.

Some of these technology types, especially pyrolysis, are being hyped by the plastics industry as a key investment opportunity to address mounting plastic waste stockpiles in the United States. Plastic and petrochemical industry associations are lobbying policymakers to make regulation of chemical recycling weaker while pushing for more public investment in their establishment (see Section 3.1). This report provides the justification to place a moratorium on these activities, to stop and reconsider whether scarce public resources should really be directed to a sector with a weak track record, and to raise awareness about the environmental and human health risks associated with chemical recycling.

Table 1 Chemical Recycling Technology Types

NAME	TECHNOLOGY	OUTPUT
Pyrolysis	Using temperatures of 250° to 700°C in a closed oxygen-free reactor under pressure to break down polymers	Mixed hydrocarbons in the form of gas, oils, waxes, and char (solid charcoal-like waste)
Catalytic Pyrolysis	A subset of pyrolysis with the addition of a catalyst that can reduce process temperatures and increase yields of the useful output	Mixed hydrocarbons in the form of gas, oils, waxes, and char (solid charcoal-like waste)
Gasification	Similar to pyrolysis but operates at temperatures up to 1,500°C with a low level of oxygen to break down polymers into gas	The higher temperature results in production of gas known as “syngas” mostly comprising CO and H2 (but not oils, waxes, etc.)
Solvolysis	Dissolving polymers using solvents at high temperatures and pressure to break them into monomers. Different solvents give the process different names, such as glycolysis, methanolysis, hydrolysis, and aminolysis (see Technical Addendum Part 1)	Monomers, oligomers, and intermediaries
Solvent-Based Purification	Polymers are dissolved in a solvent, contaminants such as additives are filtered out, then target polymers are precipitated out and can be used for plastic production	Pure polymers

The following chapter introduces the 11 chemical recycling plants constructed in the United States as of September 2023, and Appendix 1 presents an in-depth analysis of these plants, covering the technologies these facilities use, their funding mechanisms, and their outputs, both as desired product and hazardous waste. Of particular interest is their apparent lack of production output, despite heavy promotion and public and private funding. This section also reveals the siting of many of these facilities in environmental justice communities that already bear the burden of high pollution levels from refineries and other polluting industries.

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CHAPTER 2

CONSTRUCTED CHEMICAL RECYCLING FACILITIES IN THE UNITED STATES: FAILURE IS THE ONLY CONSTANT

Source: VM, iStockphoto

2.1. INTRODUCTION

As of September 2023, 11 chemical recycling facilities have been constructed in the United States. A detailed case study of each one can be found in Appendix 1 starting on page 80 of this report. This chapter summarizes the findings from the case studies.

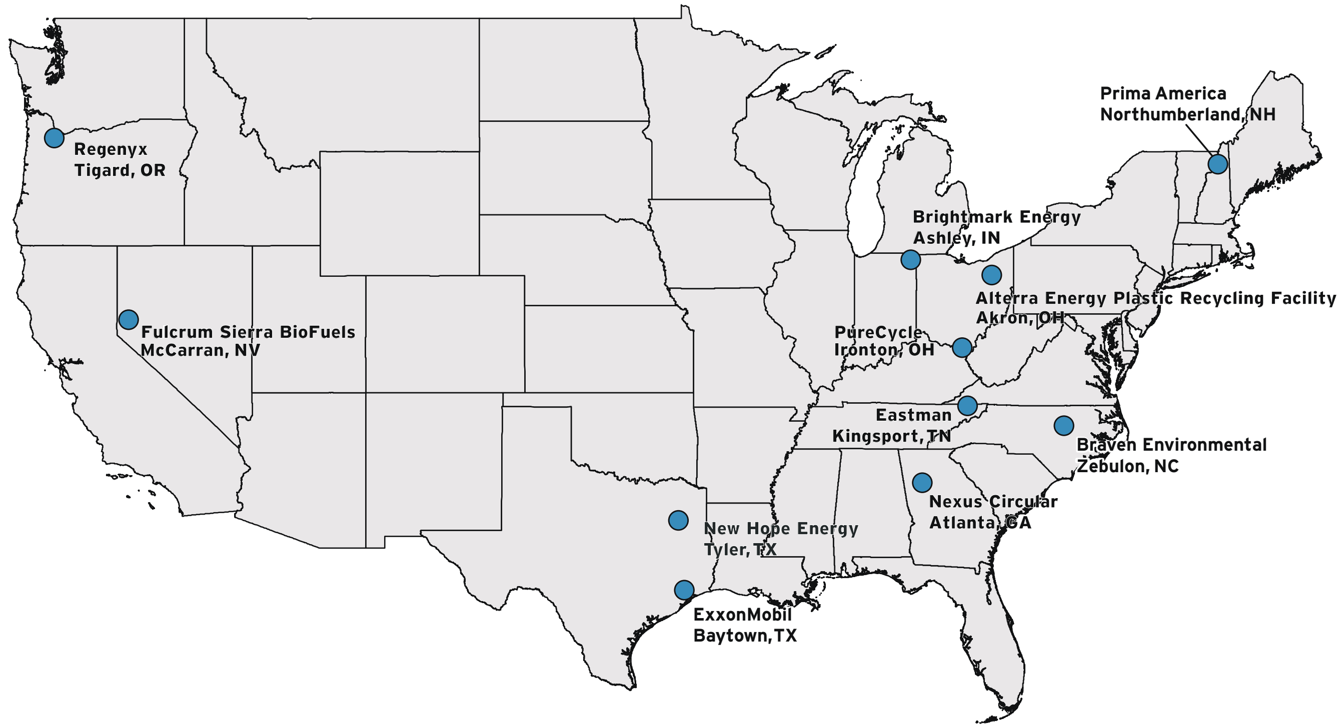
Given the growing public awareness about waste management and plastic pollution since the 1970s, and the failures of mechanical recycling to manage plastic waste, the plastics industry has had every incentive to find a way to make chemical recycling work. Yet, after decades of failure, the industry remains willing to spend tax dollars on fruitless chemical recycling projects.

Chemical recycling is not a new idea and companies have been trying for decades to make it work, without success. In the 1980s, Disney designed and built a pyrolysis facility to process waste from its operations and the surrounding community and create a substitute for oil that it could use to power its operations. The plant opened in 1982. Shortly after initiating its operations, it became clear that the plant was more expensive than Disney had anticipated because it required more gas and twice as much electricity as originally projected, and it closed the plant.(2)

This is a common storyline with chemical recycling: delays, barriers, cost overruns, and pollution. As evidenced by the problems with the current 11 constructed facilities and those that have tried and failed before, chemical recycling will never work, at least not in a way that makes it a preferred choice for managing waste. It is energy-intensive, expensive, and infeasible with a mixed and contaminated feedstock.

The 11 constructed facilities are spread out across multiple regions of the country: the Southeast (Georgia, North Carolina, and Tennessee), the Southwest (Nevada), the Gulf Coast (Texas), the Midwest (Indiana and Ohio), the Northeast (New Hampshire), and the Pacific Northwest (Oregon) (see Figure 5).

Figure 5 Constructed U.S. Chemical Recycling Plants, as of September 2023



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(2) "Disney's Failed Trash Plant: The Solid Waste Energy Conversion Plant." Midway to Mainstreet YouTube channel: https://www.youtube.com/watch?v=5rFLlw95maQ. Accessed Oct. 25, 2023.

KEY FINDINGS FROM THE CASE STUDIES

1. Chemical recycling processes insignificant amounts of plastic waste.
2. Chemical recycling rarely produces recycled plastic so it is not recycling. It mostly produces low-quality fossil fuels for burning.
3. Chemical recycling harms the environment and human health and threatens already overburdened environmental justice communities.
4. Chemical recycling is expensive and risky and draws public funds that could be used for truly renewable, sustainable projects.
5. Industry secrecy makes it difficult to determine how much chemical recycling costs and its impact on public health, the environment, and managing plastic waste.
6. Companies market the technology as successful and "green" with little to no accountability.
7. While each facility takes a somewhat different approach, failure is a constant.

2.2 A DROP IN THE BUCKET

While all of the companies profiled in Appendix 1 of this report tout optimism for their ability to "recycle" plastic waste, the actual quantities of plastic waste being processed at existing chemical recycling plants is miniscule, especially compared with the amount of plastic waste generated in the United States. As of September 2023, the 11 plants profiled in this report in total have a rated capacity to process only 459,280 tons of plastic waste per year.

Even at full capacity, these 11 chemical recycling facilities would process less than 1.3% of the plastic waste generated annually in the U.S.

Rated capacity is the maximum amount of waste plastic that their equipment is designed to process in one year. This means that the 11 constructed chemical recycling facilities have the potential to process less than 1.3% of the 35.7 million tons of discarded plastic generated in the United States each year — and most of them are not operating at their rated capacity. Despite the large volume of plastic waste available and the decades that the industry has put behind building out chemical recycling, at least eight of the 11 constructed chemical recycling plants in the United States are either pilot-scale or small-scale plants (a capacity of under 25,000 tons per year), are still in the testing stages, or have not achieved commercial operation at their rated capacity. Even if these facilities' current throughput was to be doubled to 1 million tons over the next few years — through the acquisition of more waste plastic supply and/or the installation of additional processing lines — it would still be a drop in the bucket.[1]

On Sept. 26, 2022, inspectors visited the Braven site and photographed vapor rising from an open dumpster filled with waste char, a potentially hazardous byproduct of the plastic pyrolysis process. Photo: N.C. DEQ Division of Hazardous Waste Management Compliance Evaluation Inspection

It would take hundreds of 100,000 tons per year plants to make a measurable dent in managing the amount of plastic waste generated in the United States — and that's assuming they could be capitalized, they could operate without producing large amounts of hazardous waste and toxic air emissions, and they could operate efficiently. The data on the 11 constructed chemical recycling plants in the United States does not support such a buildout. Despite this, at least 30 other chemical recycling facilities have been proposed, including two currently under construction, as Appendix 1 shows.

While some of the facilities advertise that their output could be used as a feedstock for new plastic, data shows that at least eight of the 11 facilities produce fuels that are meant to be burned (Agilyx, Alterra, Braven, Brightmark, Fulcrum, New Hope, Nexus, and Prima). Turning plastics into fuels to be burned is a losing proposition for the environment and public health and fails to meet the basic definitional standards for recycling.

2.3 THREATS TO THE ENVIRONMENT AND PUBLIC HEALTH

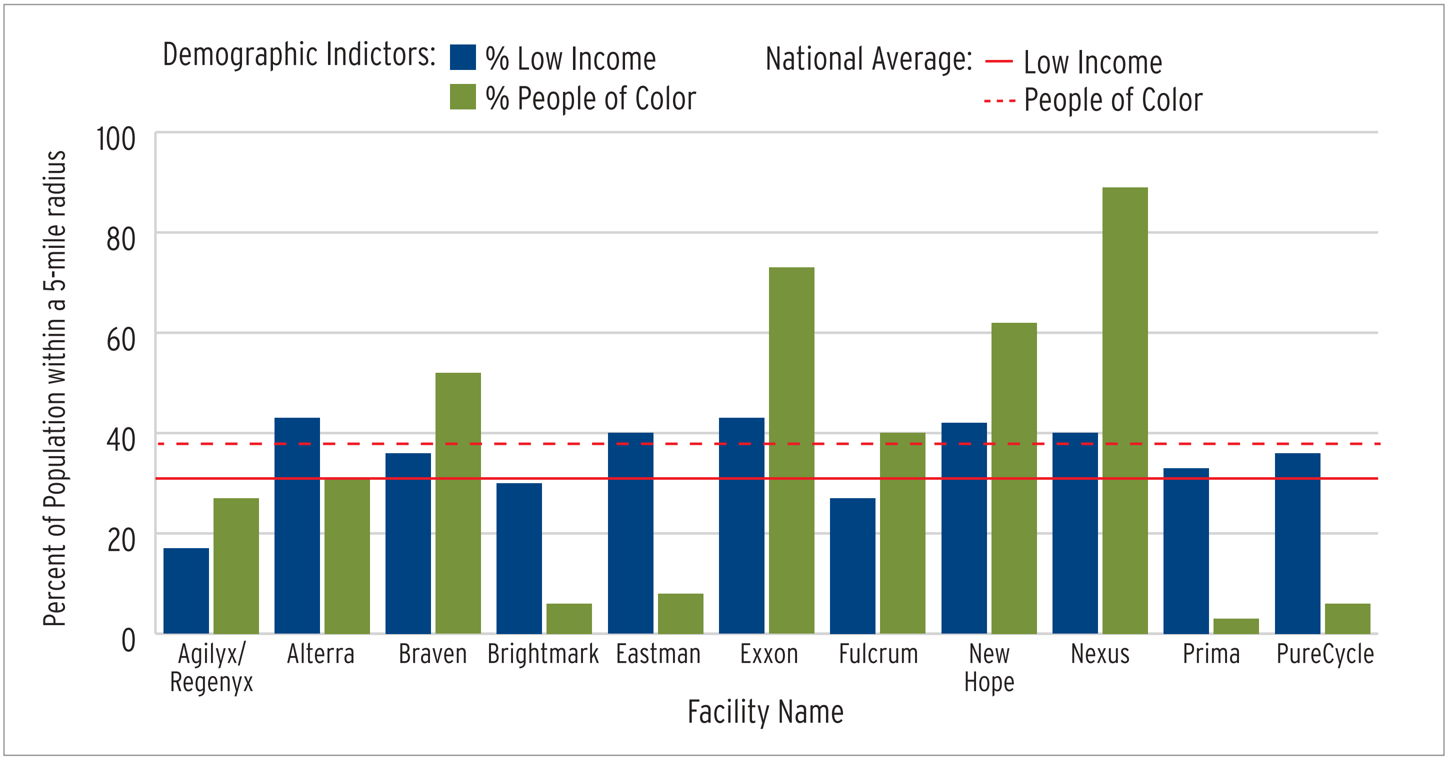
Chemical recycling generates a tremendous amount of hazardous waste. Four of the 11 facilities are registered with the U.S. Environmental Protection Agency as generators of hazardous waste (Regenyx, Alterra, Braven, PureCycle). Two of the companies — Exxon and Eastman — have their chemical recycling processes embedded on a larger facility that is classified as a large generator of hazardous waste, but neither provide numbers specific to their chemical recycling processes. Five facilities are not listed as hazardous waste generators.

Every facility has a permit for air emissions, and the largest facilities produce a few hundred tons of criteria air pollutants each year. Data gaps exist for greenhouse gas emissions, even though many of the facilities burn fossil fuels as part of the process to run their technology.

2.4 ENVIRONMENTAL INJUSTICE

Beyond Plastics conducted an analysis of a 5-mile ring around each of the 11 constructed plants using the U.S. Environmental Protection Agency's Environmental Justice Screening and Mapping Tool.[2] The analysis reveals that eight of the plants are located in areas with lower-than-average levels of income, compared to the national average; and five have higher-than-average concentrations of people of color than the rest of the country.

Figure 6 Prevalence of Low-Income Households and People of Color Around Constructed U.S. Chemical Recycling Plants



2.5 PUBLICLY FUNDED FAILURES

Project financing information is scant, especially regarding private investment. Depending on plant size and throughput, a commercial-scale chemical recycling plant can cost anywhere from tens of millions of dollars to more than $500 million to build.

Owners of five of the 11 plants have secured some direct public subsidies — most notably $100 million in federal grants and state tax abatements for Fulcrum's Sierra BioFuels plant in Nevada. Three facilities (Brightmark, Eastman, and Fulcrum) have collectively secured almost $1 billion in low-interest green bonds and government loan guarantees.

Two plants (Brightmark and Fulcrum) retained the firm New Energy Risk to secure private equity and bond financing where the investments are insured.[3, 4] In June 2023, Plastics News quoted a representative for Closed Loop Partners as saying that investors are "still sitting back" on chemical recycling, noting "I think there's a lot of interest, but the dollars aren't quite being deployed yet. We're going to need to prove that there are long-term offtake agreements that aren't going to have significant regulatory risks before the bigger dollars come in."[5]

Despite the failures of these and other chemical recycling plants to process plastic waste at their rated capacity, most of the companies have plans to expand their chemical recycling businesses, many with eyes on securing more government funds and incentives. In May 2023, the U.S. Environmental Protection Agency confirmed that "pyrolysis/combustion" units are "municipal waste combustion units."[6, 7, 8] Regardless, various federal incentives may make it more likely for future plants to secure financing. These have included the Department of Energy's $25 million Strategy for Plastic Innovation[9], and multimillion dollar grants and loan guarantees made by the Department of Defense[10] and the Department of Agriculture.[11] The federal Inflation Reduction Act also qualifies chemical recycling "approaches" for a $10 billion 48(c) tax credit program,[12] though it is not clear how such approaches are defined. This needs to be closely examined.

States are another matter. As noted in Chapter 3, the American Chemistry Council has lobbied for laws in 24 states to reclassify chemical recycling plants as manufacturing rather than solid waste management facilities, or other policies that promote a similar deregulatory approach. This reclassification "lowers the barrier" for new chemical recycling plants in terms of permitting[13] and economic development agencies have already offered incentives to multiple chemical recycling facilities that are profiled in Appendix 1: U.S. Case Studies.

2.6 LACK OF TRANSPARENCY

Specific information on feedstock processing, output volumes, and revenues from the sales of products from these 11 plants is scarce. Owners of six of the 11 plants (Alterra, Braven, Brightmark, Fulcrum, New Hope, and Nexus) have not issued public annual reports and publicly available revenue data on these plants appear to be estimates — sometimes wide-ranging.[14] In several cases (Brightmark,[15] Eastman,[16] ExxonMobil,[17] and PureCycle[18]), publicly available revenue data pertains to the companies as a whole — across the United States or the world — not exclusively to the chemical recycling facilities profiled in this report.

In one case (Prima), the annual report submitted to the state of New Hampshire is blank.[19] The Agilyx Group, co-owner of the Regenyx plant in Oregon, sustained operating losses of $22.4 million in 2020 and 2021[20] and as of May 2023, Regenyx co-owner Trinseo is trying to sell off its styrenics business.[21] PureCycle's 2022 SEC report indicates that the company sustained net losses of $215 million from 2020 through 2022[22] because the facility was still under construction, three years behind schedule.

2.7 SELLING SUSTAINABILITY WITH NO ACCOUNTABILITY

Many of the plants market their facilities or their outputs to attract the business of companies seeking to meet consumer-facing sustainability goals. Eastman markets its Tritan Renew product as a way to offer consumers "the same high quality they expect while feeling good about the plastic they are using"[23] and ExxonMobil promotes its Exxtend technology as a "foundation for certified-circular products that can help our customers advance their sustainability goals."[24]

Nexus has partnered with Chevron Phillips to market its "circular liquid"[25] used to make Marlex Anew polyethylene[26] and Braven's PyChem pyrolysis oil is touted as "a building block of second-life plastics and alternative fuel."[27] PureCycle markets its future output as Ultra-Pure Recycled Polypropylene that promises to "transform polypropylene plastic into a versatile, replenishable resource" and its "PureZero" event recycling program is trademarked.[28]

The words "circularity" and "sustainability" are used frequently in company websites, press releases, and product brochures. To promote these concepts and brands, many chemical recycling companies have secured the imprimatur of an ISCC Plus certification.[29] International Sustainability and Carbon Certification (ISSC) is a voluntary industry-led certification program for "circular and biobased products" and renewables that tracks the movement of feedstocks along the supply chain. ISCC became popular among corporations as it offers less stringent rules than other certifiers. Indeed, ISCC has been criticized for standards that encouraged deforestation, leading to "biofuels" that have a carbon footprint several times worse than fossil fuels.

For chemical recycling, ISCC uses a mass balance approach that blends virgin and recycled content, an approach that has been criticized[30] as not providing customers with an accurate assessment of how much recycled content any given product actually contains. The "mass balance" approach allows companies to claim products are made from sustainable, recycled materials even when the product contains little or no recycled content (see Section 4.5).

The idea of "certified-circular" is an industry-created myth. There are no agreed-upon standards for circularity, especially for plastics. A 2023 study assessing "circular" claims about plastic recycling found all criteria for circular plastics lacking, noting that "suggestions for circular economy initiatives targeting plastic may have limited effect and not lead to the intended impacts."[31]

Our detailed case studies, found in Appendix 1, suggest the same: For all of the company promises and press releases about chemical recycling's potential to combat the plastic pollution crisis, there has been little progress — and the process has its own threats to environmental and human health.

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CHAPTER 3

STATE DEREGULATION OF CHEMICAL RECYCLING: BOOSTING HAZARDOUS WASTE PRODUCTION AND POLLUTING NEARBY COMMUNITIES

Source: UNEP/Ollivier Girard

The U.S. petrochemical and plastics industry, spearheaded by the American Chemistry Council, has been highly active in seeking to deregulate or minimize regulations in the chemical recycling sector. They use the term “advanced recycling” to suggest that some new form of novel technology is about to resolve the plastic waste crisis.

In addition, industry lobbies for laws to reduce environmental regulation at the facility level and for public funding of its buildout via subsidies, tax breaks, and other financial incentives. This enormously profitable industry, which can well afford to fund any kind of recycling activity itself, is counting on chemical recycling to distract policymakers into thinking chemical recycling will solve plastic pollution and keep them from restricting plastic production and associated growth in profits.

The attempts to deregulate chemical recycling at the state level are preemptive regulatory strategies to enable chemical recycling plants to avoid strict pollution control laws that would apply to waste incinerators — mostly before regulators are even aware of the environmental impacts of these plants. Instead, the ACC advocates for chemical recycling operations to be treated as “manufacturing facilities” with much lower levels of environmental regulation (see Section 3.1).

As technology assessors are finding out at the highest level of international waste management regulation, data is scant on the hazards, emissions, and waste profiles of chemical recycling, but what is available suggests that grave risks are involved. Currently, 24 states[1] have enacted laws that will regulate chemical recycling as manufacturing processes and not waste management facilities. While this may make it easier for chemical recycling proposals in these states to access funding and support for construction of facilities, federal regulation by the U.S. EPA may still override critical issues related to emissions and other environmental impacts.

Positioning an end-of-pipe solution as a silver bullet was an effective strategy in the 1980s, when plastic pollution generated high levels of public concern. At that time, the plastics industry message[2] to lawmakers was that mechanical recycling of plastic would solve the plastic waste problem. Polymer numbers appeared in recycling triangle symbols on plastic products, consumer education advertising was rolled out, and Americans were encouraged to recycle. Policymakers and regulators were encouraged to let recycling grow and solve the problem.

Forty years later, the recycling “solution” has been an abject failure, with only 9% of all plastic produced having been recycled by mechanical means, while the rest has been dumped, landfilled, or incinerated (Geyer et al. 2017). A great deal of that plastic now circulates the planet as tiny, toxic particles of microplastics in the atmosphere, our food, our water, and our bodies (Sharma and Chatterjee 2017, Jung et al. 2022).

Most observers expect Big Plastic to have a carefully prepared playbook to hold off any kind of regulation that would limit production and profits. But few would expect such an effort to extend to measures like promoting significant deregulation of chemical recycling emissions control, putting neighboring communities at risk — all while pushing for the public to subsidize operations.

Those who will bear the highest of these risks are the nearby residents and workers, many of whom are already impacted by toxic emissions of petrochemical refineries and plastic production facilities. Environmental injustice, or the distribution of high-risk, unwanted land uses in communities of color and low-income communities, will be a key factor in the siting of chemical recycling plants.

Those who will bear the highest risks from chemical recycling facilities are the nearby residents and workers, many of whom are already impacted by toxic emissions of petrochemical refineries and plastic production facilities.

People already bearing an unequal share of the environmental risk imposed by hazardous facilities for the benefit of the wider community should not be forced to endure even greater risks for the failure of the plastics industry to deal with the pollution caused by their products. There is a growing trend for companies to seek to co-locate chemical recycling plants near or alongside existing petrochemical refineries, many of which are located in areas that undermine environmental justice. ExxonMobil has stated it intends to build chemical recycling plants at "many of its other manufacturing sites around the world" and is assessing sites in Louisiana, Illinois, Belgium, and Singapore. Such co-location will further exacerbate local emissions and fire hazard risks.

Those risks could be great. When considering the siting of high-risk polluting facilities, state regulators calculate a standard measure of one additional risk of cancer in a lifetime per 1 million people as an acceptable level of risk for emissions. Sometimes a project will be allowed to proceed under certain circumstances with a higher emission risk level than 1 in a million, but allowing a risk level of 1 to 100,000 is considered very high.

Yet, a proposal by Chevron in Pascagoula, Mississippi, to refine plastic-derived pyrolysis oil into jet fuel was recently assessed by the U.S. EPA as having a public risk[3] factor of 1 out of 4 — a level 250,000 times greater than would normally be permitted. This means that 25% of the local population would likely develop cancer in their lifetime as a result of exposure to the facility's emissions. Dr. Linda Birnbaum, a toxicologist and the former head of the National Institute of Environmental Health Sciences, said of the proposal's emissions, "That kind of risk is obscene; you can't let that get out."[4]

25% of the local population would likely develop cancer in their lifetime as a result of exposure to the facility's emissions.

In the case of the Chevron pyrolysis oil-to-fuel proposal in Pascagoula, Mississippi, an assessment of public health impacts by the "EPA identified skin and eye irritation; acute toxicity; systemic toxicity (neurotoxicity, body weight effects, and liver, kidney, blood, spleen, and other organ effects); reproductive and developmental toxicity; oral and inhalation portal of entry effects; genetic toxicity; and carcinogenicity as hazards of these new chemical substances." (US EPA 2022)

The EPA also noted that the fuel made using plastic-derived pyrolysis oil would lead to food-chain contamination and that "overall, these new chemical substances have the potential to bioaccumulate and be persistent in the environment, such that repeated exposures may cause food-chain effects via accumulation in exposed organisms." (US EPA 2022) The actual specifications of these new substances are redacted in the U.S. EPA consent order as commercial business information (CBI) and are not available to the public.

Investigative journalists have recently uncovered another astounding issue at Chevron's refinery in Pascagoula, Mississippi. In this instance, the EPA approved Chevron's use of a component for boat fuel that was to be made from plastic waste and which had a calculated risk of 1.3 to 1[5], meaning that all people exposed to the chemicals in the fuel over a lifetime would be expected to develop cancer.[6] Instead of the acceptable regulatory limit of 1 in 1 million cancer risk, the risk from the boat fuel equates to a level 1 million times higher — that is, of nearly 1 million people exposed over a lifetime, there would be nearly 1 million excess cancer cases.

However, the emissions from making and burning this fuel are not the only reason for the extremely high risk to the public - indirect risks are also a factor. Indirect impacts include exposure from environmental contamination. Investigative journalists who researched the EPA consent order found that "for every 100 people who ate fish raised in water contaminated with that same product over a lifetime, seven would be expected to develop cancer — a risk that's 70,000 times what the agency usually considers acceptable."[7]

In response to criticism over this and other plastic to fuel proposals at the same facility, the EPA has proposed a rule[8] — which has not been approved — that would allow them to test the oil from the chemical recycling process for contaminants such as dioxin, PFAS and flame retardants before it could be used to make the 18 fuels and associated chemicals listed in the Chevron consent order. It is not clear if the EPA would then be able to prohibit the manufacture of the fuels if the contamination was considered too high. Testing of oils and other outputs from chemical recycling should be mandatory before they are used as fuel or feedstock to prevent widespread contamination of products and human exposure to unacceptable toxic risks.

These risk factors are due to emissions of persistent, cancer-causing compounds from the chemical recycling facilities or their fuel products. Typical emissions from pyrolysis include carcinogenic polycyclic aromatic hydrocarbons (PAHs) (Zhou 2015, Blankenship 1994), volatile organic compounds (VOCs), chlorinated and brominated dioxins, furans (PCDD/DF, PBDD/DF) (Weber and Sakurai 2001; Blankenship 1994; Chen 2014, Rosemann et al 1998; Ortuño et al 2014), and acid gases, such as HCl, heavy metals, ammonia, and sulphur dioxide (Chen 2014). PFAS may also be a contaminant of concern in chemical recycling output, but little information is available on the subject.

While examples such as the Chevron proposals seem extreme, they support the case that all chemical recycling facilities must be subject to full environmental impact assessments, whether new facilities or modifications to existing facilities. The community must be given the opportunity to meaningfully participate in these assessments at the earliest opportunity. Proposals must not be permitted to proceed unless they include measures to monitor emissions and mitigate waste streams to ensure they are within acceptable limits. If proposals are assessed that represent a high risk to the community, they should not be approved. Removing impact assessments and monitoring of all relevant air emissions should not be the primary objective of the chemical recycling industry in seeking to convince lawmakers to regulate the operation of their facilities as manufacturing plants.

Given the detail of the scale of the hazards that are now emerging, environmental justice and siting considerations suggest that it may never be appropriate to locate such facilities in areas of low income, communities of color, and/or other vulnerable communities.

3.1 THE STATE DEREGULATION STRATEGY: INCREASING SUBSIDIES WHILE DECREASING EMISSION CONTROLS

The strategy of the ACC is to convince U.S. state lawmakers to pass bills that significantly deregulate chemical recycling using several key provisions. The most significant provision is to have chemical recycling facilities regulated as manufacturing plants[9] and not as waste management facilities (ACC 2018). This would also require pyrolysis and gasification units to be removed from the classification covering incineration, combustion, or waste-to-energy facilities and be reclassified as manufacturing plants by the state EPA — another rule change being pursued by the ACC[10] on the U.S. EPA level.

This has several flow-on effects, including removal of requirements to monitor many hazardous air emissions, which would be required for waste management facilities, such as waste incinerators. Typically, the U.S. EPA regulates pyrolysis and gasification units as incineration processes with hazardous emissions, requiring monitoring, emission limits, stack bypass limits, and filtration controls. The European Union also classifies these technologies as incineration processes under EU directive 2000/76/EC (WI Directive)[11] and the U.S. EPA continues to regulate pyrolysis and gasification as solid waste incineration processes as it has since, 2005[12] despite recent attempts to change[13] the regulations.

The state-by-state deregulation process may allow much weaker regulation of emissions under the Clean Air Act, including air toxics (e.g., benzene, particulate, VOCs, and PAHs), GHGs, and even POPs emissions (e.g., dioxins and furans) with little or no monitoring, limits, mitigation, or enforcement. These pollutants have frequently been identified in emissions of pyrolysis and gasification technologies, which make up the bulk of chemical recycling proposals. Deregulation may also allow high levels of hazardous waste to be generated, stored on-site, and shifted to other locations with reduced oversight.

The ACC produced a set of guidelines on how U.S. state policymakers and regulators should, in its view, regulate chemical recycling facilities, first in 2014 (ACC 2014) and then with a version dated 2018 released in 2021 (ACC 2018). At the core of the ACC regulatory proposal is its claim that the mixed plastic waste received at a chemical recycling facility is not, in fact, mixed plastic waste. In yet another variation on the term chemical recycling, the ACC renames such facilities “plastics-to-fuel and petrochemistry” (PTFP) plants and claims they do not burn or combust plastic or waste (ACC 2018), hence they should not be regulated as solid waste disposal facilities.

The Basel Convention (see Section 4.2.1) classifies these facilities as waste disposal operations if they produce fuel from plastic waste. Such plants are coded as “Annex IV Disposal Operations Part B, R1 — Use as a fuel or other means to generate energy.” If the plastic waste is combusted without energy recovery, the facility is considered Annex IV Disposal Operations Part A, D10 — Incineration on Land. At the 2023 Conference of the Parties of the Basel Convention, an unsuccessful attempt was made to insert chemical recycling as an “Annex IV Part B Operation R3 — Recycling/Reclamation” of organic substances that are not used as solvents (see Section 4.1.1), in hope of codifying these technologies as recycling. In any of these operational interpretations, chemical recycling would be defined internationally as a waste disposal operation, not a manufacturing operation.

The ACC’s claims that it does not handle mixed plastic waste are not credible. It suggests companies will be paid to receive “mixed plastics” and has coined a new category for these materials: non-recycled plastics (NRP) instead of solid waste or plastic waste (ACC 2018). It is not clear if the ACC means post-industrial, post-consumer mixed plastics, or some form of residual plastic waste left after recyclable material has been removed.

The ACC notes that chemical recyclers may be paid a fee to take these “clean pre-processed” materials, which they describe as “sorted and graded feedstock.” But they fail to explain why the generators of these non-recycled plastics would clean, sort, and grade them for the chemical recycling facility and then pay the facility to take them.

Despite the ACC’s claims that plastic arriving at chemical recycling plants will be clean and sorted, their guidance discusses the need to dump ”off-spec feedstocks” that are contaminated, as well as “process wastes.”

The ACC guidelines have several internal contradictions. They claim chemical recyclers will not combust plastic or waste, but acknowledge they will have flares to combust contaminated waste gases from heating plastic. “Alternately, these gases may be fully combusted without energy recapture to destroy certain compounds,” said the ACC in 2018.[14]

The ACC also admits chemical recyclers will resort to burning gases produced by heating plastic waste, including “combustion of any vaporized portion of the plastics that cannot be condensed into liquid petroleum products” and “combustion to supply electricity.” These gases can be of very large volumes, with ACC claiming they constitute “10% to 15% of the mass of the vaporized plastics and can be combusted like natural gas in commercial-scale PTFP systems to provide process energy” (ACC 2018). By any account, it is not possible to conclude that chemical recyclers will be doing anything other than burning a large part of the waste they receive.

The ACC asserts that pyrolysis is not “combustion” or “incineration” because the process is an “oxygen-free environment” (ACC 2018 p 3, 11). However, it neglects to mention in its guidelines that many polymers, such as polyester and polycarbonates, contain a significant amount of oxygen in their chemistry. However, the ACC does acknowledge this on its website under “Facts and Highlights”: “The term ‘plastics’ includes materials composed of various elements, such as carbon, hydrogen, oxygen, nitrogen, chlorine, and sulfur” (ACC 2023).

This is an important omission, as U.S. regulators are aware that heating wastes containing carbon and chlorine in the presence of oxygen has similar potential to generate emissions expected from incinerators, such as chlorinated dioxins, PAHs, chlorinated VOCs, and other highly hazardous chemicals. By claiming an “oxygen-free” process for pyrolysis, promoters of chemical recycling are hoping to avoid categorization as incinerators and regulation as persistent organic pollutant (POP) emitters, particularly of highly toxic dioxins.

Also, in trying to claim an oxygen-free process, the ACC only describes the initial pyrolysis reactor component. But the flaring of plastic waste vapor and its combustion as process fuel are all indisputably incineration operations involving combustion with oxygen. If outputs of the chemical recycling process are used as fuels beyond the facility, then there is also potential for the contaminants to be released into the atmosphere, increasing human exposure.

By trying to obscure the formation of highly toxic chemicals, such as dioxins, caused by oxygen in pyrolysis, promoters of chemical recycling hope to conceal the fact that the gases, char, and hydrocarbon output of their process may also be contaminated — a situation the incineration industry has never been able to overcome, as it is highly regulated for these substances, especially in the EU.

Indeed, it is difficult to reconcile the “low-emission” PTFP facilities described by the ACC in its 2018 guidelines for regulators with the 2023 Chevron PTFP proposal in Pascagoula, Mississippi, which was assessed by the U.S. EPA as having an astronomical public cancer emission risk factor of 1 to 4.

> ***The classification as a manufacturing facility can also have financial benefits for the operators opening the door to access state tax benefits and potentially to government bonds for construction support.***

The classification as a manufacturing facility can also have financial benefits for the operators opening the door to access state tax benefits and potentially to government bonds for construction support. A proposal by Brightmark for a plastics-to-fuel operation in Bibb County near Middle Georgia Regional Airport came close to securing $500 million in exempt facility revenue bonds[15] from the Macon-Bibb County Industrial Authority. If the agreement had been signed, the county would effectively have been endorsing the proposal, signaling reduced risk, which would attract investors who would also avoid state and federal tax on any interest on the bonds.

While there was no direct financial risk to the county, its reputation[16] in the bond market would have been at risk[17] if the proposed Brightmark facility turned out to be unprofitable and investors lost money. In turn, this could have had implications for the ability of the county to raise funds in the future. Although this project was rejected after failing to meet administrative deadlines while facing community opposition, an earlier Brightmark plastic-to-fuel plant in Indiana claims to have been operating at pilot scale, but has not been reported to be producing any output. (Other examples of chemical recycling facilities in the U.S. receiving different forms of public subsidies are detailed in Appendix 1: U.S. Case Studies.)

The attempts to pass state laws minimizing regulation of chemical recycling are a political ploy to hide the true environmental and health risks associated with this process.

The attempts to pass state laws minimizing regulation of chemical recycling are a political ploy to hide the true environmental and health risks associated with this process. Attempts to politicize such risks have also been seen at the federal level. Toward the end of the Trump administration, the U.S. EPA proposed a new rulemaking stating that pyrolysis is not combustion and thus should not be regulated as incineration, aligning itself with the ACC's advocacy for state bills that deregulate chemical recycling.

However, in September 2021, the Biden administration re-examined the EPA proposal and opened it to public comment. In July 2022, 35 members of Congress wrote to the EPA urging them to retain the definition of pyrolysis and gasification as incineration with all the emission controls that are warranted for such technology.

The lawmakers pointed out that,"[C]hemical recycling facilities emit highly toxic chemicals — including benzene, toluene, ethyl benzene, xylenes, and dioxins — many of which are linked to cancer, nervous system damage, and negative effects on reproduction and development. The plastic and petrochemical industry has lobbied at the state level to eliminate emission control requirements for incinerators using these technologies, exposing vulnerable fenceline communities to toxic emissions from these processes."

More recently, similar concerns were raised by federal lawmakers in a House Appropriations Committee report[18] related to the federal budget that called for the U.S. EPA to continue to regulate chemical recycling as incineration and ensure that strict clean air requirements were met. At the time of writing this report, no decision had been finalized by the U.S. EPA on this matter. The attempts by the plastics industry to pre-empt federal U.S. EPA regulations on emissions control from chemical recycling through a state-by-state deregulation campaign may yet prove to be ineffective.

However, if the industry push to remove emission controls at both the state and federal level is successful, local communities can expect more carbon emissions, microplastics pollution, air toxics emissions, ramped-up hazardous waste generation, and even threats to waterways.

3.1.1 COMMUNITIES' RIGHT TO KNOW

Citizens cannot fully participate in the democratic decision-making process for waste management facilities in their community unless they have been informed of the typical and worst-case scenarios associated with their operation.

In many countries, an environmental impact assessment (EIA) or similar public consultation processes are conducted where the proponent of a new or expanded facility is required to detail the anticipated emissions, releases, and other environmental impacts of the facility, including increased traffic, lighting and noise impacts, visual pollution, and specific impacts on local protected species or natural features.

The proponent is typically required to release a report detailing all relevant impacts, including emission types, concentrations, and volumes; ground-level concentrations; stack heights; air pollution control equipment; mitigation measures (process controls); seasonal emission fluctuations (inversion layers, wind directions); hazardous waste management; stockpile management; fire control and emergency response; and much more.

Key issues, such as worst-case emission scenarios during OTNOC (other than normal operating conditions) for the facility when filters and flares break down, must also be detailed. Opportunities to make these impacts transparent through an environmental impact assessment (EIA) process will mostly be lost if the facility enjoys weaker regulatory oversight as a manufacturing facility.

The EIA report should be open to public and expert comment, and if the risk of operation is deemed by the public to be too high, it should not proceed. If the local community already faces numerous risk facilities and significant emissions (i.e., environmental justice considerations), the impact of any additional plant must be considered as part of a cumulative assessment and not as a single facility divorced from the context of the reality on the ground.

In addition, chemical recycling facilities should have a social license to operate (Bice and Moffat 2014) and this can only be obtained via transparency about the impacts of the facility. A social license to operate refers to the level of acceptance or approval by local communities and stakeholders of industrial operations in their community. It is not a regulatory or legal permit, but it is in the interests of the facility operator to ensure the community is not opposed to the project. Some projects present such significant risks to the community that they may never be accepted.

In the next section, more detail about the impacts associated with chemical recycling are outlined with a specific focus on the intrinsic toxicity of plastic and how this contributes to high levels of pollutants from the chemical recycling process.

3.2 PLASTICS IN, TOXICS OUT (PLUS CLIMATE CHANGE IMPACTS)

Nearby communities around chemical recycling plants are right to be concerned about the impacts of the facilities, which will be handling and stockpiling plastic waste, as well as processing it in ways that generate hazardous emissions and toxic waste streams — all while increasing the risk of significant plastic waste storage fires and microplastic releases.

Several factors influence the risks faced by communities around a chemical recycling facility. These include the toxicity of the plastics and the additives they contain, the creation of additional toxic compounds in the processes used, the use of hazardous agents in the process, and the generation of hazardous wastes from the processes (UNEP 2023). In addition, stockpiling and processing of plastic waste at such facilities releases microplastics (Brown et al. 2023) and increases the risk of fires with hazardous emissions and long-term soil contamination. Carbon emissions from chemical recycling are also high and will contribute to climate change at local and global levels, especially if the industry scales up.

A recent study[19] found that greenhouse gas emissions from plastic waste pyrolysis were likely to be between 10 and 100 times higher than those emitted from the production of virgin plastic. If carbon pricing mechanisms were applied, it could render chemical recycling unviable.

Chemical recycling claims to be able to recover either monomers, polymers, or hydrocarbon mixes that can be used as plastic feedstock from mixed plastic wastes. This report makes it clear that in most cases, mixed plastics are not suitable for chemical recycling (see Technical Addendum 2.4). However, if it is to be assumed that chemical recycling can "extract" useful materials from mixed plastic waste, it logically follows that the process separates "contaminants" from the target chemicals/polymers, creating a hazardous waste stream.

3.2.1 TOXIC ADDITIVES IN, POLLUTANTS OUT

The majority of these contaminants will be chemical additives, intentionally or otherwise present in the waste feedstock. As many are hazardous, they will form a significant hazardous waste stream at each facility, due to the large volume of plastic needed to make the plant economically viable (see, for example, the Alterra case study on page 85 of Appendix 1). This may take the form of contaminated char, sludges, filter residues, effluents, and emissions.

The lower the yield from a chemical recycling process, the greater the hazardous waste stream. In many cases, contaminated gas from the process will be flared — a process of gas incineration, which has the capacity to contribute further contaminants like dioxins, particulates, and other products of incomplete combustion to the emissions of a facility.

At least 3,200 plastic additives have been identified as substances of potential concern, based on their hazardous properties (Aurisano et al. 2021, Wiesinger et al. 2021), including carcinogenicity, mutagenicity, reproductive toxicity, endocrine disruption, and ecotoxicity to aquatic organisms, according to the UN Globally Harmonized System of Classification and Labelling of Chemicals (GHS) and the European Union's Classification, Labelling and Packaging Regulation (CLP) (European Commission 2008).

Many of these toxic additives have the potential to contaminate plastic waste streams, emissions, and outputs of chemical recycling. There is little transparency about or regulation of the additives used in plastic formulations, which contributes both to human exposure and problems with plastic recycling.

The toxicity of plastics varies between polymers and is heavily influenced by the type of additives that are used to impart different properties to plastic products, including colorants, flame retardants, UV stabilizers, plasticizers, and so on. Virtually all plastics contain combinations of additives, and some are more toxic than others.

The chemical additives business is a major global activity, and various market analysts place the plastic additives sector's current market value at between $30 billion to $50 billion, with a compound annual growth rate (CAGR) around 4% to 5%[20] by 2032. Many market analysts vary in their predictions, but the CAGR and total value tend to be of the same order of magnitude. Much of this growth is predicated on future demand and production increases for plastics, which require increasing volumes of additives to form products. Some polymers have intrinsic toxicity even before additives are used in the formulation.

Table 2 The Types of Toxic Additives Commonly Used in Plastics in a Multitude of Combinations

Flame retardants	Bisphenols	Biocides
Per- and polyfluoroalkyl substances (PFASs)	Certain alkylphenols and alkylphenol ethoxylates	UV stabilizers
Phthalates	Polycyclic aromatic hydrocarbons	Metals and metalloids

Many of the thousands of chemicals used as additives in polymers are hazardous and can be released from the plastic products via a range of pathways that cause human exposure (Hahladakis et al. 2018). While additives are major contributors to the toxicity of plastics, some monomers — the building blocks of polymers — are also toxic to humans. Common monomers and their toxicities include:

- Acrylonitrile: human carcinogen (liver, brain);
- Vinyl chloride: human carcinogen (liver);
- Formaldehyde: animal carcinogen (nasal) and human carcinogen (can cause leukemia and cancers of the nose, throat, and sinuses);[21]
- Methylenedianiline: suspect human carcinogen (Gad 2005); and
- Bisphenol A (BPA, IUPAC ID: 4,4ğ-(propane-2,2-diyl)diphenol). (Human Developmental Toxicity, Female Reproductive Toxicity)[22]

3.2.2 NON-INTENTIONALLY ADDED SUBSTANCES (NIAS)

NIAS are not added to improve the polymer product, but include breakdown products of polymers during virgin production and use, impurities in starting materials, unwanted byproducts, and various contaminants from recycling processes (Geueke 2018). They may also include organic contaminants from the mixed waste collection process. When plastic waste is removed from the ocean, NIAS may also include chemicals, some that are POPs such as PCBs and dioxins, that adsorb (bind) to the plastic from ocean pollution. Breakdown products can evolve from polymers, additives, and processing aids (which can include PFAS compounds to help with plastic extrusion, etc.) — for instance, hazardous volatile organic compounds (VOCs) such as toluene, xylene, or ethylbenzene (Kato and Conte-Junior 2021).

Contaminants can occur in both additives and raw materials for polymer production (Roosen et al. 2020). One example is the presence of brominated furans in commercial brominated flame-retardant additives (Wahl et al. 2008). Output products from pyrolysis can become contaminated within the process, and these contaminants can be transferred back to polymer products if outputs are used for plastic feedstock, thereby perpetuating a chain of contamination into new plastic products (DiGangi et al. 2017).

In virgin polymer production, side reactions occur as the starting substances, materials, and additives are mixed in subsequent steps and can generate NIAS (Kato et al. 2021). While the main reactions are important to determine the properties of the polymer, side reactions also occur that can result in NIAS formation, but this is rarely measured. Contaminants can also enter plastics previously recycled and continue through the chemical recycling chain. These include legacy additives, such as prohibited POPs (e.g., PBDEs, PCBs, and SCCPs) and the transfer of pesticides from recycling of plastic pesticide containers (Eras et al. 2017).

3.2.3 PERSISTENT ORGANIC POLLUTANTS

Many chemicals have been used as additives in plastics that have subsequently been assessed as persistent organic pollutants (POPs). These are among the most dangerous and toxic chemicals ever developed and are prohibited or otherwise regulated by the Stockholm Convention on Persistent Organic Pollutants (see Section 4.6). They include polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCD) used as flame retardants, short-chain chlorinated paraffins (SCCPs) used as plasticizers, polychlorinated biphenyls (PCBs) used as plasticizers and flame retardants, and others. Plastics in electronic waste casing and automotive upholstery can contain very high levels by weight of brominated flame retardants. Large stockpiles of plastic waste still exist that are contaminated with POPs and are not easily separated as they are often mixed with other plastics.

Plastic waste may also contain unintentional POPs (UPOPs) as a result of its production, usually carried into the plastics as contaminants in plasticizer additives (Takasuga et al. 2012), color pigments (Anezaki et al. 2015; Government of Japan 2006;), or as degradation products of polymerization catalysts (Herkert et al. 2018). PBDD/DFs (brominated dioxins and furans) have been identified as NIAS in plastics containing PBDEs or other BFRs (Weber and Kuch 2003; Sindiku et al. 2015). These brominated dioxins have been identified as being transferred via mechanical recycling into new products, including toys (Petrlik et al. 2018; Budin et al. 2020).

At the 2023 Conferences of the Parties to the Basel, Rotterdam, and Stockholm Conventions, two widely used plastic chemicals, the phenolic benzotriazole UV stabilizer UV-328 and Dechlorane Plus, a flame retardant for polymers, were added to the Convention's list of globally banned POPs chemicals. Other chemicals used in plastics are under consideration for listing.

3.3 HAZARDOUS WASTE GENERATION AND EMISSIONS

As mentioned above, when the target monomers/polymers or hydrocarbon outputs are obtained from the chemical recycling process, they are termed the "yield" — which, for pyrolysis, is typically relatively low, at 20% to 30% of plastic waste input, meaning up to 80% of the plastic waste going in for "recycling" is actually lost as process fuel, emissions, or becomes hazardous waste consisting of additives, NIAS, POPs, non-target hydrocarbons, and a range of chemicals that are produced in the process as side reactions. These include PAHs, dioxins/UPOPs, VOCs, heavy metals, and other contaminants. These non-target materials become solid wastes, oily wastes, gaseous wastes, char, and liquid effluents (depending on the emissions scrubbing system), and all are hazardous.

The Regenyx so-called "plastic-to-plastic" facility in Tigard, Oregon, United States — owned by parent company Agilyx — claims to convert polystyrene back to usable styrene feedstock using pyrolysis. However, in 2015, Agilyx reported to the U.S. EPA that much of the styrene output from its facility (totaling 165 tons) supposedly intended for polystyrene feedstock was actually sent for incineration.[23] Data submitted to the U.S. EPA in 2019 indicated the plant sent 283 tons[24] of hazardous waste off-site for incineration and co-processing in cement kilns, consisting of corrosive waste, cadmium, chromium, lead, selenium, benzene, 1,2-dichloroethane, vinyl chloride, and other ignitable wastes.

Source: Tina Schoolmeester, Grid Arendal https://www.grida.no/resources/13305

Plastic waste must be stockpiled to allow sufficient uninterrupted supply of inputs for the chemical recycling process. Such stockpiles are well-known fire risks and, if stored on-site with large volumes of hazardous waste from the chemical recycling process, could represent a serious danger to the surrounding community. Hazardous waste streams from chemical recycling will be significant. If a facility claims 100,000 tons per year throughput of plastic waste and has a very high yield (output product) of 50%, then it could be assumed that the other 50% of input material (50,000 tons per year) will have become waste in the form of gas, char, or unwanted hydrocarbon fractions. The lower the yield, the more waste is created.

Pyrolysis units produce oils and gas and generally have a flare to burn dirty gaseous emissions during startup and shutdown, as well as gas released to keep pressure within safety specifications for the unit during emergencies (Elsdon and Pal 2011). Flaring of contaminated gases from these units will release some entrained pollutants, such as VOCs and PAHs, into the local atmosphere (Kindzierski, 1999) and may create new combinations of pollutants, such as dioxins, which are carried on fine particulates from the flares.

Many unknown products of incomplete combustion may also be released from flares, including benzene and naphthalene, carbon black particles (Fawole et al. 2016) CO, and partially burned and altered hydrocarbons and BTEX (Mirrezaei and Orkomi 2020). Also emitted are nitrogen oxides (NOx) and — if sulfur-containing material, such as hydrogen sulfide or mercaptans, is flared — sulfur dioxide (SO2) (US EPA Emission Factors – Industrial Flares).

However, the exact composition of emissions from any chemical recycling facility will depend on the input plastic waste types and operational controls. For example, if high levels of PVC and brominated WEEE plastics are used, brominated and chlorinated dioxin levels can be expected to be much higher, due to the precursor levels of chlorine and bromine in the system. Contaminants identified in flue gas from plastic pyrolysis plants include dioxins, PCBs, and large quantities of VOCs, including mono-aromatics, oxygenated VOCs (O-VOCs), chlorinated VOCs (Cl-VOCs), and acrylonitrile (He et al. 2015, An et al. 2014; Paladino and Moranda, 2021).

As an example of the volume of gas burned, the photo on this page shows an under-construction pyrolysis facility that will make fuel from plastic waste using a flare to burn off excess syngas from the process. The Brightmark plant in Ashley, Indiana, intends to process 100,000 tons of plastic waste per year. Most of the gas produced from pyrolysis of plastic waste will be mixed with natural gas to power the plant, leading to contaminated emissions that may exceed safe regulatory limits.

Brightmark Energy facility in Ashley, Indiana. Source: The Last Beach Cleanup

Produced waxes are proposed to be sent for commercial use in candle manufacture, and no information is available about potential contamination of the wax. The solid char is proposed to be dumped at a non-hazardous waste landfill, but no information is provided on heavy metal, dioxin, PCB, or other POPs levels in the char, all of which are key determinants of hazardous waste.

In December 2021, Brightmark provided documents to the EPA noting that just 20% of the output of the facility is fuel, the business's primary product. Around 70% is output syngas that will be mixed with natural gas to produce process heat. (Twenty percent of that syngas will be incinerated in an open flare.) The balance is solid char, which has not been tested for POPs content.

Flares and other emissions stacks are the key day-to-day sources of hazardous air emissions with any chemical recycling facility, although fugitive emissions (those which escape from other points in the process and are unfiltered) may also represent a hazard. Solvent-based chemical recycling has the potential for fugitive emissions, due to the volatility of some solvents used, and may also use flares (see Technical Addendum Sections 2.3 to 2.3.3). Solvent-based chemical recycling will also generate hazardous waste, as it specifically seeks to separate useful monomers/polymers from the mixed plastic waste with a range of solvents. In many cases, the solvents themselves are hazardous and/or flammable, and even if recyclable, a certain fraction will be as waste fraction or as a byproduct of the process.

3.4 MICROPLASTICS AND CONTAMINATED WASTEWATER

Stockpiling, shredding, cleaning, and other pretreatment of plastic waste at recycling plants has recently been found to be a major source of microplastic pollution, especially in wastewater released from such facilities. In one study, up to 13% of all incoming waste ended as microplastics waste at the facility (Brown et al. 2023).

At the Brightmark, Indiana, chemical recycling facility, which shreds and pelletizes plastic waste on-site before feeding it into six pyrolysis units, an employee has claimed their lung injuries followed from exposure to microplastic dust. The facility has also recently experienced several fires and significant oil spills. These problems have occurred even before the plant is commercially operating, with an inspector[25] from the Indiana Department of Environmental Management noting that it "has yet to create product on-site."

Other forms of water pollution from chemical recycling facilities can also impact fenceline communities when wastewater is discharged to local waterways. As water use is very high at some plants for washing plastic waste and process cooling, wastewater volumes can be significant. Microplastic pollution from wastewater has been identified as a potential problem at plastic recycling plants (Brown et al. 2023), and PFAS and phenol contamination of waterways may also occur (see Technical Addendum Section 2.5).

Fire at New Hope Energy's Trinity Oaks plastics recycling plant in Tyler, Texas. Source: City of Tyler Fire Department

3.5 FIRES AND EXPLOSIONS

Since China's National Sword Policy, which banned the importation of certain types of solid waste, including plastic, plastic waste stockpiles in the U.S. and other OECD countries have multiplied and grown rapidly, and in many cases pose fire risks. Since plastic wastes are petrochemicals, they are flammable, and stockpile fires are difficult to extinguish. In the U.S., plastic waste stockpile fires have been increasing in both size and severity, though not all such fires are reported in the media. The U.S. nonprofit group The Last Beach Cleanup has been mapping plastic-waste fires[26] that are reported in the U.S. (see Figure 7).

Plastic waste stockpile fires release a complex cocktail of poisonous chemicals, including air toxics such as volatile organic compounds, benzene, chlorine, and hydrogen cyanide, and particulates that are sometimes monitored[27] by the U.S. EPA and other emergency response officials. Open burning of plastic waste has also been demonstrated to contaminate soil and the food chain with brominated and chlorinated dioxins (PBDD/DF and PCDD/DF), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers, per- and polyfluoroalkyl substances (PFAS), hexabromocyclododecane (HBCD) compounds, and a range of other highly toxic persistent organic pollutants (Petrlik, et al. 2021a, Petrlik et al. 2021b).

Very high levels of dioxin and other POPs were found in chicken eggs at many locations around the world where plastic waste had been open-burned on the ground or burned as a fuel. While chicken eggs are effective indicators of local soil contamination as chickens forage from the soil, humans can be impacted by exposure to the contaminated soil and dust blown around following a fire. The persistence of some of these highly toxic chemicals means they can recirculate in soil and dust through the community for many years without breaking down.

Process fires from the operation of solvent-based and pyrolysis facilities can also be expected. Even though not yet fully operational, the Brightmark, Indiana, facility has already had several fires,[28] including reactor fires that resulted in releases of contaminated process vapors that ignited and developed a fire jet from the reactor that was difficult to bring under control. The New Hope pyrolysis plant in Tyler, Texas, also suffered a fire in 2020.[29]

In other countries, there have been several major fires and explosions at pyrolysis plants. In 2020, a plastic waste pyrolysis plant near a school in the town of Egebjerg, Denmark, experienced a major explosion, causing damage to the equipment. It exploded again in 2021, resulting in plastic waste stockpile fires and the complete destruction of the plant. The cause was attributed to flammable pyrolysis vapors self-igniting (Hedlund 2023). This was also the cause of a fire at the Brightmark, Indiana, facility. In Finland in 2014, the Fortum Power and Heat Oy in Joensuu suffered a significant explosion[30] due to nitrogen levels (used to suppress oxygen ingress to the reactor) dropping below acceptable levels due to a system blockage. Three workers were injured.

These incidents sometimes occur because pyrolysis is an inherently dangerous process using flammable gases under heat and pressure. Unless high levels of risk assessment and hazard mitigation as well as strict operating procedures are observed, the possibility of fire, explosion, and toxic gas release remain a concern.

Figure 7 Fires at U.S. Plastic Recycling Facilities

Source: The Last Beach Cleanups

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CHAPTER 4

LINKAGES TO INTERNATIONAL POLICY

Source: UNEP/Ahmed Nayim Yussuf

Chemical, or advanced recycling is promoted and/or invested in by plastic producers, petrochemical corporations, fast-moving consumer goods companies (FMCGs), and related industry associations as the solution to plastic pollution. It is not.

Influential bodies at an international level are not convinced such technologies present a solution. The international environmental policy community is rightly asking questions such as "Is burning plastic-derived fuels really recycling?" "At what point in the chemical recycling process can plastic waste be considered recycled?" "Is chemical recycling even environmentally sound management for plastic waste?" and so on. Some international legal instruments and regional economic entities have already arrived at a determination for some of these questions.

This chapter explains how the global environmental policy community is currently approaching this issue and the implications for chemical recycling in a world blanketed by plastic pollution.

Important global legal instruments that govern plastic waste are the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, more commonly referred to as the Basel Convention. Another is the Stockholm Convention on Persistent Organic Pollutants, otherwise known as the Stockholm Convention. Both these conventions deal with plastic waste as a subset of larger groups of hazardous wastes.

A third legal instrument is currently under negotiation and may become a global plastics treaty. The third international negotiating committee (INC 3) determining the scope and text of this new convention is scheduled to meet in November 2023 in Nairobi, Kenya. An outcome of this process and a new treaty or convention specifically targeting plastic waste may yet be several years away. However, it is likely that such a treaty will rely on existing technical guidance for plastic waste management, including guidelines on different forms of plastic waste management, recycling, and disposal, as this is typical of the chemical and waste multilateral environmental agreements.

In considering international linkages to plastic waste, it is important to reflect on how these international legal instruments address chemical recycling, if at all.

There is no global legal definition of chemical recycling. However, the terms and techniques that are associated with this sector are covered in Part 1 of the Technical Addendum. The American Chemistry Council promotes the use of chemical recycling, which it calls "advanced recycling," and refers to such plants as plastics-to-fuel and petrochemistry[1] (PTFP) manufacturing facilities. To assess whether chemical recycling does constitute some form of environmentally beneficial recycling, it is also important to consider policy principles that underlie international instruments on waste and chemicals, such as environmentally sound management of waste, sustainability, the waste hierarchy, and the circular economy.

4.1 THE BASEL CONVENTION AND ENVIRONMENTALLY SOUND MANAGEMENT

The Basel Convention has the primary function of regulating transboundary trade in hazardous waste. To support that function, it has defined most types of hazardous waste and developed a range of technical guidance that is considered best practice for managing these wastes. Best practice constitutes the management of hazardous waste in an environmentally sound manner.

For example, burning plastic waste in an open field is not considered environmentally sound management as it produces many hazardous emissions, releases toxic compounds into the soil and the food chain, and can cause severe direct and indirect human health impacts. Mechanical recycling of plastic waste is currently regarded as environmentally sound management because regulatory agencies state it is able to retain the resources in recyclable plastic wastes; it can be controlled to limit hazards, emissions, and wastes to acceptable levels; and it has a comparatively low greenhouse gas footprint, depending on how it is conducted.

This becomes important in international law, as the Basel Convention guidelines for hazardous waste management can only include those practices considered to be environmentally sound. The application of this term to chemical recycling has been subject to intense and protracted debate and is discussed further in the next section.

4.1.1 THE BASEL CONVENTION'S POSITION ON CHEMICAL RECYCLING

As part of the negotiations for the Basel Convention, a decision was made at the Conference of the Parties (COP) in May 2019 to include plastic waste in the scope of the convention. This would require prior informed consent (PIC) to be given by importing parties before exporting parties could ship plastic waste to them. This was consistent with the rules for transboundary movement of most other types of hazardous waste under the convention. In addition, the Basel Convention Ban Amendment[2] was adopted on December 5, 2019, and this went further to prohibit the export of hazardous wastes from member states of the European Union, the Organization for Economic Cooperation and Development (OECD), and Liechtenstein to all other countries.

The amendment effectively banned exports of most plastic waste from wealthy countries to developing countries. In turn, this drove the need for a solution to growing stockpiles of plastic waste in wealthy countries that could no longer legally or easily dump their plastic waste on developing countries, which had been a widespread practice for years. Within this context, the Conference of the Parties (COP) of the Basel Convention also decided to update its technical guidelines on plastic waste management, which had not been reviewed since 2002.

During the update process, which ran from September 2019 to May 2023, it had been proposed that a section on chemical recycling should be included in the updated guidelines. While most of this update process was negotiated within a small intersessional working group[3] of the convention and much was agreed upon, the section on chemical recycling became highly problematic and nearly prevented the adoption of the guidance at the May 2023 COP.

Over 50 countries objected to the inclusion of chemical recycling in the guidelines on the basis that there was no available independent data to demonstrate that chemical recycling constituted environmentally sound management of plastic waste.

During the extended negotiations on the matter, over 50 countries objected to the inclusion of chemical recycling in the guidelines on the basis that there was no available independent data to demonstrate that chemical recycling constituted environmentally sound management of plastic waste.

Despite 50 years of operation of these technologies, no empirical data was presented to demonstrate they met criteria for environmentally sound management. The information that was available included data on widespread failures of the technology over decades, high volumes of toxic waste produced, and very high energy use and associated greenhouse gas emissions.

This raised serious concern among delegates, who, despite last-minute negotiations, opted to place the entire chapter on chemical recycling in brackets in an annex to the guidance. Therefore the inclusion of chemical recycling in the guidance was not agreed to and the text has no guidance status. This represents a blow to the credibility of chemical recycling on the international stage, demonstrating that chemical recycling remains unproven and is not regarded as an environmentally sound management technique for plastic waste.

One of the main reasons for this decision is the chemical recycling industry's refusal to reveal data on emissions, hazardous waste streams, environmental impacts, and performance characteristics. The decades-long history of bankruptcies, case studies of pollution, and technological failures suggest they were unable or unwilling to present such information.

As noted by an industry analyst, "Throughout this report, the overriding finding is that there is a general lack of transparency or robust evidence base that can be used to verify claims or generate firm conclusions around the viability of many technologies.... In the interests of confirming the role, scale, and scope of these technologies, there is an urgent need for more transparency within the chemical recycling industry." (Eunomia 2020).

4.2 PLASTIC TO FUEL: RECYCLING OR BURNING MORE FOSSIL FUELS?

As explained in the Technical Addendum to this report, chemical recycling has major technical and economic challenges that limit its commercial viability to operate at scale as a plastic-to-plastic (PTP) recycling technology. As a result, the majority of output from chemical recycling to date has been plastic to fuel (PTF).

The main outputs of chemical recycling technologies like pyrolysis are a mix of hydrocarbon liquids (pyrolysis oil), solid char, waxes, tars, and pyrolysis gas. These are all flammable and possible to use as fuels, although some level of further refinement is often necessary even for low-grade fuel oils. To obtain high-grade fuels, expensive upgrading is required.

While major petrochemical and plastic-producing corporations claim they are investing billions[4] of dollars in chemical recycling globally and promoting this investment as plastic-to-plastic recycling, it is anticipated that most of the output will end up burned as fuels. This is especially true of pyrolysis technologies, which form the majority of chemical recycling proposals and startups.

The EU has been concerned about this tendency for pyrolysis output to be used as fuel, noting its potential to undermine a circular economy: "There is significant uncertainty about whether building a pyrolysis infrastructure to recycle plastics will actually lead to new materials, or only to fuels. Such a linear lock-in is clearly not in line with the basic principles of a circular economy and is one of the major concerns when considering the role of pyrolysis in the plastics economy" (Crippa et al. 2019).

Use of plastic pyrolysis output as crude fuels for power plants or a substitute for bunker fuel in ships has been identified as the current main market for this material in the EU, though other markets may exist for waxes and other outputs (Crippa et al. 2019). If the market position does not change substantially, then plastic-to-fuel may become an entrenched feature of chemical recycling. This establishes a linear rather than circular future for plastics, perpetuating a cycle of petrochemical extraction, plastic production, and burning — thereby requiring the cycle to be repeated to produce new plastic.

Other analysts have reached the same conclusion: "To invest in pyrolysis infrastructure to treat all types of currently unrecyclable plastic might 'lock in' increased environmental impacts over the long term in a similar way in which the shift toward WTE has done so in countries that have invested heavily in incinerators" (Eunomia 2020).

Some market analysts[5] estimate the global plastic-to-fuel market size was valued at $231.0 million in 2020 and is expected to grow at a compound annual growth rate of 29.5% from 2021 to 2028, with pyrolysis accounting for 61% of the revenue generated in the sector. Other analysts[6] suggest similar U.S.-specific market values of $121 million but a much lower compound annual growth rate of 7% between 2022 and 2032. This suggests more than 50% of the value of the global plastic-to-fuel market is based in the U.S.

Analysts suggest that obstacles to growth of the sector include plastic-derived fuels being less lucrative than fossil fuel production and a lack of economies of scale. But most important, the quality of the plastic waste feedstock will be the major determinant of future plastic to fuel market trends. In other words, heterogenous feedstock, contamination by additives, and external substances may severely impact the ability to process the waste into fuel, let alone new plastic.

Plastic is mostly made of petrochemicals derived from fossil fuels, so its use as a basis for fuel is neither good for the climate nor an environmentally friendly substitute for traditional, oil-based fossil fuels or even coal. In addition, fossil fuels are required to power most pyrolysis and gasification plants so they can reach and maintain operating temperatures, even if some of the outputs are used to fuel the process itself. The term for such an energy draw is "parasitic load," and in some cases, it can use the majority of the process output. While some proponents claim their operational energy needs can be entirely met by their outputs and still remain profitable, such hyperbole has been categorically debunked, not least because it contradicts the laws of thermodynamics (see Technical Addendum, Section 1.4).

From a climate impact perspective, or even a financial perspective, it does not make sense to use fossil fuels to power a process to convert fossil-fuel-based plastics back into hydrocarbon fuels and then burn them. We cannot burn our way out of the climate crisis using plastic waste.

4.2.1 THE BASEL CONVENTION'S POSITION ON PLASTIC TO FUEL

The Basel Convention Technical Guidelines for the identification and environmentally sound management of plastic wastes and for their disposal (UNEP 2023) addresses plastic to fuel and confirms that plastic to fuel is not recycling but is instead a disposal operation.

> ***"Plastic to fuel is not recycling but is instead a disposal operation."***
>
> ***—Basel Convention Technical Guidelines***

The U.S. signed the convention in 1992 but has never ratified it and therefore is not a party to the convention. However, by signing the convention, the U.S. does have certain responsibilities, the foremost of which is to refrain from acts that would defeat the object and purpose of the treaty. Such acts would include classifying plastic to fuel as recycling, exporting plastic wastes to parties of the convention (in contravention of the Basel Ban Amendment), and potentially exporting plastic-to-fuel technologies to convention parties under the guise of plastic recycling.

4.2.2 THE EU'S POSITION ON PLASTIC TO FUEL

The European Union agrees that burning materials, including plastic, to capture energy is not recycling[7] but is actually energy recovery that does not contribute to a circular economy for plastics. Energy recovery from wastes is a less preferred option for sustainability than recycling, and so fuels from processing plastic waste are not regarded as recycling. This has important implications for chemical recycling technologies that only produce hydrocarbon fuels, since they cannot be labeled recycling technologies. However, the same technologies, such as pyrolysis and gasification, can be determined to be recycling technologies only if the output (hydrocarbon liquids, waxes, and syngas) are used as feedstock to make new chemicals or plastic.

Clearly the EU has taken a rational approach and concedes that turning plastics, which are petrochemicals, into hydrocarbon fuels to burn does nothing for sustainability or circularity and exacerbates climate change. Plastic-based fuels are not green, renewable, or an alternative to fossil fuels, and they perpetuate a linear economy for plastics. The manufacture of plastic-based fuels should be prohibited as their manufacture and use represent significant hazards to human health (see Section 3) and the environment.

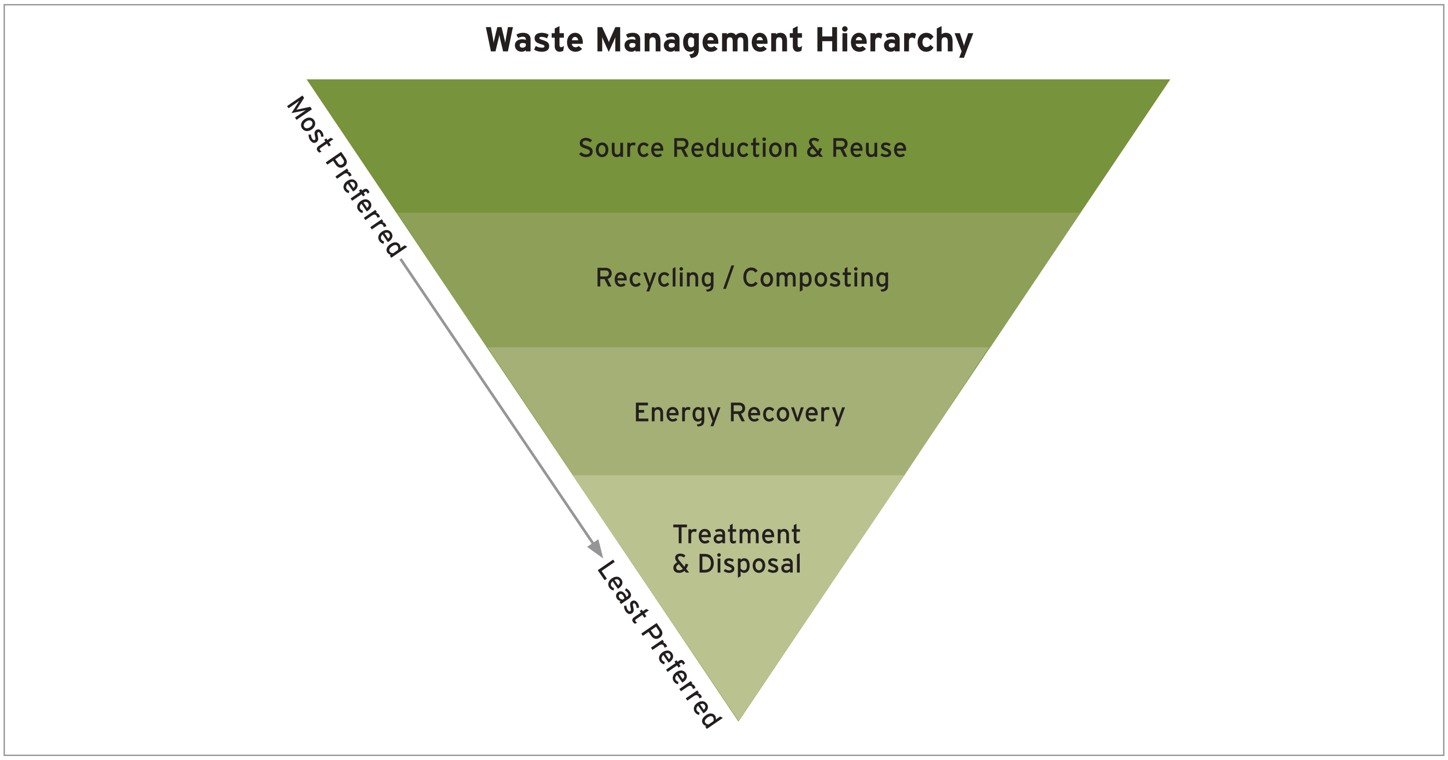
4.3 THE WASTE HIERARCHY AND CHEMICAL RECYCLING: DISPOSAL, RECOVERY, OR RECYCLING?

The common waste hierarchy is used in waste policy as a ranking system of preferred options for managing the material resources that make up waste. Over the years, the waste hierarchy has evolved and been refined as technology has developed and the emergence of the circular economy concept (European Commission 2020) has been more widely adopted.

Recycling definitions vary from country to country, but most people understand recycling as taking waste materials and giving them a further useful life by processing them into products, materials, or substances to be used for their original or other purposes. Governments and researchers have developed priority actions for wastes that try to meet sustainability principles and achieve the best and highest-value use of materials in the waste stream while protecting the environment. While concepts of the waste hierarchy emerged in environmental literature in the 1970s, and some elements appeared in the European Union's Waste Framework Directive[8] of 1975, it was not until the 1989 European Commission's Community Strategy for Waste Management[9] that the elements were formalized into a series of guidelines by priority.

Typically, recycling has been placed midway within a waste hierarchy that prioritizes waste avoidance and reuse of materials over recycling. Further, the hierarchy prioritizes recycling over recovery and disposal. Recovery typically describes either material or energy recovered from wastes. Energy recovery is the burning of waste materials in incinerators to generate electricity or municipal steam heating or the conversion of wastes to liquid or solid fuels to burn. Co-processing plastic waste in cement kilns may also be deemed recovery, as the energy from the burning plastic contributes to the fuel needs of the cement plant. Typically, the least preferred level of the hierarchy is disposal, which refers to dumping, landfilling, and incineration without energy recovery, such as in the U.S. EPA conceptual waste hierarchy (see Figure 8).

Figure 8 U.S. EPA's 2023 Version of the Waste Hierarchy (currently under review)[10]



Source: U.S. Environmental Protection Agency

However, as science reveals more about the impacts of various waste management methods including climate impacts, generation of hazardous emissions, and waste's fate in the environment, the conceptual waste hierarchy continues to evolve. In parallel, the prioritization of recycling may also shift within the hierarchy, which determines the best and highest value of waste materials and the most sustainable practices.

In addition to the waste hierarchy, the concept of a circular economy — which places material resource reuse at its highest value within a closed loop — has also gained traction in many countries and especially in the European Union and at the global policy level (European Commission 2020). The development of the circular economy concept, concerns over climate change, and the breaching of planetary boundaries by certain chemical substances continue to influence the development of the waste hierarchy.

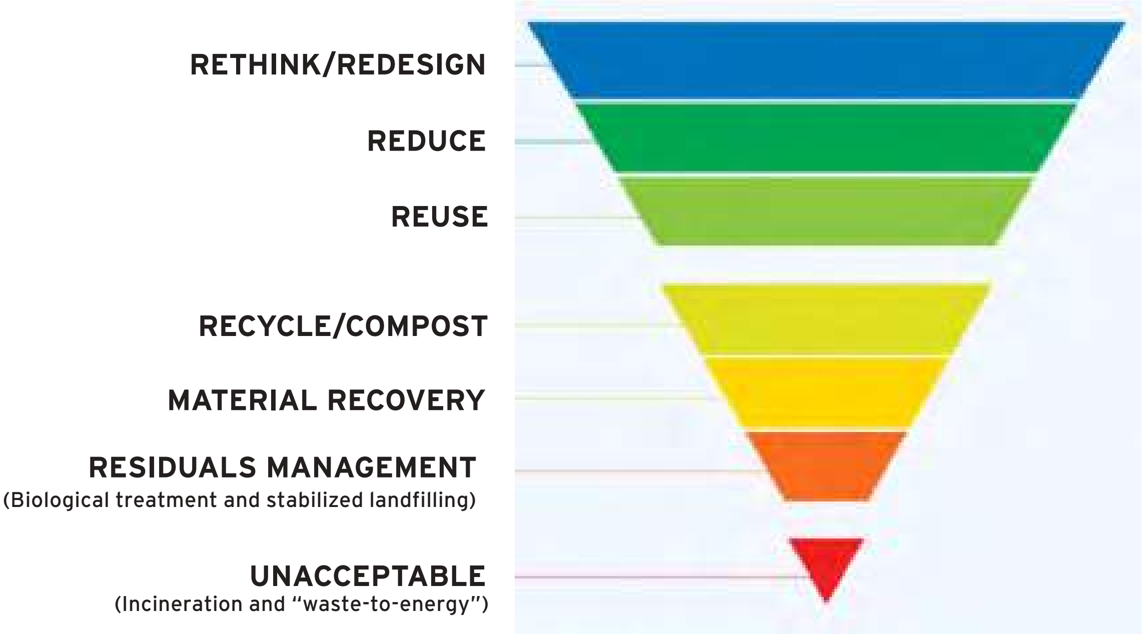
This has been underscored by the UN's recognition of the triple planetary crisis of climate change, pollution, and biodiversity loss, which overlap and have many linkages, demonstrating the currently unsustainable nature of our societies and economies. Despite growing awareness of these ecological crises, in most instances concepts of the waste hierarchy and the circular economy are still couched in an industrial, consumer/producer efficiency paradigm rather than expressing an approach centered on environmental protection and human health and well-being.

Assumptions behind the circular economy, including for plastics, tend toward technical fixes and material efficiencies within a growth economy that is both socially inequitable and at odds with finite resources. Some analysts point out that a circular economy for plastics is not achievable unless the concept of "sufficiency" is integrated into the design of the system (Mederake 2022).

The concept of material, financial, and social sufficiency for society is at odds with the current growth model and technocratic concept of a circular economy. It envisages a society in which people tolerate sufficient resources and belongings, prioritize human health and well-being over monetary accumulation, and collectively plan for the long term with a sense of collective responsibility (Bocken and Short 2020). For plastics, this would mean a significant reduction in virgin plastic production, reduced use of toxic chemicals, and a greater focus on the upper part of the waste hierarchy — avoidance, reuse, repair, and so on.

One waste hierarchy concept that does center on the need for protection of the environment and human health from the negative impacts of waste is the Zero Waste Hierarchy,[11] which is best described as "the conservation of all resources by means of responsible production, consumption, reuse, and recovery of products, packaging, and materials without burning and with no discharges to land, water, or air that threaten the environment or human health" (ZWIA 2018) (see Figure 9).

Figure 9 The Zero Waste Hierarchy



Source: Zero Waste International Alliance

Importantly, a Zero Waste hierarchy for approaching end-of-use materials prioritizes redesign of products and materials to allow, where possible, for highest-value options to apply to those products in and beyond the waste phase (see Figure 9). The current design of plastics with toxic additives and immiscible polymers is a key factor in preventing the conventional recycling of plastics, forcing them into the least desirable levels of the waste hierarchy, largely landfill and incineration, sometimes with energy recovery. Redesign of plastics to improve durability to allow more reuse and repair while prohibiting toxic ingredients and polymers could improve conventional recyclability. We do not need everyone doing zero-waste perfectly — we just need many people doing it well.

In the Zero Waste Hierarchy, chemical recycling at best falls into the category below recycling called "material recovery" because of high energy use, large residual waste streams, low yields for pyrolysis, and the lock-in to more plastic production. The generation of large volumes of hazardous and solid waste from chemical recycling is also at odds with the Basel Convention Guidance on environmentally sound management since the generation of new and hazardous waste from plastic waste management is not permitted.

It is also the case that no yield from a chemical recycling process has actually been recycled until it has been directly used to make new plastic or chemicals. It is simply recovered material. If this yield is then used to make some form of fuel, it is then relegated further down the hierarchy to the least preferred "waste to energy" category and cannot be considered recycling. This position is supported in EU legislation and in the Basel Convention guidelines on plastic waste, where use of plastic waste as a fuel is categorized as a disposal operation and not recycling.

The unacceptable practices tier at the bottom of the hierarchy, such as waste to energy (e.g., plastic to fuel and refuse-derived fuel), acknowledges the serious toxic emissions, resource loss, and carbon footprint typical of the sector. Even these options are unavailable in many developing countries, leading to open dumping and burning of plastic waste, which causes extremely toxic soil contamination and poisons the food chain, endangering human health (Petrlik et al. 2019, Petrlik et al. 2021, New York Times 2019,[12] BBC 2019[13]). Notable in this waste hierarchy configuration is the preference for stabilized landfilling (and perhaps plastic monofil) over processes that burn plastic waste, mainly due to the climate and toxicity impacts of the latter.

There are advantages to landfilling plastic over burning it, but these are attained only if plastic is disposed of separately from organic and all other wastes, essentially creating a plastic monofill. This can allow, over time, attribution of extended producer responsibility and polluter-pays mechanisms to specific plastic waste stockpiles. Monofill allows storage of only plastic waste until treatment processes with minimal environmental impact can be developed. However, leaching of toxic additives to groundwater can still be a problem unless the landfill is completely sealed to precipitation, which is unlikely.

4.4 CHEMICAL RECYCLING: AT WHAT POINT DOES ANY RECYCLING ACTUALLY OCCUR?

A critical element to define whether a certain activity is recycling or not is to examine at which point in the waste/materials management process such material ceases to be waste and becomes something that has been "recycled." In common usage, many people believe they are recycling when they place their discarded plastic bottle or wrapper in a recycling bin. However, there is no guarantee that their discarded items will ever be recycled; they could end up in a landfill, cement kiln, or incinerator. Collection does not equal recycling. Similarly, sorting, washing, shredding, extruding, and otherwise pretreating plastic waste should not be regarded as recycling. The same principle should apply to chemical recycling processes.

Treating plastic waste in a pyrolysis, gasification, or solvent plant does not, of itself, equate to recycling. Even producing output from such plants may not be considered recycling, since it depends on how the output is used. If the output is stockpiled in warehouses, dumped in a landfill, used as fuel, or incinerated, then nothing has been recycled. Only outputs that are directly used to create new base chemicals or plastic feedstock chemicals count as recycling. Simply stockpiling such outputs at the chemical recycling facility does not constitute recycling, nor does using output to heat or fuel the chemical recycling plant — the so-called parasitic energy loads.

Often, a significant fraction of the chemical recycling output used as feedstock for plastic production will be lost within the refinery processes as gaseous emissions and solid and liquid wastes. Thus, 100% of the feedstock input to a refinery cannot be counted as "recycled" material due to process losses within the refinery. This leads to the issue of recycled content traceability (see Section 4.5).

In many current chemical recycling facility proposals, offtake agreements with petrochemical refineries are lauded as examples of plastic waste recycling and successful chemical recycling. An arrangement between a producer and a buyer to purchase or sell portions of the producer's upcoming goods, an offtake agreement, is usually agreed upon before the final construction of a facility to secure a market and revenue stream for future output. The claims often suggest that pyrolysis oil will be upgraded and refined further before being blended with virgin feedstock at the refinery. All of this leads to further losses of material once the output leaves the gate of the chemical recycler and before anything has actually been recycled.

At this point, very little information has been released to suggest that U.S. refineries have received any shipments of pyrolysis outputs, and if so, how much. A number of claims referring to such agreements and potential shipments are noted in the case studies (see Appendix 1). However, tracing the percentage of the chemical recycling output delivered to refineries that might actually end up in new chemicals or as usable polymer is notoriously difficult to measure and almost impossible to determine (Eunomia 2020). Traceability of this material is critical to determining whether and how much recycling has actually taken place, and various accounting mechanisms have been proposed (see Section 4.5).

Most output from chemical recycling, such as pyrolysis oil, is too contaminated to use directly in chemical or plastic manufacturing (Sundaram and Stancato 2018). To prevent system problems, it must be blended into large volumes of virgin hydrocarbon feedstock, such as naphtha, at the refinery. Any refining of the pyrolysis oil to decrease process problems reduces the volume of material left to recycle. Further losses in the steam cracking/reformation systems increase the amount lost as waste from the system. A refinery may also direct part of the pyrolysis oil to fuels or even use it for parasitic loads for the refinery, neither of which constitutes recycling.

Under these loss scenarios, the volume of chemical recycling output that reaches the refinery cannot be said to match the amount that may become feedstock for recycled polymer production. Once a consignment of chemical recycling output reaches a refinery, it effectively enters a black box, and determining its fate as "recycled content" in a finished product may not be possible. Indeed, industry analysts[14] have conceded that with a plastic production and refining complex, "it is not possible to physically track where recycled feedstock ends up" (Recycling International 2023).

Further, if chemical recycling output can only be blended at low rates with virgin fossil-based feedstock due to process limitations, it becomes untenable to argue that chemical recycling will somehow achieve circularity for plastics, since it will always be highly dependent on virgin feedstock to become an even partially recycled end product.

The chemical recycling industry knows that traceability of its output to the production stage of new plastics is almost impossible. Therefore, it is now pushing regulators to adopt a "mass balance approach" with "free allocation" to calculate how much of its output can be called recycled content. However, this concept is fraught with problems when applied to chemical recycling and can be highly misleading.

4.5 THE MASS BALANCE 'FREE ALLOCATION' APPROACH TO RECYCLED CONTENT: WIDE OPEN TO EXPLOITATION

As countries attempt to develop new policies for materials, the issue of traceability of recycled plastics content within products becomes increasingly important. As an example, the European Commission has developed a Single-Use Plastics (SUP) Directive to ensure at least 25% recycled content in PET bottles by 2025, and 30% in all beverage bottles by 2030 (European Commission 2019).

This type of policy is intended to drive demand for recycled plastic and help support that market. However, to determine if these criteria are being met, the ability to trace and measure recycled content is paramount. As it is practically and physically impossible to trace chemically recycled feedstock content through the plastic production process when it is mixed with virgin inputs, a form of measurement is required to certify the recycled content in the final product. There are currently no credible international laws,[15] regulations, or standards that have been developed to determine chemically recycled content used in new plastic products.

Despite the lack of any credible standards for determining recycled content in products made from chemical recycling outputs, the chemical industry[16] is promoting a "free allocation," flexible mass-balance approach. Mass balance is an accounting approach to track the inputs, outputs, and distribution of a substance within a process. When outputs from chemical recycling are mixed with virgin hydrocarbons as inputs to new plastic production processes, as at refineries, the distribution of recycled and virgin inputs cannot be physically measured in the final product.

Mass balance accounting creates theoretical attribution of recycled content, based on the physical volume of the recycled material input. The higher the level of flexibility in the mass balance accounting, the lower the confidence level in the actual physical content of recycled material in the final product. The industry's mass balance accounting proposal is focused on high levels of flexibility, including creative accounting that allows recycled content allocation within a company at multiple plants, across product lines, and even between countries.

Arbitrary allocation of recycled content across product lines of the same company could mean some products could be claimed as fully recycled when containing only a small fraction of recycled content or even none. The concept effectively divorces the physical reality of a plastic product from its recycled content in favor of a theoretical distribution of recycled inputs across multiple production facilities and/or national borders. This approach has been labeled as greenwashing and blatantly deceptive to consumers.[17]

Mass balance approaches derive from chain-of-custody models and are not a single formula, varying dramatically based on the assumptions and degree of flexibility allowed in the system. The greater the flexibility, the less the transparency in the system. If the system is not transparent and products containing only a small fraction or no recycled content are marketed as "recycled," public confidence in the products will diminish and the credibility of the recycling industry will be at risk. It raises the serious issue of truth in labeling and the consumer's right to know about what they are purchasing.

A consumer wanting to purchase products that are more sustainable may read a label claiming their beverage bottle has 30% recycled content when in fact it has little or none, constituting false advertising and leading to less sustainable purchasing decisions. It may also have implications for governments wishing to tax products that don't meet minimum recycled content criteria or present risks to those in the supply chain using such materials.

The petrochemical and plastic products industry is promoting the International Sustainability and Carbon Certification[18] (ISCC) group's ISCC Plus certification for mass balance, which supports the free allocation approach. Critics contend that the ISCC scheme does not mandate the source of the plastic feedstock, so it does not have to be post-consumer plastic waste. Under the ISCC scheme, it could be clean, post-industrial plastic scrap, "wide-spec resins" (resins that are off-grade for commercial application), or even used cooking oil.[19] This would do nothing to address post-consumer plastic waste recycling.

The opaque "free allocation" mass balance can be manipulated to the point where 100% virgin plastic could be labeled as 100% recycled plastic. However, there is also a batch-level mass balance approach, which is much more accurate.

1) **Batch-Level Mass Balance:** In this calculation, the recycled input is averaged across a batch of plastic produced in a production line, but will only show accurate and low levels of recycled content, because pyrolysis oil must be heavily diluted with virgin naphtha. While not accounting for process losses of, for example, pyrolysis oil input, it is more accurate than other mass balance approaches that the industry is seeking.

2) **Group-Level (Free Allocation) Mass Balance:** In this calculation, the recycled feedstock can be allocated to certain products within the entire product range of a company, or at "group level" to products at one company facility but not another, or distributed across many facilities. This divorces the end product from actual measurement of recycled content in favor of theoretical, distributed recycled content input somewhere in the company's processes.

Eunomia notes that this "means that rather than the material being traded as recycled, it is the 'right' to claim recycled content that is traded (i.e., the link becomes abstract rather than physical by the time it reaches the consumer)."

Further, Eunomia 2020 warns, "At the extreme, it is possible at the group level that 100% virgin material output from a particular plant could be claimed as 100% recycled if a customer of that region requires it and there are 'credits' within the group available. Such an approach seems likely to give rise to issues with consumer communication."

For example, if a polymer production facility hypothetically produces 1,000 tons of polymer using 40 tons of pyrolysis oil feedstock and 960 tons of virgin feedstock, the physical reality (ignoring process system losses of the pyrolysis oil for the moment) is that the 1,000 tons of output contain, on average, 4% recycled content if calculated on batch-level mass balance.

However, under flexible mass balance accounting using "free allocation" (group-level mass balance) with the same inputs, the production facility could claim that it has produced 80 tons of "green plastic" with 50% recycled content and make no claim about the remaining 920 tons of plastic produced. Alternatively, it might claim 40 tons of "green plastic" with 100% recycled content and make no claim about the remaining 960 tons — thereby allowing it to meet certain recycled content requirements for at least part of its production or certain product lines. High flexibility levels within the free allocation scheme could allow pyrolysis oil burned as fuel in plastic production processes to be counted as recycled content in a final plastic product, even though it actually contains none.

Some industry associations argue that having to use dedicated individual chemical recycling/plastic refining facilities rather than blending pyrolysis oil at refineries using virgin stock will be a cost barrier to scale up, have impacts due to transport logistics, and force them to build new infrastructure. However, the motive is more likely that only small quantities of poor-quality pyrolysis feedstock oil can be used at any facility and will need to be blended with large volumes of virgin hydrocarbons, hence the need to distribute it to existing refining facilities. The plastics industry is also seeking a self-regulatory system to audit the transparency of these systems.

Even some industry associations are wary of the implications of free allocation mass balance. In a submission to the U.S. Federal Trade Commission on the review of its Green Guides,[20] a guidance document that advises product marketers how to avoid false or misleading marketing of "green" products, the Association of Plastic Recyclers commented:[21] "Consumers purchase a product with recycled content with the implied understanding there are recycled materials in that actual product, and claims must conform to that understanding. Making recycled content claims in on-pack labeling, based on mass balance calculations, is deceptive to the consumer because there is little to no physical traceability to prove that there is any physical recycled content in the actual product, which is contrary to what the consumer believes to be true."

A key international decision on the issue will be the accounting method for the EU Single-Use Plastics Directive (SUPD) calculating recycled content (currently under development), which will, in some form, become the industry standard for a globally harmonized system within which the petrochemical and FMCG companies seek to operate. To this end, 33 European industry associations[22] related to plastics have recently called for the EU to adopt the free allocation mass balance systems proposed by the Ellen MacArthur Foundation (CEFIC 2023). Other stakeholders[23] have opposed this approach for its lack of transparency and support batch-level mass balance, which allocates feedstock proportionally to any plastic production line and links the physical product to the recycled content it contains.

In the UK, discussions over their calculation method have been ongoing for a year and half as regulators have reservations about the free attribution approach, and have now opened a public consultation process[24] on the issue. This is due to UK tax officials having implemented a tax on plastic packaging that falls below 30% recycled content at a rate of £210.82/metric ton under the Plastics Packaging Tax (PPT)[25] as of April 1, 2023. The use of free allocation mass balance has the potential to significantly distort such a scheme and allow plastic producers to engage in tax avoidance and to frustrate efforts to move policy to a more sustainable footing around plastic production.

If transparency in mass balance models is poor and enforcement of standards is weak, then the manner in which products are traded, as recycled or otherwise, will become critical for the credibility of chemical recycling and recycled plastic products more generally. It could also unfairly impact plastic producers using recycled plastic from the conventional recycling industry and producers who are able to accurately measure recycled content in their products. A lack of transparency around recycled content from those using feedstock from the chemical recycling sector could prevent a level playing field for those using mechanically recycled plastics, and consumers may lose confidence in both sectors as a result.

At this point, the industry's call for free allocation mass balance systems that lack transparency and are wide open to exploitation suggests a cynical exercise in greenwashing while appearing to meet recycled content regulations.

4.5.1 PLASTIC CREDIT TRADING SCHEMES: LESS TRANSPARENCY, MORE GREENWASHING

A similar but even less transparent approach to recycled plastic is the "plastic credit scheme," whereby companies producing plastic can buy and trade credits from a third party to offset collecting, recycling, and/or repurposing plastic waste in other locations in an attempt to achieve "plastic neutrality."[26] Much like carbon credits, such schemes are open to exploitation and do nothing to curb the unfettered production of new plastic or widespread microplastic pollution.

Recycled-content credit trading schemes[27] have been identified as lacking consistent definitions, standards, and best-practice principles, with some actors playing several potentially conflicting roles that could undermine the credibility of the schemes and amplify the risks of greenwashing.[28]

If combined with free-allocation mass balance schemes, the use of plastic credits will remove transparency about the recycled-content of plastic products, mislead consumers about the nature of the plastic products they purchase, and could cause perverse outcomes that see demand shift to products that are positioned as sustainable, but are actually made from virgin plastic. This would amount to an elaborate accounting regime allowing business as usual for plastic production to continue, while misleading regulators and consumers.

4.6 THE STOCKHOLM CONVENTION: CONTAMINATED PLASTICS, UPOPS EMISSIONS, AND POPS WASTE IN CHEMICAL RECYCLING

The Stockholm Convention on Persistent Organic Pollutants (POPs) is relevant to chemical recycling in several ways. It is a global treaty to restrict or prohibit the use and production of chemicals that have been assessed as POPs by a scientific review committee that advises the Conference of the Parties (COP), which considers listing new chemicals for restrictions at each of its meetings.

There are currently over 30 of the world's most hazardous, toxic, and persistent chemicals listed on the convention annexes. The convention also lays out strict guidance on the mandatory destruction of POPs waste and provides ”best available technique/best environmental practice” (BAT BEP) guidance on how to run industrial processes that are known to generate POPs or have exemptions to use them.

The relevance to chemical recycling is that many plastics are known to contain POPs as intentional additives (Pivnenko et al. 2017, Chakraborty et al. 2022), unintentional trace contamination from production, or from environmental adsorption as marine pollution (Hirai et al. 2011).

When the contaminated plastics are processed through gasification and pyrolysis plants, the contaminants can be transferred to emissions, solid waste, or output products of the process. This can also result in a POP-contaminated residual hazardous waste stream from the process. Additionally, it could cause contamination of the chemical recycling output, which acts as a vector to carry POPs into new plastic products made from such outputs. If the output is used as fuel, then the POPs may be emitted into the atmosphere as the fuel is burned. Open burning of plastic waste containing POP additives has resulted in serious food-chain contamination (Petrlik et al. 2021, Tue et al. 2016).

Gasification and pyrolysis are also known to be sources of dioxins and furans (PCDD/DF), some of the most hazardous POPs ever studied, due to their operation at the UPOP formation temperature range combined with contaminated plastic waste inputs. Dioxins and furans are the most toxicologically potent of the unintentionally formed POPs (UPOPs) typically formed in industrial processes like waste incineration, cement kilns, and metallurgical plants. Other unintentionally formed POPs from these processes include:

- Hexachlorobenzene (HCB);
- Hexachlorobutadiene (HCBD)
- Pentachlorobenzene (PeCB);
- Polychlorinated biphenyls (PCB); and
- Polychlorinated naphthalenes (PCN).

Industrial processes known to produce UPOPs are required to implement BAT BEP measures (usually process controls and filtration methods) to minimize the formation and release of UPOPs. This is one of the key pillars of the convention to prevent global POPs contamination. There is currently no available BAT BEP guidance for pyrolysis, gasification, or other forms of chemical recycling under the Stockholm Convention.

In summary, the Stockholm Convention may be relevant to POP contamination of chemical recycling waste inputs, emissions, wastes streams, contamination of outputs, and contamination of sites used for chemical recycling.

4.7 THE CIRCULAR ECONOMY

The circular economy is a concept that has been gaining more prominence in recent years, both as a national and international concept of moving away from economic models that are linear (extract –> produce –> consume –> dispose) to models that retain materials and resources within the economy in a circular flow.

The original objectives of a circular economy were twofold: to conserve finite resources (natural capital) within economies and to make economies more efficient by minimizing the release of materials and chemicals into the environment in the form of waste or pollution, also known as "externalized cost of production" (Sauvé and Bernard 2016). Avoiding negative impacts on the environment and human health from pollution (including carbon emissions), waste, and chemicals is considered an additional benefit from a circular economy. Implementing such an economic system requires that the full life cycle of products be assessed, and leakages of materials and chemicals from any point in the production and recycling chain must be accounted for and minimized.

Some analysts have described this as a move toward an "R-9 model" of "Refuse, Reuse, Reduce, Redesign, Repurpose, Remanufacture, Repair, Refurbish, and Recycle" (Aurisano et al. 2021), which focuses on the higher levels of the waste hierarchy (see Section 4.3). The European Commission[29] Circular Economy Action Plan of 2015 concluded that "a circular economy is based on sharing, leasing, reuse, repair, refurbishment, and recycling in an (almost) closed loop, where products and the materials they contain are highly valued. In practice, it implies reducing waste to a minimum."

The European concept of the circular economy attempts to align closely with the United Nations Sustainable Development Goals (SDGs).[30] This is a series of 17 goals that attempts to resolve poverty and other social deprivations through strategies that improve health, education, and inequality through sustainable economic development, while protecting forests and oceans and tackling climate change.

Of the 17 SDGs, several have relevance to plastics and their impact, including SDG 3 Good Health and Wellbeing, SDG 8 Decent Work and Economic Growth, SDG 12 Responsible Consumption and Production, and SDG 14 Life Below Water. The SDGs emerged from earlier policy initiatives, such as Agenda 21,[31] a plan adopted in 1992 by 178 countries at the Earth Summit in Brazil. This was the earliest attempt to create a global partnership for sustainable development intended to protect human health and the environment while creating economic growth. The development of sustainability goals at the international level culminated in the 2030 Agenda for Sustainable Development,[32] which was adopted by all United Nations member states in 2015 and incorporates all of the SDGs.

However, sustainable development has been susceptible to capture and manipulation by corporate interests, especially petrochemical companies (Miller and Dinan 2015). Sustainable development implementation has also proven flawed, with undue focus on economic growth, which is at odds with sustainable development (Eisenmenger et al. 2020). Similar criticisms have now emerged about the implementation of the circular economy and its divergence from its early core principles to the point that the credibility of the term is being undermined[33] in global policy discussions.

The current toxicity, non-recyclability, and life cycle pollution associated with plastics effectively relegates them to the status of non-circular materials.

The current toxicity, non-recyclability, and life cycle pollution associated with plastics effectively relegates them to the status of non-circular materials. Most research on the issue is directed to potential ways of making plastics more circular or overcoming barriers to circularity (Bucknall 2020, Aurisano et al. 2021, Lisiecki et al. 2023).

Some reports suggest many companies in the petrochemical and plastics sector have now adopted circularity as their new buzzword.[34] In doing so, they seek to appropriate and narrowly define circularity of plastics as "recycling" and, more specifically, as chemical recycling.

Cefic, also known as the European Chemical Industry Council, conflates chemical recycling of plastic with plastic circularity, effectively ignoring the life cycle impact of fossil fuel extraction and virgin plastic production, as well as the hazardous waste stream that will flow from chemical recycling. Its "Virtual Exhibition on Chemical Recycling"[35] includes videos with titles like "Chemical Recycling: Making Plastics Circular."

The American Chemistry Council also features chemical recycling as its main strategy for achieving "circularity,"[36] noting:

- "The chemical industry has set an ambitious goal that 100% of U.S. plastic packaging is recycled, recovered, or reused by 2040."
- "The chemical industry is working to keep plastics out of landfills and the environment by pursuing advanced recycling that creates new, high-quality plastics out of used plastics."

The Alliance to End Plastic Waste[37] — an association of FMCG, plastic, and chemical companies — even suggests that a circular economy is hampered without implementing chemical recycling technologies like pyrolysis[38] and strategies to supply them, noting: "Today's markets are developed around the requirements of mechanical recycling, a system that is more commonly employed. Although chemical recycling can play a complementary role to it, existing collecting and sorting systems limit the feedstock that can be used solely for pyrolysis. Materials that can otherwise be put back into the circular economy are then prematurely left in its end-of-life stage."[39]

It is becoming increasingly clear that petrochemical and plastics interests are now co-opting, if not taking over the concept of the circular economy and narrowly redefining it for the plastics sector to mean more recycling — specifically, chemical recycling. Time will tell if they can successfully co-opt the concept of the circular economy as an extension of their public relations campaign on chemical recycling. Alternatively, the global policy community may see through the ploy and regain control over what could become a policy concept that advances human health, prosperity, and environmental protection.

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CHAPTER 5

CONCLUSIONS

Source: Flickr/Florida Sea Grant

The plastic pollution crisis has now reached the point at which plastic, microplastics, and nanoplastics have become ubiquitous in the environment, in human bodies, and in wildlife. The production and disposal of plastics is a major problem in environmental justice communities. The human health impacts of this widespread contamination have not been fully characterized, but early research suggests they may be significant and prolonged. The key reasons are the toxicity and persistence of most plastics combined with their ability to penetrate deep into the human body, where they can release endocrine-disrupting chemicals, carcinogens, and other hazardous substances. Of particular concern is the fact that microplastics have been found in the human placenta and newborn infants.

Some policymakers are now increasingly aware of these risks and are poised to take action in the form of a global plastic treaty currently being negotiated through the United Nations. There are many policy measures that may be taken, but few will have an obvious and immediate impact on the volume and toxicity of plastic waste being created. The most direct impact would come from mandated reductions in plastic production — i.e., turning off the tap. Equally important is minimizing and, where possible, eliminating hazardous substances in plastics, such as chemical additives.

Subsidizing, promoting, and deregulating chemical recycling in the absence of major plastic production cuts will not have any significant impacts on plastic pollution levels. However, such actions are likely to exacerbate pollution impacts on nearby communities, generate large quantities of hazardous waste, and generate very high-carbon emissions while producing nothing more than low-quality fuel to burn or relatively small yields of plastic feedstock.

Fenceline communities, especially in the U.S., already bear the brunt of environmental injustice with a high concentration of petrochemical facilities imposed on them. They are right to be concerned about additional high-risk facilities being sited in their communities and the impact on their families — even more so if emission regulations are weakened to allow chemical recycling to operate as “manufacturing facilities.”

Plastics are not a circular material due to their toxicity and degradation characteristics. Production levels should be cut. Hard-to-replace plastics should be redesigned to allow maximum conventional recycling to take place by removing toxic additives and polymers and increasing polymer compatibility.

The argument that chemical recycling is complementary to mechanical recycling because it can use mixed, contaminated plastic waste that conventional recycling cannot is a myth.

The argument that chemical recycling is complementary to mechanical recycling because it can use mixed, contaminated plastic waste that conventional recycling cannot is a myth. The chemical recycling industry has over 50 years of technology failures, bankruptcies, and an inability to perform that have been detailed in this report. Chemical recycling has significant technical limitations that prevent it from using mixed plastic waste in any significant way. As a result, chemical recycling facilities create demand for clean, polymer-specific plastic waste, often post-industrial, and therefore compete with mechanical recycling for the same feedstock.

Chemical recycling, particularly pyrolysis, also has a propensity to distribute toxic contaminants into its outputs. This reduces the quality of the output and may contaminate end products, increasing human exposure to toxic chemicals. When burned as fuel, the contaminated outputs release highly toxic chemicals into the atmosphere and exacerbate fossil fuel-based climate change.

The technical limitations of chemical recycling will render it at most a marginal activity toward creating new plastic. In a world swamped with virgin plastic and production set to quadruple by 2050, chemical recycling has no effective role to play. Oil and gas extraction for plastic production and profit will continue unabated, irrespective of conventional and chemical recycling activity.

Those countries and corporations with the most to gain from exploitation of oil and gas also have the most to gain from the promotion of chemical recycling and the least to lose from its implementation, especially as public funds and subsidies are increasingly sought to finance the operations and bear the risk of failure. They are counting on chemical recycling marketing as their last option to fend off cuts to their production and profit. It’s a last-ditch effort to distract from the truth: the plastic waste crisis can’t be solved without significant reductions in plastic production.

APPENDIX 1

U.S. CASE STUDIES

Source: Google Maps

APPENDIX 1: U.S. CASE STUDIES

A NOTE ABOUT DATA USED FOR COMPARISONS

In order to develop the comparisons of facility capacity to overall plastic waste generation, we rely on data published by the U.S. Environmental Protection Agency. According to the agency's website, its primary source for data on the generation of plastics in the United States is the American Chemistry Council, a trade association of the plastics and chemical industries.

REGENYX | TIGARD, OREGON

Facility	Regenyx Chemical Recycling Facility
Companies	Agilyx Corp.; AmSty
Location	Tigard, Oregon (Washington County)
Operational Status	Pilot/demonstration
Process(es)	Pyrolysis
Feedstock Type	Mixed plastic and polystyrene waste
Rated Feedstock Processing Capacity	3,650 tons per year
Total Feedstock Processed	4,400 tons from 2004 through July 2021
Output Type	Oil, naphtha, styrene monomer
Stated Purpose of Output	Fuels, recycled content polystyrene
Output at Capacity	Unknown
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	Yes
% Low-Income Residents in Community	17%
% Residents of Color in Community	27%
Hazardous Waste Generator	Yes, classified as a large quantity generator
Project Cost	Initial: at least $47 million, Total: unknown
Subsidy Value	Tigard plant: unknown Portland plant: $0.5 million
Other Financials	$173 million in private investment IPO on Oslo stock exchange

OVERVIEW

The Regenyx Chemical Recycling Facility in Tigard, Oregon, is characterized by its parent companies as a demonstration plant.[1] It is jointly owned and operated by Agilyx Corp. and Americas Styrenics (AmSty). This pilot-scale facility currently has the capacity to process 10 tons of waste per day (3,650 tons per year) and can create styrene monomer, naphtha, propylene, and heavy oils.[2] It does not appear to operate at full capacity.

No plans for expansion of this facility have been announced. Company records indicate that Agilyx AS (parent company as of 2020) intends to license use of the proprietary technology that has been developed at this site. None of the announcements made by Agilyx for building new facilities around their technology have resulted in broken ground.

PROJECT HISTORY

Agilyx (previously named Plas2Fuel) attempted multiple generations of chemical recycling technology for waste plastics between 2004 and 2012,[3,4] which eventually resulted in its ability to create small amounts of pyrolysis oil that it trademarked as "Agilyx Synthetic Crude Oil," or ASCO.[5] The branded oil was shipped from the Tigard facility to Tacoma, Washington, to be refined into fuel by U.S. Oil and Refining[6]; and in 2013, Agilyx received EPA registration for the ASCO fuel under the Toxic Substances Control Act.[7] According to the company's paperwork to offer shares on the Merkur Market (Oslo Stock Exchange), by 2014 Agilyx had processed only about 4,000 tons of mixed-waste plastic that it had converted into 2,880 tons[8] of crude oil.[9]

When fuel prices dropped in 2016, the Tigard plant temporarily suspended operations.[10] Between 2016 and 2017, it retooled to exclusively process polystyrene waste into a petrochemical composed primarily of styrene.[11] By 2018, Agilyx had the capacity to produce approximately 555,000 gallons of this styrene-based pyrolysis oil.[12] In November of that year, it announced an agreement to supply up to 2,500 barrels (378 tons) of synthetic crude per day to Monroe Energy, a Delta Air Lines subsidiary, for processing into jet fuel. However, it is unclear how much fuel, if any, was sold to Monroe from the Tigard facility, and Agilyx's plan to develop a new facility near the Monroe refinery outside Philadelphia[13] has not materialized. According to a 2021 Reuters news article, the project was on hold.[14]

Joint Venture With Americas Styrenics (AmSty)

Meanwhile, in 2011, AmSty announced it had created a new brand of recycled content resin, called Poly Renew, that incorporated recycled polystyrene and was approved by the U.S. Food and Drug Administration for food service in the United States. By 2013, AmSty claimed that PolyRenew was being used in "recycled foam containers,"[15] but never specified the percentage of post-consumer content used.[16]

In August 2017, Agilyx signed an offtake agreement[17] with AmSty to ship styrene monomer from its Tigard plant in Oregon all the way to AmSty's existing styrene production facility in St. James, Louisiana.[18] According to U.S. Environmental Protection Agency records, however, since 2018 Agilyx has sent about 225 tons of styrene to primarily four facilities in the U.S. that have burned it for energy. Three of these plants — in Hannibal, Missouri; Freedonia, Kansas; and Henderson, Colorado — were quite a distance from Oregon.[19]

About two years after signing the offtake agreement, on April 10, 2019, AmSty announced that it had generated new styrene from polystyrene waste in St. James, Louisiana, using styrene monomer sourced from Agilyx's Oregon plant, and that the pellets generated from the process were being used for food service packaging. In the same press release, Agilyx said it was creating a range of chemicals, polymers, and fuels that it deemed "low carbon."[20]

Ten days later, Agilyx and AmSty announced they had formed a joint venture as Regenyx LLC to own and operate the Tigard plant, then "scaled at 10 tons of feedstock per day" (less than 4,000 tons per year), and that the two companies would now pursue developing a 50 tons per day facility somewhere on the West Coast,[21] which has yet to materialize. The 2019 joint announcement characterized the venture as a "commercialization" of the Tigard, Oregon, facility, but company records as recent as 2022 categorize the facility as "demonstration."

Company records indicate that by April 2020, Agilyx had sold about 1 million pounds (less than 0.5 tons per day) of recycled styrene monomer to AmSty.[22] The amount of plastic waste processed during this time is undisclosed, and therefore it is unclear whether the differential of 10 tons per day feedstock capacity to 0.5 tons per day product is due to limited operation, low yield rates, or a combination of both.

PROJECT FINANCING

Between 2010 and 2012, Agilyx raised at least $47 million in venture capital in two rounds[23] to continue developing its pyrolysis technology at the Tigard plant and converting mixed plastic waste into a pyrolysis oil.

In 2013, Agilyx received a $577,255 business energy tax credit from the Oregon Department of Energy[24] to develop a separate waste plastics-to-oil pilot plant using Agilyx technology and owned by Waste Management in Portland. After operating for 16 months, the pilot plant was shuttered in August 2014 and did not reopen.[25] For its part, Waste Management received $10.5 million in tax credits/rebates from the state of Oregon from 2008 to 2015, but it is unclear which projects these benefits supported.[26]

In January 2020, Carnegie Investment Bank helped Agilyx secure an undisclosed amount of "growth financing" to support potential expansion into the European market. Agilyx AS, the new parent company, chose Oslo, Norway, as its corporate headquarters[27] and began trading on the Oslo Stock Exchange's Merkur Market in October 2020 after having raised NOK 300 million (about $30 million) in equity.[28] According to records compiled by Crunchbase, Agilyx raised $172.7 million in private equity over nine rounds between January 2005 and September 2020.[29]

Agilyx AS sustained operating losses of $22.4 million in 2020 and 2021.[30]

PLANS FOR EXPANSION

There are no plans to expand the facility in Tigard, Oregon. Company records indicate that this facility is treated as a demonstration site. Announcements for expansion have mostly been focused on building larger facilities in other locations that use some of the technology that has been developed in Tigard or selling the use of its technology to other facilities. However, not a single expansion announcement seems to have materialized.

Channahon, Illinois

In December 2019, Agilyx and Ineos Styrolution, a $65 billion global styrenic chemicals company headquartered in Great Britain, announced plans to build a chemical recycling facility in Channahon, Illinois, which they claim will have the capacity to process 100 tons of post-consumer polystyrene per day.[31]

In June 2021, the global energy company Technip Energies (headquartered in Paris) and Agilyx AS announced a partnership agreement wherein Technip would market and license Agilyx's polystyrene depolymerization technology together with Technip's "purification technology."[32] The two companies branded the combination as "TruStyrenyx" in August 2022[33], and in March 2023, they issued a press release announcing that they would employ it in developing the proposed plant in Channahon.[34] At the same time, they were working to get a bill passed in Illinois (HB 1616) that would extend the deadline for the project from 2025 to 2027.[35] Four years after the initial announcement, the project has not moved forward.

St. James, Louisiana

In April 2021, AmSty and Agilyx announced their intent to build a polystyrene chemical recycling facility at AmSty's existing complex in the environmental justice community of St. James, Louisiana.[36] The companies claim the proposed chemical recycling plant would have a capacity to process between 18,250 and 36,500 tons per year. For comparison, AmSty's two existing virgin production lines can churn out almost a million tons of Styron resins a year.[37] At full capacity, the planned facility in St. James would not be able to process more than 3.6% of the Styron that AmSty currently produces. Note that between 2008 and 2016, AmSty St. James received at least $29 million in local and state property tax abatements.[38]

Expanding Into Waste Brokering

On January 1, 2021, Agilyx AS and ExxonMobil formed a joint venture to create Cyclyx International LLC, a consortium of companies focused on aggregating and delivering plastic waste.[39] Agilyx has a 75% stake in Cyclyx. Member companies include “AmSty, Regenyx, INEOS Styrolution, LyondellBasell, Braskem, Chevron Phillips Chemical, North American Plastics, Corning, Merck, Casella, Hefty, and Sonoco.”[40] The venture has partnered with ExxonMobil to design a $100 million sorting and processing facility in Houston to supply waste plastics for ExxonMobil’s and LyondellBasell’s mechanical and chemical recycling plants (see ExxonMobil section on page 100 of Appendix 1: U.S. Case Studies).

CAPACITY AND SCALE

According to the Agilyx 2021 Annual Report, the Regenyx plant had only processed a cumulative total of “4,400 tons of mixed waste plastic and polystyrene waste”over the life of the facility.[41] The Agilyx website indicates that the plant reached the milestone of processing 8 million pounds (4,000 tons) of waste in 2014, which would mean that only 400 tons were processed between 2014 and 2021. According to U.S. EPA records, Regenyx has produced 211 tons of styrene waste since 2018, which has all been shipped offsite to be burned.(3) Combined with data about the company’s hazardous waste generation of 493.4 tons during the same period,(4) it raises the question of whether any product leaving the facility is being used to make new polystyrene, or whether it is all being burned for energy.

According to the EPA, 2.26 million tons of polystyrene was discarded in the United States in 2018 — the most recent year for which data is available — and only 20,000 tons of this was recycled, or less than 1% of the total.[42] (5) Even if it was operating at its rated capacity of 3,650 tons per year, Regenyx would be capable of processing only 0.16% of the nation’s polystyrene waste. It would take more than 613 Regenyx facilities operating at full capacity to convert the 2.24 million tons per year of polystyrene waste into any usable product, be it fuel or plastic feedstock.

HAZARDOUS WASTE AND AIR EMISSIONS

Despite the small scale of the Regenyx facility in Tigard, Oregon, it is classified as a “large quantity generator” of hazardous waste. According to the U.S. EPA’s Biennial Report database, Agilyx/Regenyx has produced more than 1,200 tons of hazardous waste at the Tigard facility between 2011 and 2021.[43] This means that Regenyx generates one ton of hazardous waste for every three tons of waste processed. These hazardous wastes included ignitable wastes and oily sludges containing benzene, toluene, xylene, 1,2-dichloroethane, and heavy metals, among other hazardous compounds.[44] Despite this waste generation, the International Sustainability and Carbon Certification decided to certify Regenyx as ISCC Plus “for the complete pathway from waste aggregation to new polystyrene production” in November 2020.[45]

This facility is classified by the Oregon Department of Environmental Quality as a “minor source” of air pollution, which permits it to emit up to 39 tons per year of nitrogen oxides and volatile organic compounds, and up to 99 tons per year of carbon monoxide.[46]

Public records from the Occupational Safety and Health Administration (OSHA) show that a complaint was filed in May 2023, for which OSHA cited as a violation.[47, 48]

(3) U.S. Environmental Protection Agency, Envirofacts Multi-System Search, Toxics Release Inventory, Releases. Facility ID: 9722WGLYXT794SW. https://enviro.epa.gov/facts/tri/ef-facilities/#/Waste/9722WGLYXT794SW. Accessed October 24, 2023.

(4) U.S. Environmental Protection Agency, Envirofacts Multi-System Search, Toxics Release Inventory, Waste Management. Facility ID: 19722WGLYXT794SW. https://enviro.epa.gov/facts/tri/ef-facilities/#/Release/9722WGLYXT794SW. Accessed October 24, 2023.

(5) U.S. Environmental Protection Agency, Envirofacts Multi-System Search, RCRA info. Facility ID: 110045561441. https://enviro.epa.gov/envirofacts/rcrainfo/facility?handlerId=ORQ000029621. Accessed October 24, 2023.

ALTERRA ENERGY PLASTIC RECYCLING FACILITY | AKRON, OHIO

Facility	Alterra Akron Plastic Recycling Facility
Company	Alterra Energy LLC
Location	Akron, Ohio (Summit County)
Operational Status	Pilot/demonstration
Process(es)	Pyrolysis
Feedstock Type	Mixed plastic waste
Rated Feedstock Processing Capacity	21,900 tons per year
Total Feedstock Processed	Unknown
Output Type	Pyrolysis oil
Stated Purpose of Output	Fuel or plastic feedstock
Output at Capacity	4.2 million gallons (21,000 tons) per year
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	Yes
% Low-Income Residents in Community	43%
% Residents of Color in Community	31%
Hazardous Waste Generator	Yes, classified as a large quantity generator
Project Cost	More than $20 million
Subsidy Value	Land, building lease, office space, $1.6 million state loan
Other Financials	Private equity investments

OVERVIEW

The Alterra Akron Plastic Recycling Facility in Akron, Ohio — owned by Alterra Energy LLC — is a demonstration facility that is using pyrolysis to process a mix of industrial plastic scrap and plastic waste sourced from material recovery facilities into pyrolysis oil that the company says is used for synthetic crude oil and feedstock for plastic resins.

PROJECT HISTORY

In 2009, Alterra's predecessor company, Cleveland-based Vadxx Energy, purchased patent rights to pyrolysis technology from the University of Wyoming.[49] Between 2009 and 2014, Vadxx built bench-scale (i.e., testing-scale) and five iterations of pilot-scale pyrolysis units at the Akron, Ohio location, after abandoning a plan to build in Cleveland.[50] According to company documents, construction on the first small-scale plant took place between 2015 and 2017.[51]

In a January 2019 permit evaluation report to the Ohio Environmental Protection Agency, Alterra indicated that the plant's initial installation was completed in August 2015, yet between August 2015 and January 2019 it had only operated at 20% to 30% capacity for just one week during 2018.[52] Even though the plant was fully commissioned in 2020 at its rated capacity,[53] a subsequent report indicated that the Akron facility didn't become operational until October 2021[54]— the same year the plant qualified for the International Sustainability and Carbon Certification Plus.[55]

In an interview with Chemical & Engineering News in November 2022, Alterra claimed an ability to process about 22,500 tons of mixed plastic waste and produce about 100,000 barrels (15,000 tons) of synthetic crude oil annually. Yet, in the company's 2022 air permit application, the actual capacity is listed at 21,900 tons per year.[56] At the time of the 2022 interview, 50% to 75% of its feedstock was coming from material recovery facilities (MRFs) in the Midwest that process household waste, and the balance was post-industrial residue. Eighty percent of its overall feedstock was being sourced from Ravago Group, which has invested in Alterra.[57]

In the same interview, Alterra reported that one to two trucks, each with a capacity of about 5,800 gallons, were leaving the facility each day to ship its product, which is solid at room temperature, to petrochemical plants on the U.S. Gulf Coast. No buyers or actual quantities were specified,[58] and there are no public records to verify these claims. Alterra also reported that between 10% and 20% of the output from its reactor is non-condensable gases that are burned on-site to help fire the kiln.[59] In the same interview, Alterra indicated that the plant may not be turning a profit, citing the "long distance between the facility and its customers" as a challenge.

PROJECT FINANCING

In December 2013, Vadxx Energy secured $19 million in financing from private equity firm Liberation Capital of Charlotte, North Carolina.[60] The investment was used to finance the first unit of the Akron facility.[61]

The City of Akron provided Vadxx Energy with several forms of early support for the project leading up to the project's launch in 2014, including office space in its Global Business Accelerator incubator;[62] help obtaining a lease on a $4 million building for the pilot plant; and a $1 per year lease on a 5-acre site for the commercial-scale pyrolysis plant, in return for "a percentage of the project's future cash flow."[63] In March 2014, the State of Ohio's Controlling Board provided assistance for the project with a $1.6 million commercial acceleration loan, generally used for early-stage entrepreneurs.[64]

In an article profiling the April 2014 Earth Day groundbreaking of the Akron facility, the Akron Beacon-Journal reported that Liberation was actually the plant owner, while Vadxx was the plant operator with a share in profits.[65] Two weeks later, Vadxx and Liberation Capital raised a single private-equity round of $500,000, with Liberation as the sole investor.[66] In 2019, Alterra purchased Vadxx[67] in an acquisition involving eight rounds.[68]

In January 2021, Neste, the Finnish oil refiner and renewable biodiesel producer with 2022 revenues of 25.7 billion[69] (about $29 billion), acquired a minority stake in Alterra Energy[70] as part of its corporate focus on the chemical recycling of plastic waste.[71] The following year, Neste purchased the European rights to Alterra technology.[72]

In July 2021, Ravago, a $4.4 billion[73] global chemicals and plastics producer and recycler based in Luxembourg, also acquired an "equity interest" in Alterra, in addition to supplying preprocessed plastic waste to the Akron facility.

PLANS FOR EXPANSION

Alterra sees its Akron facility more as a demonstration plant than a profitable stand-alone venture, and has been seeking to expand globally by licensing its technology[74] instead of building its own plants.[75] However, as of August 2023, no terms, construction activity, or progress about any of their announced expansion could be found in the public domain, and therefore the following projects appear to still be in the conceptual stage.

In May 2021, Alterra announced a goal to eventually process more than 90,000 tons of waste per year,[76] almost quadrupling their current capacity, and that the company hoped to have "between 1 and 2 million tons per year of capacity up and running" in facilities around the world by the end of the decade.[77]

In October 2021, Neste and Ravago announced their plans to build a pyrolysis facility in North Sea Port in Vlissingen, the Netherlands, as a joint venture.[78] That same month, the Abundia Global Impact Group, a New York-based company that attempts to convert biomass and plastic waste into fuels and chemicals,[79] signed a licensing agreement to use Alterra's technology at a site in the United Kingdom with an initial annual capacity of 40,000 tons of waste plastics, and a stated goal to increase to 120,000 tons by 2027.[80]

In April 2022, the French engineering and technology company Technip Energies announced a joint development agreement to integrate Alterra's pyrolysis technology with Technip Energies' pyrolysis oil purification technology.[81]

In February 2023, Alterra announced its first North American license agreement with a subsidiary of Freepoint Eco-Systems Holdings LLC for a proposed chemical recycling plant on the U.S. Gulf Coast. The announcement states that the plant would initially process 192,000 tons per year of plastic waste, with an aspiration of increasing annual capacity to 288,000 tons.[82] Shell would be the sole offtake for the proposed plant's output, which Freepoint says will be ISCC Plus certified.[83]

CAPACITY AND SCALE

The Alterra Facility in Akron, Ohio, has a capacity to process 21,900 tons of feedstock per year.[84] For comparison, the U.S. Environmental Protection Agency reports that in 2018, Americans generated 35.7 million tons of plastic waste, of which 26.9 million tons was landfilled.[85] It would take more than 1,200 facilities the size of the Alterra facility in Akron, Ohio, to process just the landfilled portion of plastic waste. Alterra's claim that they can convert 21,900 tons of feedstock into 21,000 tons of oil would make its material conversion efficiency rate 96%, which may be an overstatement.

HAZARDOUS WASTE AND AIR EMISSIONS

According to reports submitted to the U.S. Environmental Protection Agency under the Resource Conservation and Recovery Act, Alterra is a large-quantity generator of hazardous waste.[86] Alterra generated nearly 2 tons of hazardous waste in the last six months of 2018 alone, despite having operated for only one week that year, and more than 86 tons of hazardous waste from 2019 to 2022.[87] These included ignitable wastes, benzene compounds, halogenated and non-halogenated solvents, methyl ethyl ketone, and the heavy metals barium, cadmium, and lead.[88]

According to permit records, each year Alterra may be releasing up to 16,343 tons of greenhouse gases, 3.9 tons of particulate matter, 18.6 tons of nitrogen oxides, 7.8 tons of volatile organic compounds, 0.4 tons of sulfur dioxide, 5.6 tons of carbon monoxide, and 0.3 tons of other hazardous air pollutants.[89]

BRAVEN ENVIRONMENTAL | ZEBULON, NORTH CAROLINA

Facility	Braven Environmental Chemical Recycling Plant
Company	Owner: TEB 10 LLC; Operator: Braven Environmental LLC
Location	Zebulon, North Carolina (Wake County)
Operational Status	Operating
Process(es)	Pyrolysis
Feedstock Type	Mixed plastic waste
Rated Feedstock Processing Capacity	12,000 tons per year
Total Feedstock Processed	Unknown
Output Type	Pyrolysis oil
Stated Purpose of Output	Fuel
Output at Capacity	2.1 million gallons (10,500 tons) per year
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	Unknown
% Low-Income Residents in Community	36%
% Residents of Color in Community	52%
Hazardous Waste Generator	Yes, classified as a large quantity generator
Project Cost	Approximately $32 million
Subsidy Value	None disclosed
Other Financials	Private equity investments

A public housing community less than 400 feet away from the back of Braven Environmental's lot. Photo: Schuyler Mitchell/The Intercept

OVERVIEW

The Braven Environmental Chemical Recycling Plant in Zebulon, North Carolina, is owned by TEB 10 LLC and operated by Braven Environmental LLC. Braven claims that the single pyrolysis unit on-site has the capacity to process up to 12,000 tons of mixed plastic waste (No. 2 HDPE, No. 4 LDPE, No. 5 PP, and No. 6 PS) per year, and produce 2.1 million gallons (approximately 10,500 tons) of pyrolysis oil.[92] As of 2020, the oil was being sold to Colonial Fuels, but recent announcements indicate that it may also be selling to Chevron to be refined into fuels.(6) (7) The company claims its pyrolysis oil could be used as plastic feedstock,[93] but there is no evidence to suggest that it is currently being sold for that purpose.

PROJECT HISTORY

Braven Environmental (formerly known as Golden Renewable Energy LLC[94]) received an air permit for its pyrolysis facility in Zebulon, North Carolina, in September 2020,[95] after about 10 years of testing.[96] The single "Recycled Fuel Production Unit"[97] produces pyrolysis oil that Braven has branded as "Braven PyChem." Braven promotes its pyrolysis oil as a fuel or a feedstock for new plastics.[98] The company has a 20-year contract with Sonoco Packaging, which pays Braven a fee[99] for the waste plastic that it sources from municipal recovery facilities.[100] According to the group Clean Fairfax, Sonoco Packaging trucks in the waste from out of state.[101]

In June 2021, Braven signed a long-term offtake agreement for its fuel output with Chevron Phillips Chemical (CPChem), but "declined to provide any information on the approximate number of tons the facility has processed over the past year via its pyrolysis process."[102] Reporting by The Intercept in September 2023 confirmed that Braven is supplying pyrolysis oil to the Chevron refining facility in Mississippi to turn into jet fuel.[103] According to U.S. Environmental Protection Agency documents and reported on by ProPublica in February 2023, this facility could expose the surrounding community to emissions "so toxic, 1 out of 4 people exposed to it over a lifetime could get cancer."[104]

A September 2022 notice of violation that Braven received from the North Carolina Department of Environmental Quality for mismanagement of hazardous wastes indicates that the plant did not operate between January and June of that year.[105]

As of July 2023, the company's website indicated it was selling product only to Colonial Fuels, a regional fuel distributor, but was "in negotiations with major petrochemical companies to purchase a portion or all of the output as an alternative."[106]

PROJECT FINANCING

In January 2018, the Yonkers, New York-based Golden Renewable Energy, which would eventually change its name to Braven Environmental, announced it had raised "an undisclosed amount of growth capital from Fortistar Capital LLC,"[107] a private investment and asset management firm with a focus on energy projects.[108] The investment amounted to an acquisition by Fortistar.[109]

PLANS FOR EXPANSION

While Braven's business strategy includes plans to build a network of plastic pyrolysis facilities throughout the United States and abroad, the company has not yet started construction on a second U.S. plant.

In June 2020, Virginia Governor Ralph Northam announced Braven's plans to construct a plant in Cumberland County at a projected cost of $31.7 million.[110] Public subsidies enabled the state to secure the project, which had also been courted by North Carolina and South Carolina. These included a $150,000 grant from the Commonwealth's Opportunity Fund and a $65,000 grant from the Virginia Tobacco Region Revitalization Commission.[111] Representatives from the Virginia chapter of the Sierra Club noted that these developments came on the heels of significant lobbying by the American Chemistry Council.[112]

New legislation that reclassified "advanced recycling" facilities as manufacturing rather than solid waste management[113] also qualified the plant for economic incentives from the state.[114] The Virginia Jobs Investment

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(6) https://bravenenvironmental.com/news/braven-environmental-executes-long-term-pyrolysis-derived-feedstock-supply-agreement-with-chevron-phillips-chemical/

(7) Corporate Overview, Braven Environmental, July 2020. https://www.serdc.org/resources/Documents/2020%20Annual%20Meeting/Braven%20Corporate%20Overview_Development_2020_SERDC.pdf

Program had agreed to supply "funding and services" to support training an estimated 52 new employees at the proposed Cumberland plant,[115] but in January 2022, Braven pulled out of the project for undisclosed reasons.[116] Ten months later, members of the Cumberland Economic Development Authority voted unanimously to put the building up for sale.[117]

Closed Loop Partners, an investment, innovation, and management firm,[118] stated in a March 2021 publication that Braven was seeking $120 million in capital equity as part of its plan to build facilities "around the world." The revenue model includes tipping fees charged to various plastic waste generators — including municipalities, material recovery facilities, waste haulers, and industrial plastic producers — and establishing spot and long-term offtake agreements with buyers.[119]

In June 2023, Braven announced it had retained Houston-based Koch Project Solutions to provide project management contracting services for further facilities, including one to be located in the Gulf Coast region. Braven claims that the newest facility will have the capacity to convert 250,000 tons of waste plastic into 50 million gallons (250,000 tons) of pyrolysis oil annually,[120] which would be a 100% conversion rate and is not possible to achieve. Evidence suggests that the company is eyeing a site in the TexAmericas Center in Texarkana, on the border of Texas and Arkansas.[121]

It remains to be seen if any of these facilities will start operating.

CAPACITY AND SCALE

The pyrolysis unit at Braven's Zebulon-based facility has the capacity to convert an average of 12,000 tons per year of mixed plastic waste (No. 2 HDPE, No. 4 LDPE, No. 5 PP, and No. 6 PS), and produce approximately 2.1 million gallons (about 10,500 tons) of pyrolysis oil,[122] but it is unclear whether the plant is currently operating at capacity.

For comparison, the U.S. Environmental Protection Agency reports that in 2018 Americans generated 35.7 million tons of plastic waste, of which 26.9 million tons was landfilled.[123] It would take more than 2,240 facilities the size of the Braven facility in Zebulon, North Carolina, to process just the landfilled portion of plastic waste generated in the United States.

HAZARDOUS WASTE AND AIR EMISSIONS

The Braven facility is categorized by the U.S. Environmental Protection Agency as a large-quantity generator of hazardous waste. Hazardous waste generated from this facility includes ignitable waste, benzene, waste char, waste pyrolysis oils, and oily water. Braven shipped 11.95 tons of hazardous waste off site for disposal in 2021 and 76.6 tons in 2022.[124]

Despite having begun operations in 2020, the facility has already been cited twice by the North Carolina Department of Environmental Quality for violations stemming from mismanagement of hazardous waste: once on September 26, 2022,[125] and once on April 28, 2023.[126] The more recent notice documented five separate violations. One was related to the generation and accumulation of heavy-cut pyrolysis oils in an on-site hazardous waste tank that had been sitting there for three years. The letter documents that "Braven was looking for a buyer for this material but had yet to secure one." Also cited in the notice of violation were four areas of concern ranging from accidental spills to inadequate storage and handling, some of which resulted in hazardous waste being discharged to the ground and into a storm drain system. Four of the stormwater samples that were tested showed high concentrations of benzene,[127] and background soil samples found mercury and hexavalent chromium.[128]

According to the facility's Clean Air Act Permit, the Braven facility is permitted to emit up to 3 tons of criteria air pollutants each year, including sulfur dioxide, which damages the lungs; nitrogen oxides and volatile organic compounds, both of which contribute to smog; microscopic soot or particulate matter, which can trigger asthma and heart attacks; and carbon monoxide, which can inhibit oxygen intake to the heart and brain.

Reporting by The Intercept in September 2023 states that "some residents within 1 mile of Braven were already at an increased risk for environmental carcinogens before the business moved in: One nearby census tract has worse particulate matter and ozone exposure, hazardous waste proximity, and air toxics cancer risk than over 90% of the country."[129]

BRIGHTMARK ENERGY | ASHLEY, INDIANA

Facility	Ashley Circularity Center
Company	Brightmark Energy LLC
Location	Ashley, Indiana (Steuben County)
Operational Status	Partially or intermittently operating
Process(es)	Pyrolysis
Feedstock Type	Mixed plastic waste that possibly includes household, electronic, and/or medical waste
Rated Feedstock Processing Capacity	100,000 tons per year
Total Feedstock Processed	2,000 tons total in four years
Output Type	Diesel fuel, naphtha blends, wax
Stated Purpose of Output	Transportation fuels and chemical raw materials
Output at Capacity	Unknown
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	Yes
% Low-Income Residents in Community	30%
% Residents of Color in Community	6%
Hazardous Waste Generator	Not registered
Project Cost	$260 million to $435 million
Subsidy Value	Grants and tax credits: $4.55 million
Other Financials	Favorable loans: $4.5 million Tax-free bonds: $185 million Indiana Green Bonds

OVERVIEW

The Ashley Circularity Center in Ashley, Indiana, is owned and operated by Brightmark Energy LLC. The facility uses pyrolysis to break down plastics into diesel fuel, naphtha, and wax, which were intended to be used as transportation fuels and raw chemical materials. Four years after breaking ground at the facility, it is still being operated at test-phase capacity, and to date has processed only 2,000 tons of plastic waste[130] — one-fiftieth of the plant's publicized yearly capacity (100,000 tons per year). Most recent announcements regarding the feedstock type indicate that it is mixed plastic waste, some of which may be from curbside collection, and some that may be electronic waste, medical waste, or both.[131, 132, 133]

PROJECT HISTORY

Based in San Francisco, Brightmark Energy operates 30 U.S. facilities that convert dairy manure into biogas via anaerobic digestion.[134] The Ashley Circularity Center is the company's first foray into chemical recycling.


Brightmark Energy chemical recycling facility in Ashley, Indiana. Source: Google Maps

In May 2019, ground was broken[135] on the plant in Ashley, Indiana, a rural town of about 1,000 people in the northeast corner of the state. Brighmark publicized the plant as being able to process 100,000 tons per year of mixed plastic waste into usable products at a commercial scale,[136] and indicated that the mixed plastics would come from Indianapolis and Chicago, including plastic films such as grocery bags and dry cleaner bags.[137] Outputs were projected to consist of 18 million gallons of ultra-low sulfur diesel fuel and naphtha, and 5 million gallons of wax per year,[138] and were intended to be used for "transportation fuels and chemical raw materials."[139] Amwax was to be the purchaser for the wax.[140] None of those projections has materialized.

Seven months after breaking ground, in December 2019, Brightmark had already shifted its anticipated feedstock to electronic waste. It announced a partnership with local nonprofit RecycleForce to take delivery of up to 1,700 tons of electronic waste (i.e., plastic used in computers, cell phones, and other electronics) per month (about 20,000 tons per year).[141] Six months later, in June 2020, Brightmark announced it expected to take 100,000 tons of plastics annually by the end of 2020 or early 2021.[142] That timeline was not met: In comments submitted to the U.S. Environmental Protection Agency in September 2021 in regard to the proposed federal regulation of pyrolysis and gasification units,[143] Brightmark reported having processed a total of 3,400 tons of plastic waste in 2019 and 2020 combined.[144] Note that this number is different from the 4 million pounds (2,000 tons) published by Brightmark on their website.

In a September 2021 press release, the oil giant BP (formerly British Petroleum) announced it was the purchaser for the Ashley plant's output.[145] Since then, BP has not revealed the quantity it has purchased. Brightmark's December 2021 comments to the EPA stated that it had sent 20% of its output off site for further refinement.

In 2022, Brightmark announced a deal to purchase an unspecified amount of plastic medical waste from Jamar Health Products.[146]

Four years after breaking ground and receiving more than $4 million in public subsidies, the plant has failed to come close to its 100,000 tons per year processing goal. A March 2023 inspection report from the Indiana Department of Environmental Management cites a Brightmark representative saying that the plant had "yet to create product on-site."[147] A June 2023 article by Inside Climate News revealed the plant was still operating in a test phase and has been affected by fires, oil spills, and worker complaints about health and safety.[148]

PROJECT FINANCING

The Ashley Circularity Center received multiple forms of government assistance at each stage of development.

In 2011, the Ohio Third Frontier Advanced Energy Program provided Polyflow LLC, the Ohio-based creator of the particular plastics-to-fuel technology used at this facility, with a $1 million commercialization grant.[149,150]

In 2016, Steuben County provided RES Polyflow, formed by Polyflow and private equity firm Ambassador, with a $1.5 million, 2% interest loan as seed money to pursue project financing.[151] Meanwhile the Indiana Economic Development Corp. provided $1 million — 90% as conditional tax credits and 10% as training grants for the 136 employees to be hired by 2021.[152]

In 2018, Steuben County made a $1.5 million loan to the Town of Ashley for improving a street and railroad crossing leading to the facility, and utilities.[153]

In 2019 Brightmark Energy became the controlling owner of RES Polyflow when it raised $260 million to finance the facility, effectively acquiring the company.[154] The financing included $185 million in tax-exempt Indiana Green Bonds that were underwritten by Goldman Sachs at an interest rate of 7.125%.[155]

Brightmark hired New Energy Risk to help it secure an insurance policy that Goldman Sachs required before it would underwrite these bonds. New Energy Risk specializes in helping companies obtain insurance and debt financing for energy projects employing technologies that are not yet widely commercialized; without such insurance, investors are unlikely to take the financial risk. (New Energy Risk also pulled together insurance and financing for the Fulcrum Sierra BioFuels chemical recycling facility in Storey, Nevada, profiled on page 103 of Appendix 1 of this report.[156]) The remaining $75 million was invested by Brightmark itself.[157]

In 2020, the Indiana Department of Transportation granted $1 million to the Town of Ashley for upgrading the road leading to the plant, which the town called a "high priority" in its grant application. The town was to absorb the remaining $350,000 needed to complete the upgrade.[158] The federal Economic Development Administration, a bureau of the U.S. Department of Commerce, also awarded the Town of Ashley $1.2 million to improve the water and sewer infrastructure.[159]

In 2021, the Indiana Economic Development Corp. provided $200,000 in Hoosier Business Investment Tax Credits[160] and $1 million in EDGE tax credits.[161]

All of this adds up to $4.55 million in grants and tax credits, $4.5 million in favorable loans, $185 million in Indiana Green Bonds, and $75 million in private equity supplied by Brightmark.

PLANS FOR EXPANSION

In July 2020, Brightmark announced it was soliciting 1.2 million tons of "post-use plastic" as feedstock for its existing and prospective facilities, and claimed it was in the process of determining the locations for next facilities, with a stated goal of having at least two sites designated and prepped by 2021.[162]

Brightmark's most pursued site was to be located in Macon County, Georgia. With a planned processing capacity of 400,000 tons per year, the Macon chemical recycling plant would be the nation's largest — and four times the size of its Indiana predecessor. In July 2021, the Atlanta Journal-Constitution reported that state and local officials had recruited Brightmark with $82 million in incentives,[163] and the company had a tentative deal with the Macon-Bibb Industrial Development Authority (MBIDA) for $500 million in exempt facility revenue bonds to help finance construction of the $680 million plant.[164]

The MBIDA made the deal contingent upon Brightmark demonstrating that its Ashley, Indiana, plant was successfully producing and selling product. As reported in the Macon Newsroom, in late December 2021 "Brightmark admitted to the authority that it had failed to meet the deadline to prove its facility in the Upper Midwest was able to deliver the recycled end-product to another user."[165] Shortly thereafter, Macon-Bibb County Mayor Lester Miller withdrew his support for the project and urged the MBIDA to do the same, writing that "we cannot ignore the long-term safety concerns of this unproven process."[166] In April 2022, the Macon Newsroom reported the project was dead.[167] Strong opposition to the Brightmark facility from local residents in Macon County, Georgia, played a critical role in preventing this facility from being built.

This is the highest-profile cancellation of a planned chemical recycling facility in the United States. Brightmark has not announced any specific plans for the other U.S. locations it was investigating in 2020,[168] with the exception of a $430 million Texas plant, the Dayton Yard Facility, for which Brightmark has sought tax breaks.[169] According to Oil and Gas Watch, this plant is currently in the "pre-construction" phase.[170] The company applied for and received an extension to its Clean Air Act pre-construction permit; it has until April 13, 2024, to start building before this permit expires. The application itself was nearly three months late and was submitted by the company only after the nonprofit Environmental Integrity Project asked the Texas Commission on Environmental Quality to confirm whether the company had commenced construction and, if not, to invalidate the expired permit.[171]

Brightmark has also announced plans to build a $260 million plant in New South Wales, Australia,[172] "in partnership with the New South Wales Government," which has publicized that construction is planned to begin in mid-2023.[173] It remains to be seen how those plans will proceed.

CAPACITY AND SCALE

The Ashley Circularity Center was publicized as having the capacity to process 100,000 tons per year of mixed plastic waste and was held up as a reliable place to process hard-to-recycle mixed plastic waste from people's homes. Four years after breaking ground, according to Brightmark's website, accessed in mid-September 2023, the facility has only processed 2,000 tons of plastic waste.

Two thousand tons is just one-fiftieth of the plant's publicized annual capacity, and this amount was spread out over several years. For perspective, Indiana as a whole generated at least 700,000 tons of plastic waste in 2018.(8) Moreover, there is no public information on how much and what type of product that processing yielded.

Brightmark's own data suggest that its conversion process is inefficient. In the same comments to the EPA referenced above, Brightmark reported that, by weight, only 20% of its material output consisted of a gasoline-diesel fuel blend that was "sent off-site for further refinement." Ten percent was char that was landfilled, and 70% was syngas. Of the syngas, 80% was used internally to power the pyrolysis unit (i.e., it was burned as fuel), and 20% was flared (burned as waste gas).[174]

HAZARDOUS WASTE AND AIR EMISSIONS

Brightmark is not currently registered with the U.S. EPA as a hazardous waste generator.

According to permit records, the Ashley Circularity Center is permitted to emit up to 263 tons of criteria air pollutants each year, including sulfur dioxide, which damages the lungs; nitrogen oxides and volatile organic compounds, both of which contribute to smog; microscopic soot or particulate matter, which can trigger asthma and heart attacks; and carbon monoxide, which can inhibit oxygen intake to the heart and brain.[175]

As referenced above, a 2023 Inside Climate News story documented that the plant has been affected by fires, oil spills, and worker complaints about health and safety.[176]

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(8) Author's derivation, based on 32,660,000 tons of plastic wasted in the U.S. in 2018 (Table 8. Plastics in Products In MSW, 2018, in "Advancing Sustainable Materials Management: Facts and Figures 2018." U.S. Environmental Protection Agency, Nov. 2020) multiplied by 2% (the proportion of the U.S. population living in Indiana).

EASTMAN | KINGSPORT, TENNESSEE

Facility	Eastman Kingsport Facility
Company	Eastman Chemical Company
Location	Kingsport, Tennessee (Sullivan County)
Operational Status	Plastic gasification: operating Solvolysis: under construction; feedstock processing startup at 10% capacity
Process(es)	Gasification and solvolysis
Feedstock Type	Gasification: mixed waste plastic Solvolysis: #1 PET only
Rated Feedstock Processing Capacity	Gasification: 25,000 tons per year Solvolysis: 110,000 tons per year
Total Feedstock Processed	Unknown
Output Type	Gasification: synthesis gas Solvolysis: monomers
Stated Purpose of Output	Chemicals, recycled content plastics, and synthetic fibers
Output at Capacity	Unknown
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	Unknown
% Low-Income Residents in Community	40%
% Residents of Color in Community	8%
Hazardous Waste Generator	Processes are part of the larger Kingsport facility, which is classified as a large quantity generator
Project Cost	$250 to $270 million
Subsidy Value	$12 million
Other Financials	$500 million in green bonds

OVERVIEW

Eastman Chemical Company is either using, or proposing to use, both gasification and solvolysis to process plastic waste at its facility in Kingsport, Tennessee. The syngas, chemicals, and monomers created from these processes would be used in the manufacturing of chemicals, plastics, and synthetic fibers.[177]

PROJECT HISTORY

A spinoff of Eastman Kodak, the Eastman Chemical Company operates a large petrochemical complex in Kingsport, Tennessee, where it has incorporated, or is planning to incorporate, chemical recycling into its operations. According to Greenbiz, Eastman's first foray into chemical recycling was in the 1990s with a line of PET that had 50% chemically recycled content, but the line was discontinued.[178] In a July 2020 interview with Recycling Today, Eastman announced that the company was using "a variety of molecular recycling technologies"[179] that the company calls carbon renewal technology (CRT) and polyester renewal technology (PRT). Carbon renewal technology is a form of gasification. Polyester renewal technology is a form of solvolysis.

Eastman chemical recycling facility in Kingsport, Tennessee. Source: Google Maps

A review of publicly available government records shows that Eastman does not have a separate operating permit for the gasification process. Officials at the Tennessee Department of Environmental Conservation pointed to two operating permits that cover Eastman's coal gasification units, but neither specifically mention gasifying plastic waste. It is possible that Eastman is already gasifying plastic in one or both of its currently operating coal gasification units, but was not required to obtain a permit modification to add plastics to its feedstock.

EASTMAN'S GASIFICATION PROCESS

Eastman claims that its "carbon renewal technology" substitutes mixed-waste plastic for a portion of coal feedstock in a process that partially oxidizes plastics[180] (all types except PVC) into syngas (a mixture of carbon monoxide and hydrogen)[181] and other chemicals, which Eastman says it is using on-site to make "cellulosic plastics and fibers" that also contain wood pulp.[182,183]

According to Eastman, the gasification operation was initiated in October 2019, with a plan to process 25,000 tons of mixed plastic waste in 2020.[184] Shortly thereafter, Eastman signed a supply agreement with Circular Polymers, a company slated to collect, preprocess, and densify post-consumer polyester carpet in California before shipping it across the country by rail to Eastman's Tennessee complex.[185] As there are no publicly available permits or reports specifically for this process, which is part of a much larger facility, it is impossible to verify this information or to know how Eastman is incorporating any of the products from the gasification process into its products.

Eastman has branded the cellulosic textile fibers manufactured from the components derived from their gasification process as Naia Renew. Eastman advertises its Naia Renew fibers as containing "60% sustainably sourced wood pulp[186] and 40% certified recycled waste material,"[187] which it sometimes specifies as waste plastic[188] and sometimes refers to as acetic acid.[189] The company has entered the women's fashion and home furnishings markets, working with Patagonia,[190] Herewear,[191] and H&M,[192] among others. Eastman promotes its Naia Renew bedding line as lustrous, smooth to the skin, and certified renewable and compostable.[193]

EASTMAN'S SOLVOLYSIS PROCESS

Eastman's "polyester renewal technology" is a form of solvolysis that will use methanol and/or glycol on waste No. 1 PET plastic only.[194] These solvents will attempt to break down polyester waste and other PET plastics[195] — including "soft drink bottles, carpet, and polyester-based clothing" — into the monomers dimethyl terephthalate and ethylene glycol,[196] which can be used to make new polyester-based copolymers. This process is also referred to as depolymerization or methanolysis.

The $250 million solvolysis/methanolysis plant was announced in a January 2021 press release, with a projected capacity to process just over 110,000 tons per year of plastic waste by the end of 2022 and convert it into the building blocks for new polyester-based copolymers.[197] The plant started up at 10% capacity on August 24, 2022.[198] The permit for this process authorizes two emissions sources: a Plastics Processing Facility (PES B-590-1) and a Methanolysis Plant (PES B-655-1).[199] The startup notification is only for the Plastics Processing Facility (PES B-590-1).

Eastman has branded the copolyester produced by its methanolysis/glycolysis process as "Tritan Renew" and advertises it as containing "as much as 50% recycled content," which is "allocated using ISCC mass balance"[200] (see Section 4.5 for a discussion of mass balance). The company lists 26 different formulations of Tritan Renew, but it has not published how much chemically recycled content each of these formulations actually contains.[201] This lack of transparency has been generally critiqued as a shortcoming of the mass balance approach.[202]

A number of consumer brand companies have touted their use of Tritan Renew as a step toward achieving their sustainability goals or attracting eco-conscious consumers. In August 2020, Nalgene Outdoor announced it would be using Tritan Renew in its reusable water bottles. Marketing the containers with the Nalgene Sustain label, the company said "the new bottles are made from 50% certified recycled material" — illustrating how easy it is for some brands to misinterpret the "as much as" qualifier.[203] Tupperware used similar language in April 2021 in announcing its use of Tritan Renew in the expansion of its ECO+ line.[204]

In August 2021, Eastman and Procter & Gamble announced an agreement for Procter & Gamble to use these materials produced by Eastman in certain products and product packaging,[205] including Herbal Essences shampoo and conditioner bottles;[206] and in March 2022, the eyewear brand FGX International announced that it had recently adopted Tritan Renew for its eyeglass frames and plans to incorporate it across its entire line.[207] This was followed by a January 2023 announcement that FGX had signed a letter of intent with Eastman to reserve "a significant volume" of Tritan Renew copolyester to be produced by the methanolysis plant once it is completed.[208]

FGX and Procter & Gamble both promoted Tritan Renew as containing 50% recycled material, as did ZAGG in promoting its smartphone cases[209] and CamelBak in promoting its Eddy+ water bottles.[210] In April 2022, the global brand Marchon Eyewear also announced it would be using Tritan Renew for frames and lenses in its glasses and sunglasses; the company correctly used the "as much as 50%" recycled content language.[211] Eastman is also targeting cosmetic manufacturers with its Cristal Renew brand and is advertising it as having 30% and 50% certified recycled content options.[212]

The company has not announced the quantities of Tritan Renew that it has produced and sold to date. Analysis of publicly available records suggest that the Kingsport methanolysis plant is the only location where Eastman is producing the material, and it is not yet fully operating. As mentioned above, the permit for this process authorizes two emissions sources: a plastics processing facility (PES B-590-1) and a methanolysis plant (PES B-655-1).[213] The startup notification at 10% capacity from August 24, 2022, is only for the plastics processing facility (PES B-590-1).[214]

The methanolysis plant was originally scheduled to come online by the end of 2022; but as of an update to investors on July 28, 2023, the project was still not complete, and Eastman claimed that low PET prices were slowing progress on negotiations for contracts to sell the chemically recycled PET.[215] In addition, according to financial records, the cost of the plant — originally $250 million — is coming in higher than initially anticipated, with Eastman having spent a large portion of a $413 million capital investment in the first half of 2023 on the Kingsport methanolysis facility.[216]

PROJECT FINANCING

The project has received several forms of public support.

In January 2021, Eastman received $1.5 million from the Tennessee Department of Economic Community Development through a FastTrack grant, for a $270 million capital investment (versus $250 million, which has been published elsewhere). The grant incentivizes Eastman to create at least 85 new jobs. The company has not disclosed whether the 85 new jobs[217] have been created.

In February 2021, the Kingsport Board of Mayor and Aldermen voted to authorize the Kingsport Industrial Development Board to "enter into a payment in lieu of taxes, or PILOT, agreement with Eastman." Under the agreement, Eastman will save an estimated $10.6 million in property taxes over a 10-year period: about $6 million in tax abatements to Sullivan County, and about $4.6 million in abatements to the City of Kingsport. In return, the company deeded 5 acres of land to the city and committed to creating 90 jobs when the plant was scheduled to begin operations in late 2022.[218] The company has not disclosed whether the 90 new jobs have been created.

In March 2023, Eastman announced it had closed on a bond offering of $500 million consisting of "5.75% senior unsecured notes," which it called "the first investment grade USD-denominated ... green bond offering by a U.S. issuer in the chemical sector." Eastman pledged to use net proceeds from the 10-year bonds for "circular economy adapted technologies," processes, and products.[219] According to WilmerHale, the law firm that represented Eastman on the offering, underwriters included BofA, Citigroup, J.P. Morgan, and Mizuho.[220]

PLANS FOR EXPANSION

Eastman is considering building an $800 million solvolysis (methanolysis) plant at its existing chemicals complex in Longview, Texas, and has already received Chapter 313 local tax abatements.[221]

A larger plant looms in France. On January 17, 2022, Eastman and French President Emmanuel Macron issued a joint statement announcing plans to build a $1 billion, 160,000-ton methanolysis plant in France[222] under the Choose France investment initiative.[223] In March 2022, Port-Jérôme-sur-Seine, a town near the coast of Normandy, was chosen as a location for the complex, which would also include PET resin production, using outputs from the methanolysis plant. At the time, Eastman had already secured long-term offtake agreements from "LVMH Beauty, The Estée Lauder Companies, Clarins, Procter & Gamble, L'Oréal, and Danone."[224]

In September 2022, Eastman announced it had secured a supply agreement with Interzero Plastics Recycling, a French recycling company, to provide 20,000 tons of PET waste that Eastman says would be otherwise incinerated.[225] Difficulties in securing waste feedstock contributed to Eastman's decision to split project development into two equal phases that would yield an eventual total of 200,000 tons of annual output in 2030 (up from the 160,000 tons originally announced). The company also projects that 200,000 tons of wood waste and refuse-derived fuel will be combusted to generate the facility's energy needs at full capacity.[226] This represents a projected ratio of 1 ton of garbage and wood waste burned for every 1 ton of waste plastic processed by methanolysis.

CAPACITY AND SCALE

According to company announcements, the two chemical recycling components of the Eastman Kingsport facility have the capacity to process a combined total of 135,000 tons of plastic waste per year. The most recent announcement for the gasification process was a projection of 25,000 tons in 2020,[227] but there is no way to verify this amount through publicly available records. The solvolysis portion was announced as having the capacity to process 110,000 tons,[228] but the plant is not yet operating. Eastman sent a startup notification to the Tennessee Department of Environmental Conservation, which indicated that they were operating their Plastics Processing Facility at 10% capacity, or 11,000 tons per year.[229]

For comparison, the U.S. Environmental Protection Agency reports that in 2018, Americans generated 35.7 million tons of plastic waste, of which 26.9 million tons was landfilled.[230] Even operating at full capacity it would take almost 200 facilities the size of the chemical recycling components at the Eastman Kingsport facility to process just the landfilled portion of plastic waste generated in the United States.

HAZARDOUS WASTE AND AIR EMISSIONS

The Eastman Chemical Facility is classified by the U.S. Environmental Protection Agency as a large-quantity generator of hazardous waste. Publicly available government records do not differentiate between the chemical recycling components of this facility and its other operations. More transparency is needed to understand the environmental impact of the chemical recycling operations at Eastman Chemical Facility.

According to the Tennessee Department of Environmental Conservation, the Eastman Chemical Facility has 31 separate Title V air permits, and it takes a single inspector three full years to inspect the facility to ensure that it is meeting the conditions of each permit.(9) The air emissions for the gasification units could not be determined, and it is unclear whether the permits for the two current gasification units on-site are processing plastic waste, and if they are, how much and how often. The construction permit for the solvolysis unit at the Eastman Chemical Facility allows for up to 87,661 tons of greenhouse gas emissions and 111 tons of criteria air pollutants each year, including sulfur dioxide, which damages the lungs; nitrogen oxides and volatile organic compounds; both of which contribute to smog; microscopic soot or particulate matter, which can trigger asthma and heart attacks; and carbon monoxide, which can inhibit oxygen intake to the heart and brain.[231]

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(9) Based on a phone call Beyond Plastics had with a Tennessee Department of Environmental Conservation representative on August 24, 2023.

EXXONMOBIL | BAYTOWN, TEXAS

Facility	Baytown Chemical Plant
Company	ExxonMobil Corp.
Location	Baytown, Texas (Harris County)
Operational Status	Operating
Process(es)	Pyrolysis
Feedstock Type	Mixed plastic waste, including synthetic turf
Rated Feedstock Processing Capacity	40,000 tons per year
Total Feedstock Processed	Unknown
Output Type	Resin pellets
Stated Purpose of Output	Plastic products
Output at Capacity	Unknown
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	Unknown
% Low-Income Residents in Community	43%
% Residents of Color in Community	73%
Hazardous Waste Generator	Process is part of the larger Baytown facility, which is classified as a large quantity generator.
Project Cost	Sorting and processing facility: $100 million Pyrolysis facility: unknown
Subsidy Value	At least $65 million[232]
Other Financials	Unknown

OVERVIEW

ExxonMobil has a large existing petrochemical facility in Baytown, Texas, a city east of Houston. In 2022, the company added a chemical recycling component to this existing facility,[233] known as the Baytown Chemical Plant. The chemical recycling process uses a proprietary pyrolysis technology to break down plastic waste and then convert the outputs from that process into plastic resin pellets.

The pyrolysis unit is projected by the company to have the capacity to process between 30,000[234] and 40,000[235] tons of plastic waste each year, including synthetic turf and bubble wrap commonly used for shipping and packaging. But the most recent publicly available information shows that the unit is not operating at full capacity.[236] ExxonMobil claims its final product is white or clear resin pellets, which would be shipped by railcar to other companies for use in plastic products.[237, 238] At the time of this report, no information was publicly available on how much plastic waste is being processed or how much resin is being produced.

PROJECT HISTORY

ExxonMobil chemical recycling facility in Baytown, Texas. Source: Google Maps

In December 2022, ExxonMobil Corp. announced it had begun operation of a large-scale proprietary pyrolysis unit, following a small pilot project it had been running in the same location for about a year.[239] According to the company, that pilot had sorted and processed roughly 7,500 tons of plastic waste, from consumer packaging to artificial turf.[240] Multiple companies have contracted to buy ExxonMobil's "certified circular polymers for food applications" that are produced from this process, including Sealed Air (SEE) and Ahold Delhaize USA,[241] Berry Global,[242] and Amcor.[243]

The pyrolysis operation is part of a large complex that includes a 1.5 million ton ethane cracker,[244] as well as an olefins plant, a chemicals plant, and a crude oil refinery capable of producing more than half a million barrels of crude per day.[245]

Just two months before the Exxon's Baytown chemical recycling plant began operating, ExxonMobil, LyondellBasell, and Cyclyx issued a joint press release announcing their agreement "to advance development" of a separate $100 million sorting and processing facility in Houston that would supply ExxonMobil's and LyondellBasell's mechanical and chemical recycling plants, like the one in Baytown, with plastic waste that could be used as feedstock.[246] Dubbed the Cyclyx Circularity Center (Cyclyx is a spinoff of Agilyx[247] — see Regenyx section on page 81 of Appendix 1: U.S. Case Studies), the plant was originally designed to handle 40,000 tons of plastic waste annually,[248] and potentially more than 150,000 tons with LyondellBasell joining as a project partner.[249]

The City of Houston, Cyclyx, and ExxonMobil signed a memorandum of understanding (MOU) on January 19, 2022, to form the Houston Recycling Collaboration, which is designed in part to bring more plastic waste to the Baytown pyrolysis plant.[250]

PROJECT FINANCING

Information on the capital cost of the Baytown pyrolysis plant is not readily available, nor is any information on possible state government support. The sorting and processing facility is estimated at $100 million.(10) The scale of the new plastics sorting and chemical recycling facilities is small compared to ExxonMobil Corp.'s 2022 profits of $56 billion[251] and 2019 investment of $2 billion in Baytown expansions.[252]

An investigation by the Texas Observer in 2018 reported that in July of that year, ExxonMobil had applied for a local property tax exemption worth about $65 million[253] under the Texas Economic Development Act (also called Chapter 313) for two proposed units at its Baytown facility: a facility that would prepare monomers for use in polymerization and a unit that would combine monomers and generate a solid polymer resin.[254] On April 2, 2019, the Goose Creek Independent School District approved ExxonMobil's application for a "value limitation," or local tax abatement, for a period of 10 years beginning in 2024.[255]

ExxonMobil's Baytown complex (not specifically the chemical recycling facility) has been the subject of multiple lawsuits for air pollution violations brought by local residents and environmental organizations since at least the beginning of the 2010s.[256] In one of these lawsuits, a federal judge ruled in 2017 that ExxonMobil Corp. should pay a $19.95 million penalty for pollution generated by its Baytown facility between 2005 and 2013.[257] In April 2023, Luke Metzger, the executive director of Environment Texas, told the Guardian, "This false 'chemical recycling' will only produce more toxic misery for Baytown."[258]

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(10) "Cyclyx, ExxonMobil and LyondellBasell Advance First-of-its-Kind Plastic Processing Facility in Houston." LyondellBasell. Oct. 18, 2022. https://www.lyondellbasell.com/en/news-events/corporate--financial-news/cyclyx-exxonmobil-and-lyondellbasell-advance-first-of-its-kind-plastic-processing-facility-in-houston/. Accessed July 3, 2023.

PLANS FOR EXPANSION

In December 2022, the Baytown Sun reported that ExxonMobil was assessing the possibility of building additional chemical recycling facilities in Texas, Illinois, and Louisiana, as well as Belgium, Canada, the Netherlands, and Singapore. The company is also working with third parties to deploy its proprietary technology in such countries as Indonesia and Malaysia.[259] According to Oil and Gas Watch, as of April 2023, ExxonMobil was also "considering building a chemical recycling plant at its Baton Rouge Polyolefins Plant."[260] So far, none of these announcements has materialized.

CAPACITY AND SCALE

The pyrolysis unit is projected by the company to have the capacity to process between 30,000[261] and 40,000[262] tons of plastic waste each year.

For comparison, the U.S. Environmental Protection Agency reports that in 2018 Americans generated 35.7 million tons of plastic waste, of which 26.9 million tons was landfilled.[263] Even operating at full capacity, it would take more than 672 facilities the size of the chemical recycling components at the ExxonMobil Baytown facility to process just the landfilled portion of plastic waste generated in the United States.

HAZARDOUS WASTE AND AIR EMISSIONS

There is little transparency around this chemical recycling project and it is difficult to determine which air permit from the overall Exxon Mobil Baytown facility covers the chemical recycling project. An air permit exists for a performance polymers unit and a monomer processing facility — from a review of public records, it is unclear if it is the air permit for the chemical recycling project. That permit allows for 439 tons of criteria air pollutants to be emitted each year, including sulfur dioxide, nitrogen oxides, volatile organic compounds, particulate matter, and carbon monoxide.[264]

The Baytown Chemical Facility is classified as a "large quantity generator" by the U.S. EPA. No specific information is available about the hazardous waste generated by the chemical recycling components of this facility because the data is collected and reported for the whole facility and not its component parts.

FULCRUM SIERRA BIOFUELS | MCCARRAN, NEVADA	
Facility	Sierra BioFuels Plant
Company	Fulcrum Bioenergy Inc.
Location	McCarran, Nevada (Storey County)
Operational Status	Operating
Process(es)	Gasification and Fischer-Tropsch
Feedstock Type	Municipal solid waste
Rated Feedstock Processing Capacity	219,000 tons per year of municipal solid waste; approximately 20% of which is plastic
Total Feedstock Processed	Unknown
Output Type	Synthetic crude oil
Stated Purpose of Output	Aviation fuel
Output at Capacity	12.3 million gallons (61,500 tons) per year
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	Yes[265]
% Low-Income Residents in Community	27%
% Residents of Color in Community	40%
Hazardous Waste Generator	Not listed with U.S. EPA, but air permit includes an ash silo
Project Cost	$300 million
Subsidy Value	At least $100 million
Other Financials	$210 in loan guarantees

Fulcrum Sierra Biofuels plant in McCarran, Nevada. Source: Google Street View

OVERVIEW

Fulcrum Sierra BioFuels' permit indicates that the facility can process up to 219,000 tons per year of municipal solid waste (i.e., household trash) into 12.3 million gallons per year of aviation and diesel fuel, which is about 0.01% of the volume of jet fuel used globally each year.[266, 267] Its website provides slightly different numbers: It states that the facility can produce 11 million gallons per year of fuel from 175,000 tons of municipal solid waste.[268]

The company uses gasification to convert the municipal solid waste (MSW) into syngas, which it then processes using the Fischer-Tropsch (gas-to-liquids) process to create syncrude. Finally, it hydrocracks the syncrude to create aviation and diesel fuel.[269] This type of fuel is promoted by the transportation industry as low-carbon when compared to fossil fuels, because the organic portion of the MSW feedstock has already captured carbon from the atmosphere. Moreover, if landfilled, these organic materials would continue to emit climate-damaging methane emissions.

This, however, is not a complete assessment. The fuels are energy-intensive to make, still produce carbon and other emissions when burned as transportation fuel, and distract from renewable energy approaches and other more preferable ways to manage waste, such as waste reduction, recycling, and composting.

PROJECT HISTORY

In 2011 Fulcrum closed a $75 million Series C financing deal to secure venture capital, with a projected cost of $120 million.[270] Four years later, in 2015, when Fulcrum hired Abengoa to design and build the plant in two years, the cost to build the facility had nearly doubled, to $200 million.[271]

In 2017, when the plant was supposed to have been completed, Abengoa reportedly abandoned construction due to a $100 million cost overrun precipitated by multiple project modifications, and requested arbitration at the International Chamber of Commerce. According to a June 2020 article in the Spanish newspaper El Confidencial, the International Chamber of Commerce ruled that the cost overruns should be split 50/50 between Abengoa and Fulcrum, and that the Spanish construction company should also absorb $17 million in financial guarantees.[272]

However, this decision could not be verified on the ICC website,[273] and Fulcrum president and CEO Eric Pryor, who was vice president and CFO at the time, has denied the story.[274] By 2022, when the Ballard Spahr legal team advised Morgan Stanley and J.P. Morgan about investing in the plant, the total project cost was listed as $300 million — nearly triple the original cost.[275]

On February 1, 2023, the company announced that its first railcar of syncrude had been shipped from Storey County, Nevada, to a Marathon Petroleum refinery[276] to be converted into aviation fuel.[277] This shipment, or the quantity of fuel contained therein has not been independently corroborated, and Fulcrum has declined to share the location of the refinery.[278]

PROJECT FINANCING

The project has received various forms of federal, state, and private support.

In 2012, Fulcrum was one of three companies collectively awarded $16 million from the federal Department of Defense for development of "drop-in military biofuels,"[279] or biofuels that do not require blending with petroleum counterparts. In 2014, the Department of Energy provided another $5 million to the same three companies.[280]

Also in 2014, the Department of Defense collectively awarded $210 million to Fulcrum and two other companies toward construction of biorefineries that would produce drop-in military biofuels.[281] Related support was supplied by the U.S. Department of Agriculture, which issued two $105 million loan guarantees to Fulcrum: one in 2012 to finance the development of the facility,[282] and one in 2014 to build a biorefinery for biodiesel jet fuel.[283]

Before Fulcrum produced and shipped its first batch of product in 2023, it had signed and announced multiple agreements with airlines and fuel companies. In 2014, Cathay Pacific Airways made an undisclosed equity investment in Fulcrum and negotiated a long-term supply agreement for an initial 375 million gallons of these aviation fuels over 10 years.[284] In 2015, United Airlines bought a $30 million stake in Fulcrum Bioenergy, stating that the deal would meet a portion of its fuel needs while also protecting against the future volatility of oil prices and impending carbon regulation. The deal allows United to buy 90 million gallons or more of Fulcrum's product for a minimum of 10 years, at a price point that is competitive with conventional jet fuel.[285] In 2016, AirBP (a division of BP, formerly British Petroleum) invested $30 million in Fulcrum and signed a contract, known as an offtake agreement, to purchase a certain amount of Fulcrum's output over a certain period of time.[286] In 2018, Japan Airlines made an $8 million investment in Fulcrum that included a 10-year offtake agreement.[287] Fulcrum also has offtake agreements with Marathon Petroleum, Marubeni, and World Fuel Services.[288]

Fulcrum received state public assistance for the project. Between 2015 and 2018, the Nevada Governor's Office of Economic Development granted three rounds of tax abatements to this project: a business tax abatement worth just under $54,000; a personal property tax abatement worth $8.1 million; a real property tax abatement worth $5.5 million; and a sales and use tax abatement worth $12.6 million, for a total of $26.3 million in state tax subsidies.[289] In 2019, Morgan Stanley's bond underwriting practice raised more than $200 million for Fulcrum in tax-exempt municipal bonds, labeled as "green bonds," through the State of Nevada Department of Business and Industry.[290]

Other government mechanisms that have provided Fulcrum with additional business certainty.[291] In 2009, after Fulcrum lobbied the California Air Resources Board, California designated municipal solid waste-derived ethanol as qualifying for the state's Low Carbon Fuel Standard.[292] At the federal level, the U.S. EPA's renewable fuel standard requires the producers of transportation fuel, heating oil, and jet fuel ("obligated parties") to blend a certain volume of biofuels into the fuel they sell; and a June 2022 rule clarified that that "biointermediates" from one facility were allowed to count toward fulfilling its renewable fuel standard obligations, even if the processing into finished fuels is done elsewhere.[293] This clarification created an incentive for Fulcrum's biointermediate fuels to be produced, marketed, and sold,[294] effectively giving the plant a green light to begin production.

In August 2022, the Inflation Reduction Act created a new incentive: a federal tax credit of $1.25 per gallon for producers and importers of qualified so-called sustainable aviation fuel.[295] Note that it is the "biogenic components of separated MSW" (paper and organic matter in the sorted garbage feedstock) rather than plastic waste that qualifies Fulcrum's fuel as a biointermediate.[296]

While the proportion of plastics (approximately 20%) in the sorted waste stream is technically discounted from the federal credit, plastics still benefit from a free-rider effect (i.e., the renewable fuels eligibility for the biogenic and cellulosic components of the separated municipal solid waste). The plant's eligibility for the federal credits helps make this facility commercially viable.

Despite Fulcrum's regulatory advantages, on October 17, 2023, UMB Bank, the bond trustee for Fulcrum's sale of $290 million in environmental improvement revenue bonds from 2017 to 2020, announced that the bonds were in default and, at the direction of debt holders, demanded an accelerated repayment of the bonds. It remains to be seen how and if the Nevada plant will navigate this financial setback.

PLANS FOR EXPANSION

Fulcrum BioEnergy claims on its website that it has identified at least 10 potential locations for additional plants throughout the U.S., but does not provide any specifics.[297] It has three plants it categorizes as "under development": one in Gary, Indiana,[298] one in Baytown, Texas,[299] and one in Cheshire, UK. The Indiana plant, known as Centerpoint, is in the pre-construction phase and is opposed by local residents who say the plant's air permit "is based on inadequate information about the company's feedstock and unsupported emissions calculations."[300] As of October 2023, Fulcrum's plans to sell $500 million of tax-exempt environmental improvement revenue bonds through the Indiana Finance Authority to finance the Indiana plant were on hold due to the company's default on similar bonds for their facility in Nevada. For the proposed Trinity Fuels plant in Baytown, Texas, Fulcrum is pursuing local and county tax abatements.[301]

Fulcrum estimates that each of these plants would require an $800 million investment and are projected to process 700,000 tons of waste annually, about four times as much as the Nevada plant.[302, 303]

CAPACITY AND SCALE

Fulcrum Sierra BioFuels' permit indicates that the facility can process up to 219,000 tons per year of municipal solid waste (i.e., household trash) into 12.3 million gallons per year of aviation and diesel fuel.[304] This amount represents about 0.01% of the volume of jet fuel used globally each year.[305]

HAZARDOUS WASTE AND AIR EMISSIONS

Fulcrum Sierra is not designated as a hazardous waste generator by the U.S. EPA.

According to permits, the site could emit up to 316,234 tons of greenhouse gases and 256 tons of criteria air pollutants each year, including sulfur dioxide, which damages the lungs; nitrogen oxides and volatile organic compounds, both of which contribute to smog; microscopic soot or particulate matter, which can trigger asthma and heart attacks; and carbon monoxide, which can inhibit oxygen intake to the heart and brain.[306]

NEW HOPE ENERGY | TYLER, TEXAS

Facility	New Hope Plastics Recycling Plant (aka Trinity Oaks Tyler facility)
Company	New Hope Energy LLC
Location	Tyler, Texas (Smith County)
Operational Status	Unknown
Process(es)	Pyrolysis
Feedstock Type	Plastic (not PVC) and paper waste
Rated Feedstock Processing Capacity	18,250 tons per year
Total Feedstock Processed	Unknown
Output Type	Synthetic crude, pyrolysis oil, chemical feedstocks, plastic feedstocks
Stated Purpose of Output	Fuels, chemicals, plastics production, asphalt
Output at Capacity	Unknown
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	Unknown
% Low-Income Residents in Community	42%
% Residents of Color in Community	62%
Hazardous Waste Generator	Not listed with U.S. EPA
Project Cost	Existing plant: unknown Expansion: Less than $150 million New plant: unknown
Subsidy Value	Unknown
Other Financials	Unknown

OVERVIEW

The New Hope Plastics Recycling Plant was permitted in August 2019 to begin using pyrolysis to process plastics and paper into synthetic oil products.[307] The company has not publicly said how much plastic it has processed, the source of the feedstock, or the volume of its output.

PROJECT HISTORY

New Hope Energy's predecessor company, Renewable Diesel Micro Refinery, was founded by Karen and Johnny Combs in 2008. The name New Hope Energy was adopted in 2013.[308] The company piloted its proprietary pyrolysis technology in Justin, Texas, north of Fort Worth, and in 2018 established Phase I of the Trinity Oaks pyrolysis plant in Tyler.[309] The plant received its air permit in 2019.(11)

In April 2021, New Hope announced a long-term agreement to provide Chevron Phillips Chemical with an unspecified quantity of renewable chemical feedstocks with the ISCC Plus certification from the International

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(11) "Letter from Texas Environmental Quality to New Hope, August 5, 2019. https://api.oilandgaswatch.org/d/3a/a9/3aa9e1f09c7e41b581ff55361ca974aa.1669992435.pdf. Accessed October 29, 2023.

New Hope Plastics Recycling Plant in Tyler, Texas. Source: Google Street View

Sustainability and Carbon Certification organization.[310] In January 2022, New Hope announced a multiyear offtake agreement to provide Dow with pyrolysis oil feedstock derived from recycled plastics collected in North America.[311]

PROJECT FINANCING

No information is available on the financing of this project beyond the signed offtake agreements and its agreement with Lummus Technology (see below).

PLANS FOR EXPANSION

New Hope has proposed to grow in three ways: licensing its technology, expanding its Trinity Oaks Tyler Facility, and building an additional plant in Texas in partnership with Total Energies.

To facilitate the licensing strategy, in October 2020, New Hope retained Lummus Technology,[312] the self-described "global leader in the development and implementation of process technologies"[313] to help it scale its product and license its technology and equipment to other companies.[314] No announcements have been made about licensing agreements since that time.

New Hope Energies announced in October 2020 that it planned to invest $6.27 million to build out almost 50,000 square feet of new space in Tyler "on or around about" September 2021.[315] According to a Eunomia study released in May 2020 and prepared for the Washington State Department of Ecology, an expansion of the Tyler plant was already due to be complete by 2020. This expansion was projected to add capacity of 960 tons per day (350,000 tons per year) of mixed post-consumer and post-industrial plastic waste.[316] According to Eunomia, the total cost of the expansion as anticipated in 2020 was to be less than $150 million.[317] This expansion plan and timeline were not realized.

In May 2022, New Hope signed a multiyear master service agreement with Houston-based S&B Engineers and Constructors, an engineering, procurement, and construction firm. The goal was to increase the plant's capacity by 420 tons per day, to a total of 150,000 tons per year, which, if completed, would make it the largest operating chemical recycling plant in the U.S. According to CB Insights, a business analytics platform, New Hope raised $5 million in one funding round from undisclosed investors on December 28, 2022.[318] It is not clear how much the publicly announced expansion will cost or where the remainder of the project financing will come from.

Also in May 2022, New Hope announced a partnership with TotalEnergies, a Paris-headquartered global energy company with 2022 profits of $36 billion,[319] to construct a new chemical recycling plant at a Texas location that has not yet been determined. TotalEnergies committed to partly purchase 100,000 tons of the new plant's pyrolysis oil for use in its Texas-based polymer manufacturing, which the company claims would be suitable for flexible and rigid food-grade containers. The companies announced that the new plant would start production in 2025[320] and that it would have a capacity of 310,000 tons/year.[321] If completed, it would be the largest pyrolysis facility in the world. Details of the deal have not been made public, but as of a June 2022 interview with the Tyler Morning Telegraph, the new plant and expansion plans appear to have been combined into one new project: an expansion at the current plant. It remains to be seen whether the expansion will be completed.

CAPACITY AND SCALE

In an October 2020 press release, New Hope's design capacity was described as 150 tons per day (about 50,000 tons per year).[322] But in the June 2022 interview with the Tyler Morning Telegraph, New Hope official Tom Sheehy said the plant was on track to process 50 tons per day by the end of the year (18,250 tons per year),[323] which is about one-third of what New Hope had originally announced. There have been no updates from the company about whether the plant has achieved this reduced projected capacity.

HAZARDOUS WASTE AND AIR EMISSIONS

The site is not listed by the U.S. Environmental Protection Agency as a hazardous waste generator.

Official records do not provide information about the total potential greenhouse gas emissions from this facility. However, they do indicate that the facility is permitted to emit up to 122 tons of criteria air pollutants each year, including sulfur dioxide, which damages the lungs; nitrogen oxides and volatile organic compounds, both of which contribute to smog; microscopic soot or particulate matter, which can trigger asthma and heart attacks; and carbon monoxide, which can inhibit oxygen intake to the heart and brain.[324]

NEXUS CIRCULAR | ATLANTA, GEORGIA

Facility	Nexus Circular Fuels Plant
Company	Nexus Circular LLC
Location	Atlanta, Georgia (Fulton County)
Operational Status	Partially or intermittently operating
Process(es)	Pyrolysis
Feedstock Type	HDPE, LDPE, polypropylene, and polystyrene
Rated Feedstock Processing Capacity	18,250 tons per year
Total Feedstock Processed	4,000 tons as of January 2023
Output Type	Pyrolysis oil
Stated Purpose of Output	Feedstock for plastic products
Output at Capacity	Unknown
Actual Production	Less than 288,000 gallons (1,440 tons) per year
Combustion of Waste-Derived Gas On-Site	Yes[325]
% Low-Income Residents in Community	40%
% Residents of Color in Community	89%
Hazardous Waste Generator	Not listed with U.S. EPA
Project Cost	Unknown
Subsidy Value	Unknown
Other Financials	Private investment

OVERVIEW

The Nexus Circular Fuels Plant uses pyrolysis to break down four types of waste plastics — HDPE, LDPE, polypropylene, and polystyrene[326] — from both post-industrial and post-consumer sources.[327] The product is pyrolysis oil, which Nexus ships by rail to clients. Nexus claims the oil is used without additional treatment as a replacement for fossil-based oil in the production of new plastics.[328] Publicly reported numbers indicate that the plant has been operating most recently at between 6% and 13% of its announced capacity and has produced less than 24,000 gallons per month, on average, of pyrolysis oil.(12)

PROJECT HISTORY

The Nexus Circular Fuels Plant is an Atlanta-area pyrolysis facility that has been operating at pilot scale since 2011,[329] and has been selling its product commercially since 2018.[330] In March 2021, Nexus' pyrolysis oil received International Sustainability and Carbon Certification Plus,[331] a third-party certification for products marketed with sustainability attributes.[332]

(12) Derivation by the author: Feedstock processing milestones were taken from three Nexus announcements on April 20, 2021; July 11, 2022; and January 23, 2023. Monthly averages were calculated by dividing the announced increases in feedstock processing by the number of months that had passed between announcements. Those estimated monthly averages were compared to the facility's rated feedstock processing capacity to derive operating percentages.

In November 2020, Shell signed a supply agreement with Nexus to purchase 66,000 tons of pyrolysis oil over a four-year period for use in Shell's Norco chemicals plant in St. Charles Parish, Louisiana.[333] As of January 2023, however, Nexus announced that it had processed a total of 8 million pounds (4,000 tons) plastic waste to date,[334] which means it is unclear whether Nexus will be able to supply the contracted amount of pyrolysis oil to Shell. In February 2023, Nexus also signed a long-term offtake agreement with Chevron Phillips for an unspecified "annual supply" of pyrolysis oil, which Chevron Phillips says will be used to produce polyethylene products marketed with the Marlex Anew brand.[335]

PROJECT FINANCING

Early financing for the Nexus Atlanta plant was provided by Cox Cleantech in 2015.[336] In December 2021, Six Pines Investments LLC, a subsidiary of Chevron Phillips Chemical (CPChem), made an unspecified equity investment in Nexus to expand its production.[337]

In January 2022, the packaging manufacturer Printpack made an unspecified investment in Nexus Circular.[338] Also in January 2022, the polyolefins producer Braskem, a recipient of a federal grant of $1.9 million for "conservation research and development" in 2023,[339] made an unspecified investment in Nexus Circular. In January 2023, Cox Enterprises provided Nexus $150 million in equity, which gave Cox Enterprises a majority stake in Nexus Circular.

PLANS FOR EXPANSION

Building on its 2015 investment, Cox invested $20 million in 2021 for Nexus to build two additional facilities.[340] Since the investment, Nexus has announced plans for an expansion of their Atlanta-area plant and three new plants, none of which has been completed: Nexus McDonough in Henry County, Georgia; Dallas Chemical Recycling Plant in Texas; and Nexus Circular-Braskem in Cook County near Chicago.

In April 2023, Nexus was issued a permit amendment to build a second production line at the existing Atlanta plant. They don't specify production capacity in the permit application or on their website. According to page 19 of their application, construction was expected to begin in the fourth quarter of 2022. However, their permit wasn't issued until April 2023.[341]

All three new plants were announced as having larger capacity than the Nexus Circular plant in Atlanta, Georgia, which has most recently been operating at between 6% and 13.6% of its announced capacity.(13) Nexus has obtained an initial Clean Air Act pre-construction permit for the proposed plant in Henry County, Georgia.[342] No specific sites have been announced yet for the other two plants.

The proposed Dallas facility was announced via a press release from Dow Chemical on July 21, 2022. At the time, the projected capacity of the planned Nexus Circular facility in Dallas was 28,660 tons per year.[343] The press release announced an agreement for Dow to take the production output of the facility, though an exact amount was not specified.

In February 2023, LyondellBasell and Nexus Circular also signed a long-term offtake agreement to supply the former with approximately 24,000 tons of recycled feedstock per year from the Texas facility. LyondellBasell announced that it will market its products made with this feedstock under its CirculenRevive brand.[344] No other public statements have been made regarding progress on this proposed facility.

The proposed Cook County, Illinois, plant was announced in a press release from polyolefins producer Braskem S.A. on July 11, 2022, which announced a partnership with Nexus Circular on a proposed facility that would have an initial capacity to process 33,000 tons annually.[345] No other public statements have been made regarding progress on this proposed facility. The press release announced a memorandum of understanding for Braskem to have "exclusive rights to the production output" from the proposed Chicago plant[346] for 10 years.[347] Business Wire reported in 2023 that Braskem intends to use the product to help meet its goal of selling 300,000 metric tons of products with recycled content by 2025.[348] It is unlikely that this announced goal will be met, given that the facility was not yet built as of August 2023.

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(13) Derivation by the author: Feedstock processing milestones were taken from three Nexus announcements on April 20, 2021; July 11, 2022; and January 23, 2023. Monthly averages were calculated by dividing the announced increases in feedstock processing by the number of months that had passed between announcements. Those estimated monthly averages were compared to the facility's rated feedstock processing capacity to derive operating percentages.

CAPACITY AND SCALE

According to an April 2021 company profile in Atlanta Inno, the Atlanta area plant was designed to process 50 tons of plastics a day (18,250 tons per year), but at that time, it had not been operating at full capacity.[349] Documents obtained from the Georgia Environmental Protection Division show that in March 2021, Nexus Circular reported it had failed to submit required data on its scrubber system because the plant was "not yet operating … at its designed rate. While we are producing quantities of product that are being sold, this is still being done on an intermittent basis."[350]

Atlanta Inno further reported that the plant had produced about 310,000 gallons (about 1,550 tons) of oil from more than 2.7 million pounds (about 1,350 tons) of plastic since it began operating a decade prior. These reports indicate a higher output of oil than input of plastics. On July 11, 2022, Nexus announced that it had diverted more than 5.5 million pounds (2,750 tons) of plastic from landfills.(14) Then on January 23, 2023, Nexus announced it had processed just over 8 million pounds (4,000 tons) of plastic to date.[351] This means that during the 15-month period between April 2021 and and July 2022, the plant processed about 1,400 tons of plastic, or about 6% of its announced capacity. And during the six months between July 2022 and January 2023, it processed about 1,250 tons of plastic, or some 13.6% of the plant's announced capacity.

For comparison, the U.S. EPA reports that in 2018 Americans generated 35.7 million tons of plastic waste, of which 26.9 million tons were landfilled.[352] Even if it were operating at full capacity, it would take more than 1,473 plants the size of the Nexus Circular facility in Atlanta to process just the landfilled portion of plastic waste generated in the United States.

HAZARDOUS WASTE AND AIR EMISSIONS

The Nexus Circular Fuels Plant is not registered as a hazardous waste generator with the U.S. EPA. It is permitted as a synthetic minor source of hazardous air pollutants with a potential to emit 51 tons of criteria air pollutants each year, including sulfur dioxide, which damages the lungs; nitrogen oxides and volatile organic compounds, both of which contribute to smog; microscopic soot or particulate matter, which can trigger asthma and heart attacks; and carbon monoxide, which can inhibit oxygen intake to the heart and brain.[353]

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(14) "Braskem Extends Relationship with Nexus Circular Through MOU for Commercial Off-Take of Circular Plastic Feedstocks from New Advanced Recycling Facility", Announcement by Braskem and Nexus Circular, July 11, 2022. https://www.prnewswire.com/news-releases/braskem-extends-relationship-with-nexus-circular-through-mou-for-commercial-off-take-of-circular-plastic-feedstocks-from-new-advanced-recycling-facility-301582393.html. Accessed October 25, 2023.

PRIMA AMERICA | NORTHUMBERLAND, NEW HAMPSHIRE

Facility	Prima America Groveton Plastics Recycling Facility
Company	Prima America Corp.
Location	Northumberland, New Hampshire (Coos County)
Operational Status	Pilot
Process(es)	Pyrolysis
Feedstock Type	Mixed non-chlorinated plastic waste
Rated Feedstock Processing Capacity	Unknown
Total Feedstock Processed	Unknown
Output Type	Synthetic diesel
Stated Purpose of Output	Fuel
Output at Capacity	Unknown
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	Unknown
% Low-Income Residents in Community	33%
% Residents of Color in Community	3%
Hazardous Waste Generator	Not listed with U.S. EPA
Project Cost	$28 million
Subsidy Value	Unknown
Other Financials	Unknown

Prima America chemical recycling facility in Northumberland, New Hampshire. Source: Google Maps

OVERVIEW

The Prima America Groveton Plastics Recycling Facility is owned by Prima America Corp. with ties to Formosa Plastics. It is a pilot-scale pyrolysis plant located in Northumberland, New Hampshire. The company intends to break down plastic waste via pyrolysis to create diesel fuel. There is no information available on the capacity of this facility, and there is no publicly available information that it has sold any product to date. The company does not have a website.

PROJECT HISTORY

In 2010, Prima America Corp. first applied for an air permit to convert powdered sawdust along with other chemical components under vacuum into synthetic diesel fuel.[354] Nine years later, according to minutes from a March 2019 meeting of the Northumberland Planning Board, the Prima plant had been "shut down indefinitely due to issues with [Department of Environmental Services (DES)]."[355]

In March 2019, DES found the Prima facility to be in substantial noncompliance with applicable rules in regard to its above-ground storage tanks.[356] In June 2019, plant representatives also received a letter of deficiency from DES for failing to submit an annual emissions report.[357] The matter was resolved the following month.[358]

Less than a year later, in a February 2020 interview with the Conway Daily Sun, a local paper, project consultant Michel Bisson said the plant was taking plastic waste, including grocery bags, hay bale wrap, and used maple sugaring lines.[359] Other inputs were to include used vegetable oil and non-recyclable non-chlorinated plastics;[360] but according to the news article, the facility had not yet received the necessary permits to begin operation.

According to a February 2020 segment on WCAX TV, Bisson projected that the facility would be able to produce upwards of 1,200 gallons of diesel an hour, 24 hours a day at full capacity,[361] which would be more than 10 million gallons per year. The Conway Daily Sun article quoted Bisson as saying that "5 million pounds of plastic could produce 1 million gallons of sulfur-free fuel."[362] Converted to tons, this statement suggests that 2,500 tons of plastic waste is producing 5,000 tons of fuel.

Despite an early, grandiose goal of taking "all the plastic on the East Coast" at this and future plants,[363] to date there is no indication that this facility has produced any synthetic diesel for sale to commercial customers. In April 2022, Prima reported to DES that emissions of all regulated pollutants was only 0.12 tons in 2021 due to limited operation since startup.[364] In March 2023, plant manager Richard Perry told Energy News Network that the plant remains in a test phase: "We're still trying to refine [the fuel we produce] for diesel engines and to make it a lot cheaper. It's so expensive right now it wouldn't be economical."[365]

PROJECT FINANCING

In 2010, Prima America Corp. purchased the Groveton property for $1.365 million[366] on a site owned by a former paper company. The total project cost has been reported as $28 million.[367] According to an official with the town of Northumberland, the project has not received any local tax abatements,[368] and an official with the New Hampshire Department of Business and Economic Affairs said the project had not requested nor received any state funding.[369]

Prima America and the Groveton facility are privately owned by a group of individuals with multiple interests in the U.S. and the global plastics industry. According to its state business registration, Prima America was incorporated in Delaware in 2010 as a foreign profit corporation with a New Jersey address. The president of the company is Dr. John Ding-E Young, who is also a widely published molecular immunologist, cell biologist,[370, 371] "and head of a health empire." [372] John D. Young is also the president and cofounder of the Inteplast Group,[373] a plastic film and sheet manufacturer with more than a dozen other plastics and packaging affiliate companies[374] and $3.15 billion in annual revenue.[375] Seven out of 10 of Prima America's registered directors[376] have ties to Inteplast.[377]

Three of Prima America's 10 registered directors are also listed as owners[378] of Formosa Plastics, the Taiwanese producer of intermediate materials for virgin plastics production.[379] Formosa, which had global revenues of $8.4 billion in 2022,[380] has an ethane cracker in Point Comfort, Texas; a PET production facility in Florence, South Carolina, under an affiliate, NanYa Plastics;[381] a plastic resin and chemical manufacturing facility in Baton Rouge, Louisiana;[382] and a history of environmental violations.[383,384] Prima America's registered business address — 9 Peach Tree Hill Road in Livingston, New Jersey — is identical to the address of Formosa's U.S. headquarters.

PLANS FOR EXPANSION

None.

CAPACITY AND SCALE

Exact capacity is unknown, but it is a pilot-scale facility, and to date there is no publicly available information that this plant has produced any synthetic diesel for sale to commercial customers.

HAZARDOUS WASTE AND AIR EMISSIONS

The Prima America facility in Northumberland is listed in the U.S. EPA's database of facilities, but it is not classified as a hazardous waste-generating facility. According to permit records, the facility is considered a minor source for air pollution with the potential to emit up to 83 tons of criteria air pollutants each year, including sulfur dioxide, which damages the lungs; nitrogen oxides and volatile organic compounds, both of which contribute to smog; microscopic soot or particulate matter, which can trigger asthma and heart attacks; and carbon monoxide, which can inhibit oxygen intake to the heart and brain. Potential greenhouse gas emissions are unknown.[385]

PURECYCLE | IRONTON, OHIO

Facility	PureCycle Ironton Plant
Company	PureCycle Ohio LLC
Location	Ironton, Ohio (Lawrence County)
Operational Status	Partially or intermittently operating
Process(es)	Solvent-based purification(15)
Feedstock Type	Waste polypropylene
Rated Feedstock Processing Capacity	Estimated at 66,430 tons per year
Total Feedstock Processed	Unknown
Output Type	Polypropylene resin
Stated Purpose of Output	Recycled polypropylene plastic
Output at Capacity	Estimated at 53,500 tons per year
Actual Production	Unknown
Combustion of Waste-Derived Gas On-Site	N/A
% Low-Income Residents in Community	36%
% Residents of Color in Community	6%
Hazardous Waste Generator	Classified as a small quantity generator
Project Cost	Less than $361 million
Subsidy Value	Tax-exempt revenue bonds
Other Financials	Private investment

OVERVIEW

The PureCycle Ironton Plant is owned by PureCycle Ohio LLC, which is a wholly owned subsidiary of PureCycle Technologies, headquartered in Orlando, Florida. Construction at the facility in Ironton, Ohio, was completed on on May 1, 2023,[386] about three years behind schedule.[387] The plant uses solvent-based purification, or dissolution, to process waste polypropylene into polypropylene resin pellets. At full annual capacity, PureCycle reports that the plant could convert as much as 182 tons of feedstock per day (66,430 tons per year)[388] of waste polypropylene into about 107 million pounds (53,500 tons) per year of recycled polypropylene resin (UPR, or UPRP).[389] The plant produced its first batch of resin pellets in June 2023,[390] but has since experienced mechanical difficulties that have caused the plant to halt production. The plant missed key milestones for its financing agreements and filed a force majeure in September 2023 to release itself from contractual obligations.[391] It is unclear whether the plant is currently processing any feedstock as of late October 2023.

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(15) Solvent-based purification is considered by many to not be chemical recycling because it does not change the chemical structure of the feedstock. We are including it in this report because it is a relatively new process which may become classified as chemical recycling under some definitions, and it has the potential to generate a large amount of hazardous waste.

PROJECT HISTORY

The technology used at the Ironton, Ohio, facility was developed by Procter & Gamble and was licensed to PureCycle in 2015.[392] The process uses butane, an alkane-based solvent, to remove dyes and pigments from waste polypropylene. PureCycle claims the process produces no byproduct.[393] However, government records show that there are a number of toxic solvents being used in the process, and that these spent solvents — along with the waste plastic's toxic additives, dyes, pigments, and other contaminants — are part of the hazardous waste stream produced by this facility.[394]

One of the largest challenges for PureCycle has been securing clean feedstocks. In March 2022, PureCycle announced an agreement with iSustain Recycling to source discarded polypropylene drink cups from events, venues, and retail locations.[395] Drink cups are the only source of waste polypropylene for which the U.S. Food and Drug Administration has issued a favorable opinion for PureCycle to use in food-grade applications.[396]

In March 2023, PureCycle announced an agreement wherein iSustain would "source and divert up to 5,000 tons of polypropylene waste from landfills and waterways," but without specifying the terms of the deal or how that would be accomplished.[397] The plant is currently using only post-industrial feedstocks, but says that it has plans to use a combination of post-industrial and post-consumer plastic waste in the future.[398]

The company has developed what it calls a feedstock preprocessing facility, or PreP, in Ironton and has announced plans to develop other PreP facilities in different areas of the country, including California and central Florida.[399] Additionally, PureCycle reports having successfully converted discarded carpet into polypropylene resin in its "feedstock evaluation unit" in Ironton, OH."[400]

The plant produced its first batch of resin pellets in June 2023.[401] On September 13, 2023, the company provided a Notice of a Force Majeure Event(16) to its lenders, the Southern Ohio Port Authority and UMB Bank. The notice claimed that it would be unable to meet a key milestone of its agreement with bondholders of producing 4.45 million pounds of pellets in a single month by September 30, 2023. In a filing to the Securities and Exchange Commission, PureCycle attributed this to a power outage in August 2023 that caused a mechanical failure in early September 2023.[402] It claimed that it is "unable to eliminate the risk that the restart will be unsuccessful, or whether other failures resulting from the August 7, 2023 power outage may be discovered in the future."[403] PureCycle is currently seeking adjustments to its September 2023 milestone.

PROJECT FINANCING

The total cost of the Ironton project has been reported as approximately $361 million "at the higher end of the project investment."[404]

On October 1, 2020, the Southern Ohio Port Authority executed an indenture of trust with trustee UMB Bank to provide PureCycle with $250 million in revenue bonds, consisting of $219.5 million in tax-exempt Series 2020A bonds, $20 million in subordinate exempt Series 2020B bonds, and $10 million in subordinate exempt taxable Series 2020C bonds. These bonds were to enable PureCycle to finance the acquisition, construction, equipping, and installation of a portion of the Ironton plant. Proceeds from the bonds were held in trust, and PureCycle was only allowed to draw funds when it performed certain obligations required by the agreement.[405]

In March 2021, PureCycle began trading on the Nasdaq stock exchange as PCT. PureCycle CFO Michael Dee said that the company had raised more than $730 million in the previous year from "a variety of sources."[406]

In March 2023, PureCycle defaulted on its agreement with the Southern Ohio Port Authority and UMB Bank by failing to complete construction of the project before December 1, 2022, as called for in the agreement.[407] PureCycle requested that the Trustee (UMB Bank) and Issuer (Southern Ohio Port Authority) waive the default. Both entities agreed to do so, but placed a number of conditions, some financial and some performance-based.[408]

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(16) "Force majeure" is a provision in a contract that frees both parties from obligation if an extraordinary event directly prevents one or both parties from performing their contractual obligations.

In September 2023, the Ironton facility experienced a mechanical failure, and its operations were halted. In filings to bondholders and the Securities and Exchange Commission, Purecycle claimed that the mechanical failures were due to a power outage on August 7, 2023, caused by inclement weather affecting a third-party power supplier. After repairs and replacement of a faulty seal, restart procedures were initiated at the facility on September 11, 2023. But PureCycle could not guarantee that the restart would be successful or whether further mechanical failures would occur as the result of the earlier power outage.(17)

Recognizing that the facility would not meet a key milestone as required in its default waiver with Southern Ohio Port Authority and UMB Bank, PureCycle filed a Notice of Force Majeure to release itself and its bondholders from their contractual obligations.(18)

PLANS FOR EXPANSION

In July 2019, before its first commercial plant was up and running, PureCycle signed an agreement to supply the L'Oréal cosmetics company with all the recycled polypropylene the Ironton plant was slated to produce. At the time, PureCycle said, demand for its product was outstripping supply, spurring it to explore developing a second plant in Europe and giving L'Oréal first dibs on any resin produced there.[409] Shortly thereafter, Bloomberg reported that PureCycle had "presold more than 20 years of output from its first plant."[410]

Another French company, TotalEnergies (also a partner in the New Hope, Texas, facility profiled on page 107 of Appendix 1), signed an agreement in May 2020 to purchase "part of the output of PureCycle Technologies' future facility in the United States and to assess the interest of developing a new plant together in Europe."[411]

In July 2021, PureCycle announced that it had reached an agreement with the Augusta Economic Development Authority to build a new $440 million plant in Augusta, Georgia.[412] PureCycle had a groundbreaking ceremony in March 2022. The company hoped the first two production lines would be completed by late 2023,[413] and announced that it had raised $250 million in private equity for the project.[414] However, the company has not yet applied for an initial Clean Air Act pre-construction permit with the Georgia Department of Natural Resources, which means they cannot begin construction on any emissions units. The only permit obtained to date is a general stormwater construction permit, which will expire on October 31, 2023.[415]

On May 31, 2023, PureCycle announced it had received approval from the Augusta Economic Development Authority to close on the project site and said this approval "confirms and preserves financial and tax incentives offered for the development."[416] At that time, the startup plan had been revised to one initial line, with the potential to expand to eight lines producing a combined 500,000 tons of recycled resin.[417]

In August 2021, PureCycle signed a memorandum of understanding with Seoul-based SK Global Chemical (later SK Geo Centric), to pursue building and operating a polypropylene recycling facility.[418] A year later, the two firms created a joint venture to build a 60,000-ton plant in Ulsan, South Korea, billed as the first of its kind in Asia.[419]

In January 2023, PureCycle's vision for a European plant advanced with its selection of a site in the Nextgen district of Port of Antwerp-Bruges in Belgium. The proposed plant would have an initial capacity of 65,000 tons.[420]

As of May 2023, before it had produced its first resin pellets at the Ironton, Ohio, facility, site engineering and permitting were proceeding for the Augusta, South Korea, and Belgium plants. In addition, PureCycle was in discussions with Mitsui about a joint venture to build potential plants in Japan,[421] the first of which would have an initial processing capacity of 65,000 tons and is targeted for completion in 2026.[422]

It remains to be seen whether these expansion plans are completed.

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(17) U.S. Securities and Exchange Commission Form 8-K, filed by PureCycle Technologies, Inc. September 13, 2023. https://ir.purecycle.com/sec-filings-reports/all-sec-filings/content/0001830033-23-000024/0001830033-23-000024.pdf. Accessed October 25, 2023.

(18) U.S. Securities and Exchange Commission Form 8-K, filed by PureCycle Technologies, Inc. September 13, 2023. https://ir.purecycle.com/sec-filings-reports/all-sec-filings/content/0001830033-23-000024/0001830033-23-000024.pdf. Accessed October 25, 2023.

CAPACITY AND SCALE

At full annual capacity, the plant could convert up to 66,430 tons of waste polypropylene into about 53,500 tons of recycled polypropylene resin (UPR, or UPRP).[423] However, the facility is not yet operating at capacity.

For comparison, according to the U.S. Environmental Protection Agency, 8.15 million tons of polypropylene waste was generated in the United States in 2018.[424] It would take at least 123 facilities the size of PureCycle Ironton operating at full capacity to process all that polypropylene.

HAZARDOUS WASTE AND AIR EMISSIONS

The PureCycle Ironton Plant is categorized in the U.S. Environmental Protection Agency ECHO system as a "small quantity generator."[425] The PureCycle Ironton Plant is generating hazardous wastes from spent solvents and solvent mixtures that include both halogenated and non-halogenated solvents, including but not limited to tetrachloroethylene, trichloroethylene, and chlorobenzene.[426] It is considered a minor source of air pollution with the potential to emit 12 tons of criteria air pollutants each year.[427]

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APPENDIX 2

Source: Beyond Plastics

APPENDIX 2: MODEL BILL BANNING CHEMICAL RECYCLING

The following model legislation is provided by Beyond Plastics. IPEN does not engage in U.S. state legislative campaigns.

A MODEL BILL

PROHIBITING THE CONSTRUCTION, OPERATION, AND PUBLIC FUNDING OF CHEMICAL CONVERSION OF WASTE IN [STATE]

FOR the purpose of protecting the environment by altering the definition of recycling to exclude the use of plastics into fuel or feedstocks through certain processes and prohibiting the construction or operation in the State of any facility that converts or attempts to convert plastics into fuel or feedstock through certain chemical conversion processes.

WHEREAS the past, current, and projected increase in the production and demand of plastics in the United States has raised concerns regarding environmental degradation caused by the proliferation of plastic waste, especially in communities of color and or low-income communities.

WHEREAS the petrochemical industry in the United States has utilized and touted chemical conversion processes as supposedly effective mechanisms to mitigate the ongoing plastic pollution problem, pointing to the supposed ability of chemical conversion to encourage more effective plastic waste management and create a circular economy.

WHEREAS recent scientific and technological evidence demonstrates that, by using heat and or chemicals to break down plastic waste into new plastic polymers or feedstock, chemical conversion releases pollutants into the environment (e.g.dioxin emissions and crude, contaminated hydrocarbon fuels) and emits carbon.

WHEREAS recent scientific and technological evidence also demonstrates that chemical conversion, despite its ascendant popularity in the petrochemical industry, has not handled a significant amount of plastic waste.

SECTION 1. BE IT THEREBY ENACTED BY THE LEGISLATURE OF THE STATE OF [INSERT STATE], that the laws of the [INSERT STATE] read as follows:

(A) DEFINITIONS.

(1) CHEMICAL CONVERSION TECHNOLOGIES: With regard to plastic, “chemical conversion technologies” means—

(a) the use of plastic as a fuel or fuel substitute or the general use of plastic in energy production; or

(b) the following processes:

(i) gasification;

(ii) pyrolysis;

(iii) solvolysis;

(iv) hydropyrolysis;

(v) methanolysis;

(vi) glycolysis;

(vii) enzymatic breakdown;

(viii) solvent-based purification;

(ix) combustion; or

(x) any other process used to transform plastic or plastic-derived materials into plastic monomers, chemicals, waxes, lubricants, chemical feedstocks, crude oil, diesel, gasoline, or home heating oil.

(2) FACILITY: “Facility” means any structure, place, amenity, equipment, tool, or operation built, installed, or established for the purpose of performing, facilitating, aiding, or otherwise engaging in chemical conversion as defined in Section 1(A).

(3) PERSON: “Person” means any natural person as well as any corporation, company, partnership, firm, society, or association of persons.

(4) RECYCLING:

(a) GENERALLY— “Recycling” means any process in which materials are collected, separated, or processed and returned to the marketplace in the form of raw materials to make new products.

(b) EXCEPTION— “Recycling” does not include chemical conversion as defined in Section 1(A).

(B) PROHIBITION ON CHEMICAL CONVERSION TECHNOLOGIES.

(1) The definition of recycling shall exclude chemical conversion technologies pursuant to Section 1(A).

(2) A person may not use, facilitate, or otherwise deploy chemical conversion technologies in the State.

(C) PROHIBITION ON FACILITIES USING CHEMICAL CONVERSION TECHNOLOGIES.

(1) A person may not build, construct, establish, or operate any facilities that use chemical conversion technologies in the State.

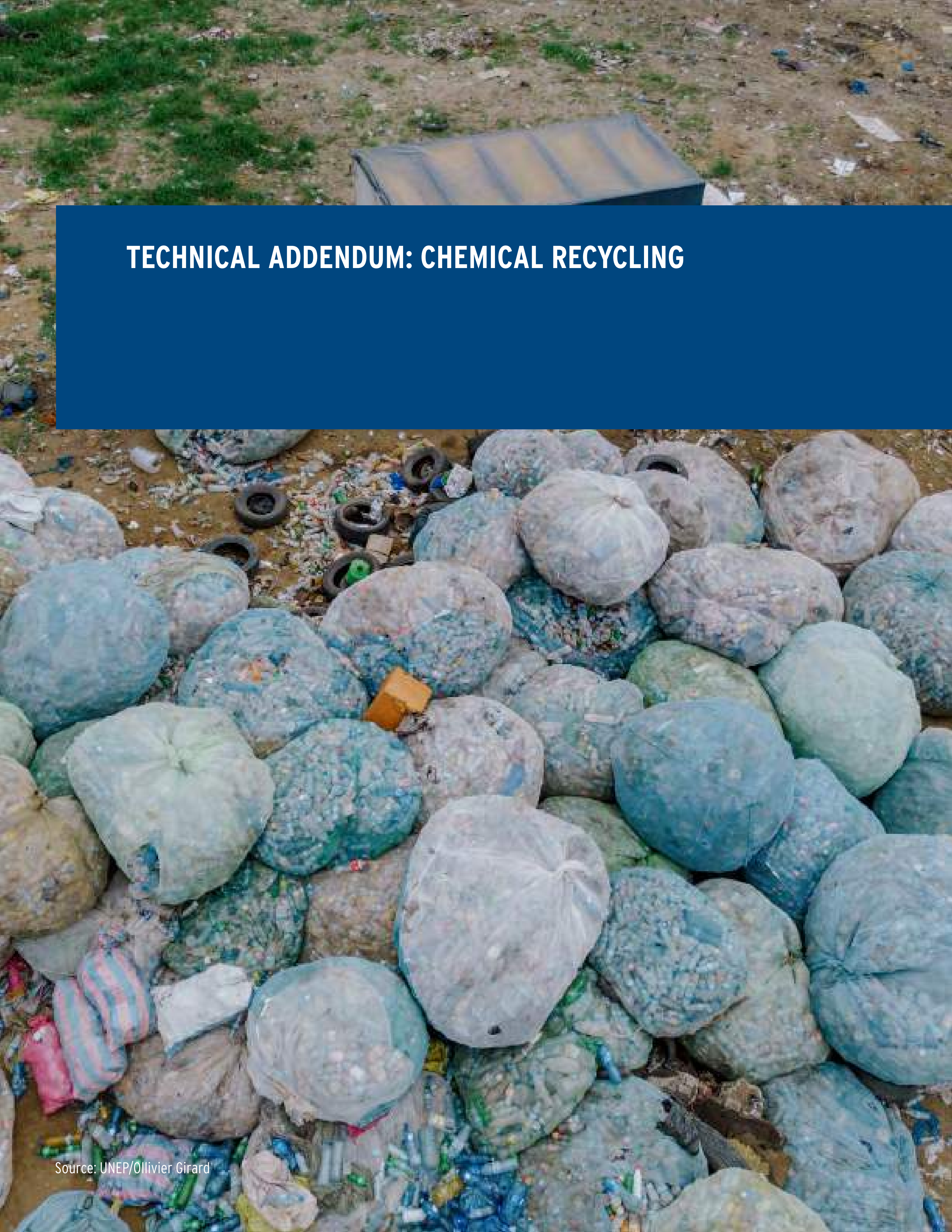
(2) The prohibition in this subsection applies to the modification or conversion of any existing non-covered facilities in the State into facilities that use chemical conversion technologies as defined in Section 1(A) and which are covered by this Act.

(D) PROHIBITION ON STATE INCENTIVES FOR CHEMICAL CONVERSION TECHNOLOGIES.

(1) The State shall not provide subsidies, grants, tax breaks, or any other financial or non-financial incentives to support the development of facilities that use chemical conversion technologies or programs focused on chemical conversion technologies.

(E) ENFORCEMENT & IMPLEMENTATION. The [Department] may adopt regulations to enforce and implement this Section.

SECTION 2. AND BE IT FURTHER ENACTED, That this Act shall take effect immediately.



TECHNICAL ADDENDUM: CHEMICAL RECYCLING

Source: UNEP/Ollivier Girard

PART 1

1. EXPLAIN THE TERMS: WHAT ARE THE CHEMICAL RECYCLING TECHNOLOGIES?

1.1 INTRODUCTION

1.1.1 THE LANGUAGE OF CHEMICAL RECYCLING

The language of chemical recycling is a jumbled one. No two authors use the same nomenclature when categorizing the systems or subgroups, and there are many synonyms. Yet, 50 years ago, the same methods were being collectively described in meta-research publications (reviews of existing research) and perhaps more importantly were being practically trialed at commercial scale (Kaminsky, 1976). Indeed, this was actually based on 30 years of prior research in laboratories (Lewis and Naylor, 1947; Seymour, 1948). Going back even further, the main methods have over a century of engineering evidence to draw upon when fed with other wastes (Goodrich, 1924; Horsfield, 1979). This history is seemingly being ignored today.

Promotional discourse on chemical recycling is influential. It originates from technology providers and major multinational corporations that profit from plastic. One significant voice is that of a trade organization called the American Chemistry Council (ACC), although there are other industry collectives, such as the Alliance to End Plastic Waste[1](note: the ACC should not be confused with the American Chemical Society, which is a scientific association).

To many, the techniques appear perpetually on the brink of success, always just within sight, or on the horizon — claims which can actually be traced back over many decades, in fact, to around the same time that plastic waste became a "crisis" and the "circular economy" became a popular part of corporate strategy (Mah, 2021). Many go by seemingly mysterious or cryptic names, and it appears they have settled into a sort of existence where it suits public cognition not to probe too deeply into their workings, failings, waste impacts, and energy use. Capabilities are unimportant to many concerned about plastic pollution. What matters is that some innovative idea can, in future, meet ambitious recycling targets while maintaining the throughflow of cheap plastic consumer goods, however illusory (Mederake, 2022).

1.1.2 WHAT IS CHEMICAL RECYCLING?

Chemical recycling is an umbrella term for an assortment of technical ideas that promise a back-end fix for the plastic waste crisis. Collectively, they target plastic downstream in its life cycle, after it has existed in product form and been thrown away. Their objective is to make chemical ingredients for more plastic or for burning as fuel. As this report shows, it is wrongly claimed that they are an advancement on, and therefore offer something more to society than, conventional mechanical recycling.

When the product of chemical recycling is to be used to replace virgin plastic, then the terminology is plastic to plastic. When it is to be burned as a fuel, then it is plastic to fuel, which usually means upgrading into a standardized type and transported off-site for combustion. Plastic to fuel is noted for having no environmental benefit (Crippa et al., 2019), since the fossil oil and gas has merely spent a part of its lifetime as a plastic product prior to releasing the same carbon dioxide in combustion as if it had been burned directly. Plastic to fuel is therefore not considered recycling in many jurisdictions.(19) Despite a half-century of commercialization, any actual environmental benefit of plastic to plastic remains disputed and unclear, for reasons related to lack of scrutiny into process energy (and therefore carbon footprint), volume and toxicity of waste streams, quality of product fit for displacing virgin plastic, and simple technical efficacy.

Chemical recycling technologies underpin a number of modern phrases. One is sustainable aviation fuels (SAF), applied when the fuel is purported to be made from waste plastic (Rollinson, 2021). Of a similar ilk is "green," "turquoise," or "red" hydrogen, depending on the point of view of the author, but again where the hydrogen[2] is to be made from plastic waste using chemical recycling techniques.

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(19) European Commission, Article 3(17), Directive 2008/98/EC (https://www.legislation.gov.uk/eudr/2008/98/contents); United Nations Environment Programme, 2023, Basel Convention technical guidelines on the environmentally sound management of plastic wastes (http://www.basel.int/TheConvention/ConferenceoftheParties/Meetings/COP16/tabid/9311/Default.aspx)

In this report, “chemical recycling” includes all methods that either involve the use of chemicals in the plastic treatment stage or produce chemicals from plastic waste. The mode of operation of these techniques will involve multiple stages, and their process lines will likely be specific to a single plastic type. They will operate by subjecting the plastic to heat, though many expose it to high pressure, too. Some treat it with steam; others immerse it in toxic solvents and then strip it out again with more solvents or anti-solvents; some use various types of metal composite or pH-adjusting catalysts; the most common will limit the presence of oxygen; and some use refrigeration, or highly energized ionic gas.

In addition, there will be necessary pre-treatment stages of sorting, washing, drying, and grinding; post-treatment by filtration, precipitation, distillation; and/or further upgrading using steam, high temperatures, pressure, catalysts, etc., all of which consume energy and resources.

1.2 CHEMICAL RECYCLING: THE TERMS

Synonyms: chemical recovery, feedstock recycling, advanced recycling, tertiary recycling, and a variety of other colorful metaphorical descriptions

The term chemical recycling, which currently leads the race for consensual acceptance, is frequently preceded by the adjective “so-called” (Cook et al., 2022; Miskolczi et al., 2009). This descriptor is assigned to identify that the term is inappropriate.

Feedstock recycling is only applicable when the products of chemical recycling processes are to be used to make new plastic, not when they are burned as a fuel. Some use it to define the whole concept, while others use it to refer to only the thermal treatment subset (pyrolysis and gasification) — these being the oldest techniques (Buekens, 2006; Crippa et al., 2019). Feedstock is a chemical engineering word for the input to a process — in this case, material for plastic manufacture.

Industry sometimes proposes its own language that pervades society through public relations activities. For example, one technology provider appears to be the sole user and originator of the phrase molecular recycling.[3] The main proponent of advanced recycling appears to be the American Chemistry Council. A comparable phrase, advanced thermal treatment (ATT), was similarly advocated by the waste industry for the same group of technologies when fed municipal solid waste, though it seems to be falling into disuse due to widespread commercial failures. None were effective, nor were they new, so antiquated is perhaps more appropriate than “advanced.”

A sober alternative is to define the methods in juxtaposition with various alternative plastic waste end-of-life treatment options. Here they are called tertiary recycling, with mechanical recycling being “secondary” and incineration with energy recovery “quaternary.” This choice of grouping has its roots in thermodynamics, referring to the fact that the deeper one goes in the plastic breakdown process, the more disorder (entropy) increases, and the more energy is needed to put the polymers back together again. Therefore, a newly proposed term is to call the pyrolysis methods long loop recycling. This describes the extensive amount of effort and energy needed to bring a small fraction of the input material back into use (Warringa et al., 2023).

A variety of metaphorical descriptions also exist, such as circular manufacturing,[4] building a better circle,[5] and closing the loop.[6] Another is unbaking the cake, although as one author observed, a more appropriate allegory would be having one’s cake and eating it too (Mah, 2021), given the thermodynamic impossibilities of the schemes and how they lock in society to the continuous need for more petrochemical plastics.

1.3 PLASTIC WASTES: THE CHEMICAL RECYCLING FEEDSTOCK

The word plastic has many meanings. Here we are concerned with the material property of deforming or flowing under temperature- or pressure-induced stress. Based on how this occurs during the production stage, there are two distinct classes:

1. **Thermoplastics:** These may be repeatedly softened under heat, then rehardened when cooled. Examples include polypropylene (PP), which, along with high-density and low-density polyeth-

ylene (HDPE and LDPE), form a group of plastics called polyolefins; polystyrene (PS); polyethylene terephthalate (PET), a form of polyester; and polyvinyl chloride (PVC).

2. **Thermosets:** These harden irreversibly once cured by conditions of heat, oxidation, or light. Examples are epoxy resins, polyurethane (PUR or PU) and polyamide/nylon (PA).

All plastics are built of long-chained macro-molecular structures called polymers, with each polymer comprising thousands of smaller units termed monomers. A part of a polymer is an oligomer. Two modes of formation provide alternative groupings:

1. **Condensation polymers** are also known as **step-growth polymers** because during production, a solvent molecule, such as H2O, is emitted in a chemical reaction usually involving two different types of monomers. In theory, solvent-based depolymerization can push the reaction in reverse by adding the solvent back in, often enabled by adjusting temperature and pH, and in the presence of a catalyst. Examples are PET/polyester, PA, and PUR.
2. **Additional polymers** are also called **chain-growth polymers**. Examples are PVC, LDPE, HDPE, PP, and PS. They are formed by joining monomers together one at a time. Thermal-based depolymerization is usually proposed for this group of plastics.

All plastic polymers are hydrocarbons — made of hydrogen and carbon — but they also contain lesser quantities of other elements, predominantly oxygen, nitrogen, sulfur, and the halogens (i.e., chlorine, fluorine, bromine) (Weisinger et al., 2021). These heteroatoms modify the polymer and impart various properties (e.g., colorants, plasticizers, flame retardants, antioxidants), facilitate processing (anti-slip agents), or reduce costs (fillers), among other purposes (Gueke, et al., 2018; Hahladakis et al., 2018), and are collectively termed "additives." The mixture of polymer and additives forms a resin, which is used to make plastic products. During their life cycle, plastic products also accumulate dirt and other contaminants that are termed non-intentionally added substances (NIAS).

Even single types of polymers can have a variety of compositions and properties (Roosen et al., 2020; Rogers et al., 2003). Also, many plastic products are multilayer composites, formed from different resins along with some non-plastic materials.

Though some biobased plastics exist — such as polylactic acid (PLA) — most are made from crude oil, natural gas, or shale gas. From this, petrochemical refining creates monomers such as ethane/ethylene, propene/propylene, and butane/butylene to make PE and PP, or aromatics (benzene, xylene) to make PS and PP.

1.4 THE PHYSICAL RULES OF CHEMICAL RECYCLING

The universal laws of energy and matter transfer (laws of thermodynamics) bring a reality check to the attractive but impractical idea of a machine that can perpetually cycle plastic molecules in a closed loop without any energy inputs or use of resources (Rollinson and Oladejo, 2019). They equally constrain any temptation to indulge the notion of a theoretical circular economy operating in the same manner (Cullen, 2017). Specifically, the deeper one decomposes plastic, the more energy and resources are needed to reconstruct it. Plus, the more processing stages there are, the more energy losses there will be overall. Chemical recycling is not a "green" technology, nor is it "sustainable."

By the rule of conservation of mass, all elements that go into a chemical recycling process must enter either gaseous, solid, or liquid products, or go into chemicals used to capture them, thus generating new toxic waste streams. With depolymerization, the aim is to get the maximum quantity of carbon and hydrogen to form monomers, but a proportion will form other unwanted organic substances and will also join the waste, or reduce the process yield and make the product off specifications, rendering it unfit for further use.

Firmly established physical principles dictate where chemical recycling reactions will settle at equilibrium and what the yield/byproduct will be at a given time, dependent on parameters such as temperature, pressure, access to reagents (i.e., quantity of solvent), and the extraction of products from the reaction mixture (Le Chatelier's principle).

1.5 CHEMICAL RECYCLING: THE TECHNIQUES

Table 1 shows a basic classification of chemical recycling techniques. Each will likely have numerous other process adaptations ,as discussed in the text.

Table 1 Chemical recycling categories.

CATEGORY	DEPOLYMERIZATION	USES SOLVENTS	TEMPERATURE	
			140 ≤ °F ≤ 662	≥ 932°F
Pyrolysis and Gasification	X			X
Solvent-Based Depolymerization	X	X	X	
Solvent-Based Stripping		X	X	

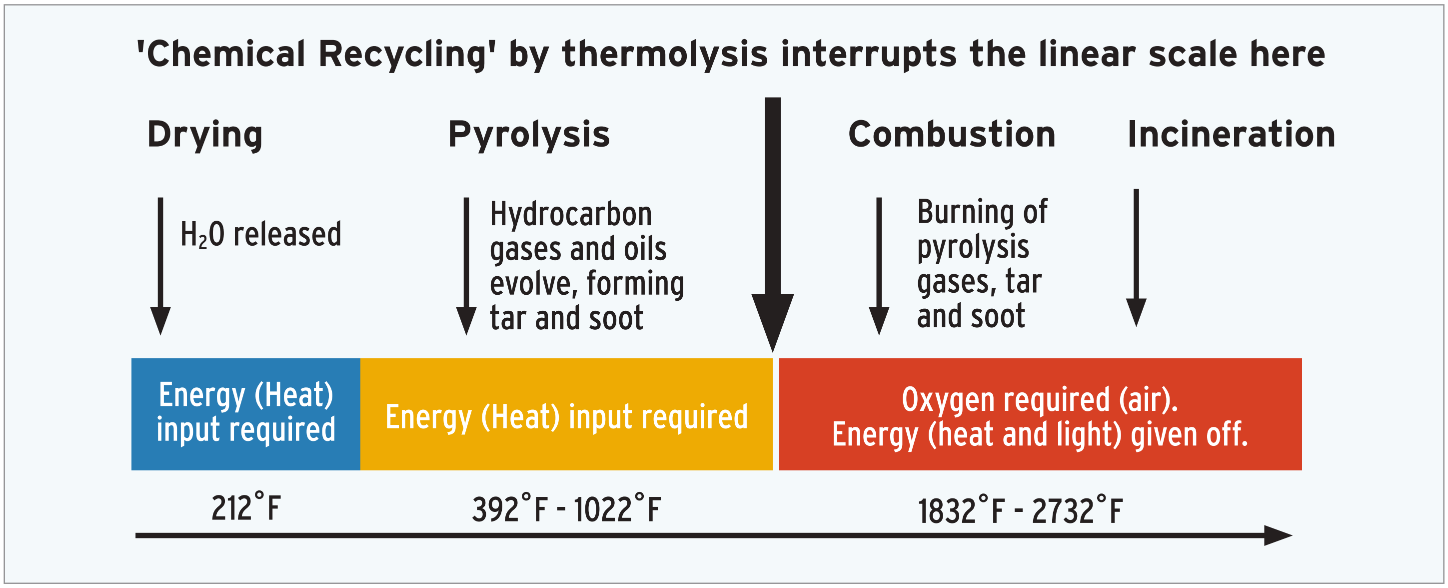
Temperature values are approximate.

1.5.1 PYROLYSIS AND GASIFICATION

Synonyms: thermal cracking, thermal depolymerization, thermochemical recycling, thermolysis

Thermal decomposition can be considered a linear scale (see Figure 1). Combustion and incineration are at the end of the scale and not considered chemical recycling, because they totally destroy the monomers — meaning, in energetic terms, that it is senseless to expend great effort and resources attempting to reconstruct the products back into new plastics or fuels. The only practicable thermal decomposition methods for chemical recycling are pyrolysis and gasification.

Figure 1 Thermal Decomposition as a Linear Scale



Source: Andrew N. Rollinson, Ph.D.

In all cases, when carbon-based substances are heated, a major fraction of mass is evolved as a condensable gas. This is pyrolysis, and the output is termed pyrolysis gas or pyrolysis oil. Pyrolysis products are toxic, chemically complex, flammable, and retain much of the feedstock's important chemical functionality.

When pyrolysis gas encounters air (specifically, oxygen), it readily ignites. So, crucially, conditions for chemical recycling are engineered to prevent combustion by applying heat, but restricting the ingress of air. A way to think about this is holding back combustion or temporarily disconnecting the thermal decomposition scale to preserve the chemical functionality of the plastic for later use.

With plastic to fuels, or where the output is burned on-site, the thermal decomposition scale is reconnected, even though— albeit more energy has been used for the intermediate processing. Recycled polymers also degrade, such that they too soon rejoin the "incineration scale," thus leading to a permanent need for new petrochemical plastics.

A variant of pyrolysis seeks higher liquid (oil) production, and this is called liquefaction. Steam or air is mainly used for gasification to carry the product gases out from the reactor. Air is for burning some of the molecules in situ and providing heat for the process, while steam is to help crack some of the unwanted tars. Where carrier gases are used for pyrolysis, they are unreactive (inert) gases such as nitrogen, so they don't contribute to the product or bring oxygen that may generate heat. Hydrogen gas is a particular variant — known as hydrogenation (also hydro-treating and hydro-cracking) — which is a mature technology for petroleum and coal refining.

In chemical recycling terms, whereas pyrolysis aims to make use of the oil, and possibly also burn the gas fraction, gasification aims to make use of the gas. Some authors differentiate gasification from pyrolysis by the quantity of oxygen present in the reactor and/or temperature. While this has a basis in fact, it is not always correct and leads to confusion. The best way to think of gasification is as a "gas production" system.

1.5.1.1 PYROLYSIS

The most common proposals for commercial chemical recycling are pyrolysis.[7] The phenomenon (pyro- is from the Greek for fire) has been known for thousands of years. Here, a pile of wood is ignited, then mostly covered with soil; the soil stops enough air from getting in to create flames, but permits just enough for some portion to smolder and emanate heat. Over many days, with hands-on management to ensure that the heating does not cool or that it does not end in a conflagration and total loss of products, this promotes the release of pyrolysis gas and leaves residual charcoal. It also yields other valuable liquids, such as wood alcohol (methanol) and creosote.

Charcoal is wood's fixed carbon framework. It is not present in most types of plastic, and this absence is important for later discussions on why gasification chemical recycling fails. Heat woody biomass without oxygen, and the fixed carbon framework will resist decomposition, keeping the same size and shape as its original form, albeit about 80% lighter — the 80% is evolved gas, some of which condenses as oil.

The invention of high-precision analytical instrumentation in the 1960s allowed for a more detailed understanding of the process (Buekens, 2006). But still there is no agreement on the best conditions and reactor design (Pires Costa et al., 2022). This is due to pyrolysis involving multiple and competing heat-consuming (endothermic) reactions, such as melting, cracking, and condensation (Kumagai et al., 2020). Variables that affect the composition and fractioning of the output mixtures are feedstock chemistry, residence time, highest treatment temperature (usually considered complete at 1,022°F), pressure, heating rate, carrier gas flow rate (if used), and interactions between products when in closed conditions.

1.5.1.2 GASIFICATION

Gasification evolved in the mid-1800s as a way of making town gas from coal, which was used for municipal and domestic lighting, and later with woody biomass gasifiers that powered cars, boats, trucks, and small stationary engines up to the 1930s and 1940s. After World War II, as oil became cheap and readily available again, "wood gas" fell out of favor. Since then, interest has waxed and waned, usually in response to oil prices and potential oil shortages. For accounts of the theory and praxis of gasification, see Kaupp (1984a, 1984b); Reed and Das (1988); Rollinson (2018).

It is important not to conflate gasification of coal, coke, and some specific types of woody biomass with the gasification of plastic and mixed waste. Intrinsic problems are associated with the latter.[8]

Under ideal conditions, a gas can be produced that has carbon monoxide and hydrogen both in concentrations between 5% and 25%, with lesser quantities of methane. All these molecules are combustible and could be used as feedstocks for chemical processing to upgrade them into finer chemicals. To achieve this, temperature must be approximately double that of pyrolysis (1,562 R °F R 2,012), but at the same time a complex series of physical and chemically interdependent set of conditions must be maintained to minimize tar formation.

With biomass gasification, the output is called producer gas, and not "synthesis gas," — referring to the "syngas" produced by methane steam reforming or coal gasification. A common conflation is made between the two that mis-projects gasification of plastics in comparison to that from cleaner feedstocks, thereby falsely setting up the concept outside of its technical limitations.

1.5.2 TAR AND SOOT

Tar is gasification vernacular for the same mixture of condensable hydrocarbons, which in pyrolysis are called oils, waxes, and occasionally pitch. In lay terms, it is a dark brown, viscous, acidic, aromatic substance, with the aroma coming from polycyclic aromatic hydrocarbons (PAHs), which are its constituents. Tar lowers the process yield. More important, it condenses in downstream components across a wide range of temperatures (known as fouling), where it chronically clogs and corrodes metallic surfaces and impairs heat transfer. Its complexity is one of the many reasons why plastic pyrolysis oil is not good enough to make into new plastics without extensive purification.

Tar PAHs are precursors to soot formation, but tar also traps soot entrained in the gas flow, thereby further increasing the magnitude of fouling. Soot is carbon-rich particulate matter (PM).

Such information generally isn't mentioned in technology provider permit applications or outreach, perhaps because the generation of these high quantities of toxic and hazardous waste streams are costly to manage in an environmentally sound way and are the main cause of commercial plant closure. According to Vreugdenhil and Zwart (2009), "The rate of thermal cracking is such that high temperatures are required — in the order of 1,200°C or higher (also depending on residence time at high temperature) in order to break down enough tars so that the remaining fuel gas can be used problem-free in a downstream device, such as a gas engine, gas turbine, or catalytic synthesis process."

Extensive research on tar has been undertaken over many decades, so that classifications and modes of formation can be understood (Grootjeset al., 2016; Kiel et al., 2004; Milne and Evans, 1998; Van Paasen and Kiel, 2004; Vreugdenhil and Zwart, 2009) (see Table 2). In short, secondary and tertiary (heavy) tars synthesize from primary (light) tars with increasing temperature; and although they decrease in quantity as temperature increases, the heavier tars are more difficult to clean out of the gas stream. Multiple stages of highly specialized, non-standard cleaning systems are required, because tar is a complex mixture of polar (water soluble) and non-polar (water insoluble) molecules (Rabou et al., 2009).

Table 2 Tar Classification, Description, and Behavior*

DESCRIPTION AND BEHAVIOR	
Class 1	Believed to be the heaviest (tertiary tars). They condense at high temperatures even at very low concentrations. Non-polar so cannot be captured by wet scrubbing.
Class 2	Heterocyclic aromatics. Secondary molecules, converted from primary tars. Polar, and highly water soluble. They form higher classification tars at 750 R °C R 850.
Class 3	1-ring aromatics — e.g., xylene, styrene, toluene. Hydrocarbons that are too light to be important in condensation and have water solubility issues.
Class 4	Light polycyclic aromatic hydrocarbons with 2 to 3 rings — e.g., naphthalenes, indene, fluorene, biphenyl, phenanthrene, anthracene. These are intermediates formed from growth of class 2 tars. They condense at relatively high concentrations and intermediate temperatures. Non-polar.
Class 5	Heavy polycyclic aromatic hydrocarbons with 4 to 6 rings. Produced at high temperature by growth of Class 2 tars — e.g., fluoranthene, pyrene, benzo-anthracene, chrysene, benzo-fluoranthene, benzo-pyrene, dibenzo-anthracene. Condense at relatively high temperature in low concentrations. Non-polar.

*Adapted from references in section text

1.5.3 PYROLYSIS AND GASIFICATION REACTOR TYPES

For pyrolysis, the classic reactor is a retort that distills vapor in a batch process. Others operate in semi-batch or continuous mode, such as screw/auger reactors, rotary kilns, stirred tanks, and fluidized beds. A discussion of pyrolysis reactor types can be found in Chen et al. (2014) and Williams (2013), while details of the plastic pyrolysis reactors trialed at commercial scale since the early 1980s are given in Kumagai et al. (2020) and Buekens (2006).

Quality gas is the titular concern of gasification, but all capable systems have tar reduction as a primary objective (Kaupp, 1984a, 1984b; Reed and Das, 1988). The classic types are ”fixed bed” or ”stratified bed” reactors (also proposed for pyrolysis) where the feedstock is heated, either indirectly or by burning some quantity in situ. A cigarette is an everyday example of an updraft gasifier, and many studies have confirmed the presence of over 500 types of PAH in cigarette smoke (Idowu et al., 2019).

1.6 SOLVENT-BASED METHODS

Synonyms: chemolysis, solvolysis

While pyrolysis is often considered the oldest method of chemical recycling, others say solvent-based methods are traditional while assigning thermal treatment as more challenging (Achilias et al., 2007). Solvents are traditional to ”wet” chemistry and are widely used in other chemical processing industries. Most are volatile organic compounds (VOCs) made predominantly by refining fossil fuels. Many are toxic and hazardous, also with high boiling points, meaning they need intensive treatment for distillation and recovery.

Like pyrolysis, many solvent-based methods exclude oxygen(20) while also treating plastic waste at high temperatures, but in a lower range (140 R °F R 662) (Arturi et al., 2018; Sherwood, 2020). They are classified separately because they also use solvents. Conditions are further adapted to speed up the process and increase yield by pressures of several hundred bar, the inclusion of catalysts and/or non-solvent reagents which adjust pH, followed by greater quantities of a second solvent (anti-solvent) to extract target molecules out of the first, with distillation, precipitation, and filtering also common.

First, however, the plastic will be washed, dried, and then shredded (sometimes cryo-milling) to reduce bulk volume and increase surface area for chemical reactions. It will then be immersed in a bath of solvent and left for a certain time period to enable a desired quantity of the plastic polymeric structure to be either decomposed to monomers or oligomers (solvent-based depolymerization), or stripped out intact from the rest of the plastic matrix (solvent-based purification). In both cases, the solvent is highly specific to the target polymer being decomposed or stripped out.

1.6.1 SOLVENT-BASED DEPOLYMERIZATION

Synonyms: chemical depolymerization, plus other names that start with the type of solvent and end in “–olysis” (though not pyrolysis)

Like pyrolysis, this varied group of methods aims to depolymerize plastic into its constituent parts to such an extent that sufficient quantities of monomers can be extracted to enable their repolymerization back into plastics again.

Condensation polymers (see Section 2.3) are the target feedstock, with the aim being to push the condensation reaction into reverse by reintroducing the solvent. The chosen primary solvents give their name to the first part of the term, followed by ”-lysis,” such as aminolysis (amines), acidolysis (acid), and ammonolysis (ammonia). Some have subcategories; for example, alcoholysis includes glycolysis and methanolysis.

First patented in the 1960s and since then continually investigated by many major companies, glycolysis of PET occurs in the absence of oxygen at temperatures of 356 R °F R 464 and pressures of 15 to 73 psi (Ghosal and Nayak, 2022). PET methanolysis is proposed as a cheaper alcoholysis alternative (Vogt et al., 2021). Some details on the history of the commercial trials can be found in Merrington (2017), Sherwood (2020), Vogt et al. (2021).

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(20) The concept of “oxygen free,” which also applies to pyrolysis, is often a misnomer, as many plastic wastes contain oxygen, which can lead to the formation of persistent organic pollutants such as dioxins (see Technical Addendum, Part 2).

Hydrolysis uses water as the solvent, again under high temperature and pressure, but with its pH adjusted to be made acidic or alkaline by chemicals such as NaOH and H2SO4 (Quicker et al., 2022). For completeness, enzymatic hydrolysis, which uses microbes in water, is mentioned, but it is not used at scale. Uekert et al. (2022) explain the reasons, such as low yield of the target molecule, a low-quality output, high water use, high electricity use — 90% which is extrusion and cryo-milling, plus steam for solvent recovery — and use of sodium hydroxide (NaOH) for pH control.

1.6.2 SOLVENT-BASED PURIFICATION

Synonyms: solvent-based stripping, dissolution-precipitation, selective extraction, and physical recycling

When classifying solvent-based purification, some authors place it outside of chemical recycling. This is the position of one technology provider, who called their technique physical recycling.[9] This has logic, for solvent-based purification does not seek to break down the polymers, but rather to strip them out intact from the additives and unwanted parts of the plastic matrix, then reintroduce them into conventional mechanical recycling systems.

As with mechanical recycling, because the recycled polymers degrade with each pass through the extruder, it is not a perpetual recycling method for plastics (Crippa et al., 2019). And as with other solvent-based techniques, forced precipitation can lead to higher recyclate crystallinity and hence a further deterioration of quality (Sherwood, 2020). Higher energy use and greenhouse gas emissions are associated with this technology, largely due to the embedded energy and regeneration of the solvents (Uekert et al., 2023).

In theory, it should be technically possible to use different stages of solvent extraction to separate different polymers — for example, with multilayer packaging — but this does not occur because the costs, greenhouse gas emissions, waste streams, and challenges are multiplied. So, all known industrial applications have a single plant or process line for each polymer type (Cook et al., 2022).

A flagship plant for solvent-based purification opened in 2002 but closed in 2018 (Sherwood, 2020). The current number of operational plants is uncertain, with one recently opened in Indonesia but already permanently closed down (Aliño et al., 2022). One is claimed to operate in Germany,[10] while another demonstration plant in the Netherlands is said to have reopened after an episode of bankruptcy.[11]

1.7 IN CONTEXT

The methods described in this section represent only the first stage in a two-stage destruction and reconstruction process. This abridgement is common to how the techniques are described. By focusing only on the first side of the system, technology providers and their stakeholders conveniently sidestep the intrinsic obstacle to the whole concept, namely the technological difficulties of making something good enough for the stated purpose and thereby meeting the concept's side of the bargain. This explains why, despite decades of commercial adventure, the present fraction of chemically recycled polymers remains "vanishingly small" (Vogt et al., 2021). Also generally omitted from the picture are the necessary upgrading steps, energy use, and waste generation, which are consequently shifted to an external domain.

When challenged by the evidence of 50 years of commercial failure, a common, almost default, response from technology providers and their promoters is, "Oh, but those were old concepts; our technique is different and new" — claims that are invariably devoid of any explanation of what makes it is different or what is new about it. Another tactic is to dismiss one subset of chemical recycling and plant a flag beside another — e.g., "Pyrolysis is no good; solvolysis is the future." (Interchange these to suit.)

TECHNICAL ADDENDUM PART 2

2. LEARNING FROM HISTORY: WHY CHEMICAL RECYCLING OF POST-CONSUMER PLASTIC WASTE HAS NOT WORKED

> *“Recently, advanced recycling technologies have changed in two important ways. First, they’re being built at commercial scale. These large, multi-million- dollar facilities are capable of processing millions of tons of plastics per year. Second, the technologies themselves can do a lot more.”* [12]
> *—Joshua Baca, former vice president of the American Chemistry Council’s plastics division*

In fact, the technical reasons for commercial failures are inherent and intractable, and in some cases actually worsen with increasing scale. These reasons are explained in this section. To understand them is to understand why there are empty or questionable claims about existing operational plants, which are often just empty warehouses behind web-based façades — and why investigations[13] reveal that plants claiming to make new plastic instead expend large amounts of energy to make something that is often burnt.

Technology providers are uncommunicative when failures occur and are equally as tight-lipped with data on operational parameters, so factual data is exceedingly hard to find (Rollinson and Oladejo, 2020). There has been little evidence of plastic being converted into plastic, with none of the plants identified by other authors verified as operational (Cook et al. 2022). Hann and Connock (2020) come to similar conclusions, and suggest an interesting reaction: that financial speculators should reserve investment for those organizations that provide transparency or robust evidence.

In a recent attempted appraisal of chemical recycling based on commercial ventures, Garcia-Gutierrez et al. (2023) express their frustration at the inadequate responses on operational transparency from technology providers, despite repeated instances for such data. This is the norm, with many other macro research publications over many decades reliant on technology provider projections. Others turn to modeling, but the same scarcity of information again limits their value.

Life cycle analyses (LCA) merit particular criticism regarding their limited understanding of operational fundamentals, superficial reliance on projected claims, and positive bias, such that authors have called for all future studies of this type to be performed not by theoreticians, but by engineers with better knowledge of the process (Pires Costa et al., 2022; Tabrizi et al., 2020). There are also many reviews that defer back to older reviews (macro research), some from 25 years ago and for which all plants are closed down. These publications have not been cited in this section. Rather, information here draws from independent empirical research, supplemented by evidence from practical commercial endeavors.

2.1 THERMAL CRACKING: ‘INCINERATION BY ANY OTHER NAME’

It is now 17 years since the publication “Incinerators in Disguise” [14] reported on the false premise of pyrolysis and gasification as fix-alls for converting municipal solid waste into energy. Total abandonment and heavy financial losses ensued in North America and Europe, so such talk is now rejected on these continents[15] (Gleis 2012).

But the technology providers have not gone away. Their techniques have been repackaged and rebranded, this time (albeit usually hidden behind other names) for the more difficult job of making plastic into new plastic and vehicular fuels. This stage of the repeating story is hereby called “incineration by any other name.”

2.2 THE PROBLEM WITH PLASTIC

Plastics burn hot. But this can be detrimental as it leads to uncontrollable combustion, which creates local oxygen deficiency, in turn leading to the formation of tar precursors (Buekens, 2006). Plastics also have low thermal conductivity, meaning they do not transfer heat well, and high viscosity, which causes the feeding systems to become clogged and unequal internal heating (Kumagai et al., 2020).

With regard to chemical composition, certain additives are especially unwanted, such as elements from the halogen group, along with oxygen and sulfur, as they form pollutants and acids that cause corrosion within the process line and deterioration of product quality. PVC and PET are particularly unsuitable for pyrolysis (Kumagai et al., 2020). Metals also act as catalysts, but little is known about their effects on fouling, along with those of other plastic additives and depolymerized monomers (e.g., styrene, butadiene), which are coke precursors (Buekens, 2006). However, numerous additional properties are needed for reactor stability, though no standard currently exists (Reed and Das, 1988). These are listed in Table 3 alongside how plastic compares.

Table 3 Feedstock Properties for Pyrolysis and Gasification in Comparison to the Properties of Plastic Waste

REQUIRED PROPERTY	REASON	HOW PLASTIC COMPARES
Consistent and rigid particle size and shape	To avoid blockages and bridging during feeding and to maintain void spaces for heat and gas transfer plus tar cracking	Poor — heterogeneous
Char durability and fixed-carbon content	To maintain void spaces for heat and gas transfer plus regions for tar cracking	Poor — most plastic has no fixed carbon framework so does not form char
Moisture content	Moisture is a heat absorber. Some moisture is good, as steam can crack tars. Reactors prefer moisture content homogeneity	Poor — plastic moisture will be at the surface, so variable
Ash-fusion temperature	Elements from groups 1 and 2 of the periodic table are fluxing agents, causing agglomeration, particularly at air entry points	Poor, due to the ubiquitous presence of additives in plastic
Bulk density	To ensure no blockages or bridging during feeding	Poor, unless plastic is very finely shredded

Source: adapted from Reed and Das, 1988

There are also practical problems with plastic waste that impact energy use. Industrial steam crackers (needed to upgrade depolymerized plastic) process 500,000 tons per annum necessitating about 1.2 million tons of naphtha, while polymerization of resins is done industrially at a lower scale but still a similar order of magnitude (150,000 tons) (Buekens, 2006). As 1 ton of plastic can be in 20,000 bottles, even once collected, sorting and transporting these lightweight items is a logistical barrier.

2.2.1 GASIFICATION

The rich, 100-year history of gasification concluded that the technology has extreme difficulty operating with heterogeneous and amorphous material. Reactor design has not improved, and this finding still holds, unless the process is bolstered by the input of fossil fuels and operates closely coupled to an incinerator (Rollinson, 2018).

The problem occurs because internal thermodynamics are extraordinarily sensitive and precariously balanced. Temperature and gas circulation must be moderated to avoid secondary and tertiary synthesis of unwanted heavy polycyclic aromatic hydrocarbons (PAHs), all from a process in which oxygen must be restricted. To achieve this, well-designed gasifiers encourage separate thermal (non-physical) zones in which different reactions are promoted and with each zone dependent on heat and mass transfers across the whole.

There must be a high temperature in the combustion zone to heat the endothermic reduction zone (where gas quality is improved) without burning too much of the feedstock (loss of yield), but the reduction zone must not be too hot — otherwise heavy polycyclic aromatic hydrocarbons (PAHs) form (loss of yield and downstream clogging and corrosion). Tar cracking occurs within hot void spaces in the reduction zone, as previously described (Rollinson, 2016).

With fluidized bed reactors, it is conditions in the freeboard that are important for tar management. But residence time is too low for satisfactory cracking reactions, so even closer focus is needed on process conditions (van Paasen and Kiel, 2004). A catalyst may be added, but there is a tendency for some to carry over into the products. Grootjes et al. (2016) described how, compared to biomass, plastic feedstock increased instability, which lowered product yield and increased tar formation. This was accentuated by various metal elements (though metals separation had already occurred), while other additives in plastic caused heavy agglomeration near the air nozzles from sticky salts binding to the sand.

Consequently, gasification of plastic to plastic exists only in theoretical reviews. One plant in Canada, Enerkem, is often cited, but there has been no new information about the venture for years, and a recent local authority Business Plan[16] says that it is looking for a new industrial partner and license for the site (Edmonton, n.d.). Notwithstanding the above, Enerkem was not plastic to plastic; rather, it claimed to be depolymerization to methanol.

One plastic gasification plant exists in Japan (Showa Denko Ebara), but it reportedly does not make new plastic. (It creates hydrogen for ammonia.) Extensive prior preparation of the feedstock is needed, and then steam or pure oxygen is used at high temperatures. Clogged extruders need two hours' cleaning every day, and there are persistent problems with slagging and damage to the linings of the reactor. Even then, the final output has to be blended with hydrogen produced from natural gas (Quicker et al., 2022).

2.2.2 PLASTIC PYROLYSIS[17]

"It's a whole lot harder than people believe ..."[18]

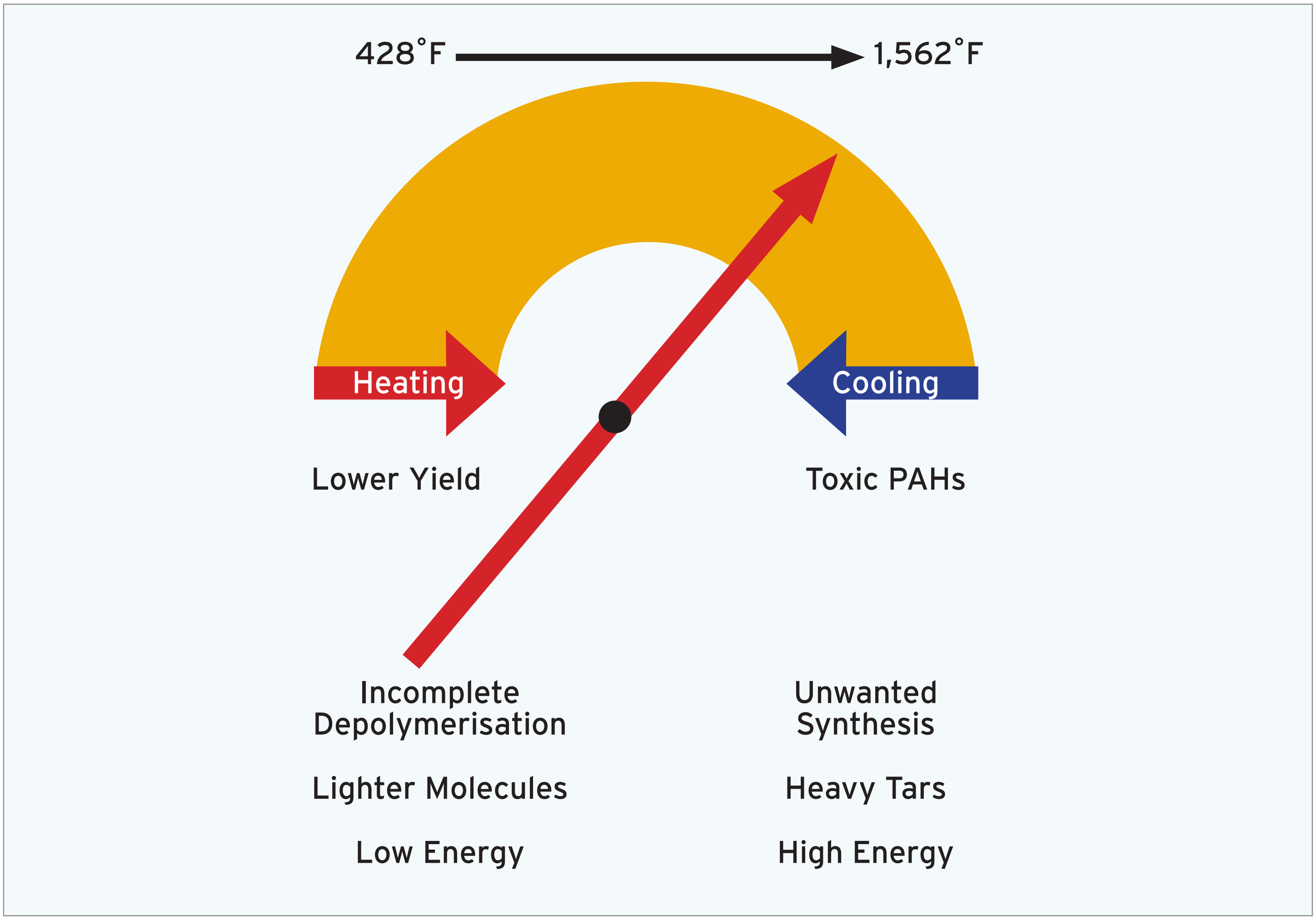
Gasification is "pyrolysis plus," so if it can't succeed with plastic, why is pyrolysis being proposed? The answer is that pyrolysis reactors are easier to design and cheaper to build, plus they are also superficially easier to operate. But this hides a truth: Such pyrolysis systems produce a much more crude output mixture. So making the first step easier merely shifts the problem down the line, putting the essential upgrading of the material outside the boundary of the plant and into someone else's hands.

Essentially, it is energy-intensive waste treatment to create a poor-quality product with low yield, while its "green" credentials can be manipulated by sophisticated and permissive accounting methods (Warringa et al., 2023). This is why plastic pyrolysis oil might well be traded, but investigations find that most of it is only fit for burning.[19]

Pyrolysis requires a continuous supply of heat over prolonged periods and needs to be able to respond rapidly to what is a very sensitive process. In modern pyrolysis plants, this heat comes from burning natural gas or diesel oil.[20] Despite some claims, the process will not self-sustain on its own gas (Rollinson and Oladejo, 2019). A balance must be sought between competing chemical reactions that produce heavy polycyclic aromatic hydrocarbon (PAH) molecules and those that selectively yield monomers, particularly in closed systems where the vapors have greater time to interact at high temperatures (see Figure 2).

Note: This is one facet of the pyrolysis trade-off. Higher temperatures produce unwanted molecules, while lower temperatures don't produce enough monomers.

Figure 2 The Pyrolysis Balancing Act



Source: Andrew N. Rollinson, Ph.D.

2.2.3 LOW YIELD AND HIGH ENERGY

"Due to the different components in the plastic pyrolysis oil, only a small portion can be used for new plastic production. Thus, the potential to obtain plastics of virgin quality from this process will be low." —Solis and Silvera (2020)

Recently, U.S. government researchers identified that pyrolysis and gasification have economic and environmental impacts 10 to 100 times higher than virgin polymer production, due to high energy requirements, subsequent need for upgrading, and low yield of suitable monomers (Uekert et al., 2023).

But few independent authors explore the problem from a fundamental chemical engineering perspective. One exception is Vogt et al. (2021), who qualify the infeasibility of pyrolysis chemical recycling, calling it a "grand challenge" that is too energy intensive. The reason is that the high energy needed to break the polymer's strong atomic bonds, in particular for the plastics often spoken of as the right feedstocks — namely PE, PP, and PS.

In 2022, an executive of Veolia announced that their company was not interested in plastic pyrolysis, citing the low yield — only 22% of the original input material — and a significantly larger carbon footprint than virgin plastic production (EUWID, 2022). These figures are corroborated by Brightmark Energy in a permit application for its plastic pyrolysis plant in Indiana. According to their information, 70% of the feedstock is burned on-site (supplemented by the burning of natural gas), while 10% is landfilled, meaning that only 20% of the input material would be reclaimed as pyrolysis oil, though they have said this was a mistake.[21]

The problem is seen more clearly in laboratory experiments, which tend to give more favorable results due to smaller scales. When PS was pyrolysed at 932°F, the oil yield was 71% by weight; but over a quarter of this oil was two- or three-ring aromatics, meaning that less than 50% of the total product yield was monomer. The authors referred to closed reactor conditions generating a wide spectrum of aromatics (Williams and Slaney, 2007).

The polyolefin group of plastics decompose via the production of free radicals, which leads to a wide product spectrum of gases, liquids, and high-viscosity waxes. Raw pyrolysis oil is unsuitable for making new plastics or standardized fuel (Kusenberg et al., 2020). Font et al. (2003) detected multiple mutagenic PAHs formed by secondary synthesis from primary decomposition products of PE above 1,292°F.

In another study (Achilias et al., 2007), at lower pyrolysis temperature (842°F), and despite the presence of a catalyst, the oil yield from individual reagent grade polymers HDPE, LDPE, and PP was in a range between 39% to 67% by weight. But the monomer yield was reduced even further by the oil containing aromatics, and what were described as “other compounds.” This shows that even at moderate temperatures, not only was depolymerization low, but that synthesis of unwanted molecules had occurred.

In a broad study of pyrolysis using several polymer types (PE, PS, PET, and PVC) in comparison to a variety of biomass samples, the plastics produced significantly more PAHs than biomass (measured as 12 of the 16 U.S. EPA priority pollutants). The amount of heavy PAH molecules produced by the pyrolysis of PS and PVC were particularly high, with the quantity of the heavier four-ring PAHs benzo(a)anthracene and chrysene approximately 1,000 times greater than their biomass counterparts for PS (Zhou et al., 2015). Similarly, Nunome et al. (2019) reported that under separate pyrolysis and steam gasification experiments at 1,292 R°FR 1,652, tars from PE and two other polymer types were mainly N-PAHs followed by O-PAHs. These heterocyclic PAHs are among the most potent mutagens and carcinogens (Idowu et al., 2019).

Even with catalysts, the depolymerization of polyolefins is said to be sluggish due to mass transfer between polymer and active surface sites (Vogt et al., 2021). Catalysts are also susceptible to clogging with carbon, — known as coking — by which their efficacy decreases, and some can be irreversibly poisoned.

2.2.4 PASSING ON THE PROBLEMS: UPGRADING OUTPUTS

Detlef Ruff, the senior vice president of process catalysts at BASF, related the difficulties of pyrolysis oil cleanup to journalists at Sustainable Plastics,[22] noting: “The purification of pyrolysis oils obtained from waste plastics is among the most demanding technical tasks in chemical plastics recycling. Impurities — such as halogen, nitrogen, oxygen, and sulfur compounds — but also higher levels of reactive components such as dienes complicate the downstream use and impose strict limitations on the further processing of such streams in the production of new materials.”

In a detailed study by Kusenberg et al. (2020), the problem is explored and assessed against the adverse impact of pyrolysis oil in industrial steam crackers, this being the main route for producing base chemicals. Although it is interesting to read as the report goes through each contaminant element or molecule in turn, in summary, it finds that any pyrolysis oil must be greatly diluted by blending in ratios of 5% to 20% with 80% to 95% petroleum oil before the output could be used in steam crackers to make new plastics:

“Contaminant levels exceed established feedstock quality specifications by one or more orders of magnitude, such as for nitrogen, chlorine, and iron. All these contaminants are known to cause corrosion issues, increase coke formation, destroy expensive reactor tubes, or deactivate catalysts in the separation sections of a steam cracker. Even the typical amounts of olefins, oxygenates, and aromatics found in plastic waste pyrolysis oils are substantially off-spec. In a nutshell, today the quality of crude plastic waste pyrolysis oils is unacceptable as feedstocks for industrial steam crackers.”

For gasification, upgrading will likely be via Fischer-Tropsh synthesis — a catalytic high-temperature gas-phase process. Here the difficulty is again getting input gas to have sufficient (and consistent) quality, as impurities (such as N, Cl, S, tar, and soot) will deactivate the catalyst, while higher oxygen and unsuitable mixtures of hydrogen and carbon monoxide will also necessitate complex gas cleaning stages, on top of other additional processing (Dry, 2002).

2.2.5 DIFFICULTIES IN SCALING UP

Laboratory trials commonly use very small plastic samples; consequently, heat and mass transfer is relatively uniform. But with increasing scale, the temperature and mass transfer distribution becomes more complex and easily destabilizes (Kaupp, 1984). In commercial operations, particularly continuously operating processes, the problems are made worse by heat losses through the larger reactor walls, but also by process management, such as cooling through feeding, emptying, and heat losses through the gas outlet. With the simpler reactors used in pyrolysis, the challenges associated with upscaling are more difficult (Kumagai et al., 2020).

Lack of attention to these fundamentals is a main reason for a very particular phenomenon — the rapid mothballing and closure of full-scale operations very soon after they are advertised as commercially open. What happens is that these systems will also operate for a time, seemingly well, but inside, excessive tar is being produced, a matter that will only become apparent when pressure builds up and/or the gas cleaning systems become blocked (Rollinson, 2016).

2.3 SOLVOLYSIS

It was the carryover of phthalate esters, used as a plasticizer in PVC, into the recycled material that led to the closure of the VinyLoop plant that opened in Europe in 2002, specifically the costs of regulatory compliance for these hazardous substances (Sherwood, 2020). But there are also other concerns: What happens to the large quantities of solvents, how much are regenerated, how much energy is needed for regeneration, how much solvent carries over into the recyclate, and the fate of plastic additives go largely undisclosed and are major unknowns. This — along with low yield, often high water use, large electricity use, and slow reaction speed — are all factors that work against the concept being practically feasible.

Vogt et al. (2021) state that the price of solvent represents nearly 40% of the whole process cost due to the large volumes needed to generate a higher yield of recycled material; but even then, this still results in a monomer/oligomer/solvent mixture from which it is difficult to purify the target molecules, and the product can be “messy,” with the highest fraction of monomer produced still under 50%. To increase the yield, more extreme conditions — such as temperature, catalyst, or more aggressive solvents — are needed, thus increasing energy and operational cost, and also creating more waste and challenges.

2.3.1 SOLVENT-BASED DEPOLYMERIZATION

Attempted for almost half a century, this technique still remains commercially unproven. Though alcoholysis can depolymerize PET, the glycolysis reaction is very slow and produces low yield without catalysts, which are then difficult to separate out from the product. Meanwhile methanolysis needs higher temperatures (356 R °FR 536) and higher pressures, and creates unwanted byproducts (Ghosal and Nayak, 2022).

Even then, the output quality is poor. For example, a Goodyear product called Repete was used to make bottles for Pepsi, but it needed to be blended with 80% virgin fossil fuel-derived PET (Merrington, 2017). The techniques are also not suited for the removal of copolymers, colorants/dyes, or other additives (Vogt et al., 2021). This requirement for a high-quality, single-polymer, homogeneous feedstock makes them a direct competitor with mechanical recycling, rather than a complementary technique.

When solvolysis is attempted with multilayer packaging there results in a broad spectrum of secondary reaction products (Arturi et al., 2018). These same authors experimented with a polyester resin in four types of solvent at 482 R °F R 617 and at high pressures (4,409 psi.). With a catalyst, the liquid-phase products consisted of hundreds of compounds, some of which were a result of secondary reactions, and these dominated the oil fraction. Without a catalyst, the quantity of monomers produced was significantly lower.

In hydrolysis, process chemicals such as NaOH and H2SO4 are needed in high amounts to shift chemical equilibrium toward higher yield. This impacts both the economic and environmental credibility of the process (Quicker et al., 2022).

A case study of PUR solvolysis at pilot scale gives a list of specific problems with glycolysis: the recycled material's polymer chains become shortened, aromatic amines form as a byproduct, and the reaction rate is slow and requires high temperature. For aminolysis, the output has a low yield (40% waste), the replacement of virgin PUR is as low as 10%, and the recycled product has a very intensive odor (Soltysinksi et al., 2018). The authors then used acidolysis to depolymerize PUR, with high energy demands and only 40% of the output usable when blended with virgin PUR.

2.3.2 SOLVENT-BASED PURIFICATION

While it is claimed that solvent-based purification can separate out hard-to-recycle multilayer packaging, commercial processes have focused on homogeneous materials, and even that has proved challenging (Crippa et al., 2019). In a recent case study of the failed Creasolv plant in Indonesia, yield was low, with reports of between 40% to 60% of the feedstock ending as waste (Aliño et al., 2022). There were also alleged reports of bright blue effluent being dumped at the site and the emission of black smoke contaminating surrounding neighborhoods (Ibid).

Solvent-based purification is part of a wider study by Ügdüler et al. (2020), who discuss the technique in terms of solvent/antisolvent pairing, solvent diffusivity (transfer of polymer into solvent), recovery, safety, and toxicity. A number of examples are listed, with median solvent recovery values of 90%. This raises the question of where the balance goes. If it goes into the recycled product, this is swapping one contaminant for another. While being a volatile organic compound (VOC), further processing in an extruder might give rise to toxic emissions that need to be managed.

The authors also provide an interesting model that assesses economic viability based on the percentage of solvent recovered, concluding that the technology still has "a long way to go" and that it will not be competitive before it is highly efficient in recovery of polymer, chemical media, and eventually also the plastic additives. The model results are, however, possibly an underestimate, as they assume a mass ratio of 1 to 1 between plastic feedstock and primary solvent, when far greater quantities of solvent have been used commercially.

2.3.3 THE QUANTITIES AND FATE OF SOLVENTS

For this report, numerous companies were contacted to ask about the percentages of solvent used and regenerated. Only one responded and said that the information was confidential.

A rough guide to the volumes necessary for satisfactory yield can be obtained from literature. The ratio of the VinyLoop solvents (methyl ethyl ketone and hexane) to PVC feedstock was 9.3 to 1, while steam was used at 3.6 to 1 (by mass) (Sherwood, 2020). The antisolvent must be in greater quantities than the primary solvent, with a ratio of about 3 to 1 stated (Ügdüler et al., 2020). Combining the two gives an antisolvent to plastic feedstock ratio of about 28 to 1.

Solvents can be recovered/regenerated using steam distillation, but this is a high-energy process (Uekert, et al., 2023). However, conventional industrial practice is to incinerate them on-site. This is stipulated in the permit application for a commercial solvolysis plant in the U.S. (PureCycle) with a polypropylene purification system controlled by flare with release of 3.24 tons of VOCs permissible over a rolling 12-month period, and a further 32.27 tons of fugitive VOC emissions permitted each year.[23] If flared and if they contain additives, will such facilities be controlled by the same tight legislation as incinerators in Europe if they are designated as manufacturing facilities?

2.4 THE MYTH THAT CHEMICAL RECYCLING CAN ACCEPT MIXED PLASTICS

> *"Today's advanced recycling technologies can handle unsorted mixed plastics, which includes all sorts of packaging (think: chip bags, snack wrappers, food pouches — even toys). This makes it much easier and more efficient to reprocess large volumes of discarded plastics that traditional recyclers can't use."*[24]
> *—Joshua Baca, former vice president of the American Chemistry Council's plastics division*

The veracity of this common promise is refuted by technology providers, independent authors, and perhaps most tellingly by the lack of actual supporting evidence.

With pyrolysis, additives and heteroatoms, soil, and other resins all lead to both operating and product specification problems (Buekens, 2006). With solvolysis, the problems are due to the prohibitive cost of different solvents and anti-solvents (one for each plastic type), the significant quantities of solvent waste generated, and the effort needed to separate the solvents from plastic additives (Vogt et al., 2021).

Following interviews with chemical recycling technology providers, Gendell and Lahme (2022) gave an exposé of the highly specific feedstock requirements. The two most wanted polymers for pyrolysis were PE and PP (thus directly competing with mechanical recycling). All should be clean and well rinsed, with minimum 85% PE or PP, and maximum moisture content of 7%; and all contaminants should not exceed 15%, along with maximum concentrations of the following: PVC (1%), PET/Nylon (5%), PS (7%), metal/glass/dirt/fines (7%), paper/organics (10%).

Similar limitations are identified, and disclosed, by the CEO[25] of chemical recycling technology provider Avangard Innovative:“Pyrolysis, for example, typically requires the minimization of chlorine content (typically to 0.1% or less) due to its corrosive effect, the removal of PET because it oxygenates the process and does not depolymerise using pyrolysis, and the avoidance of nylon and flame retardants.”

Pyrolysis of PVC has been well studied and is considered unsuitable as it forms the corrosive gas hydrogen chloride (HCl). In an experiment at temperatures up to 932°F, 53% of the PVC formed HCl, 24% tar, and only 14% fractioned to gas and oil, while 10% of the chlorine remained in the polymer until higher temperatures, where it formed chlorinated alkenes and aromatics (McNeill et al., 1995). In another, corrosion was so bad that part of the reactor burst (Williams and Slaney, 2007).

High sulfur content is also bad, needing to be lower than 10 parts per million for use as automotive fuel, while oxygen creates acids in the pyrolysis oil. These acids are corrosive and clog piping/heat exchangers, cause thermal instability, and result in elevated soot levels (Roosen et al., 2020). This is why oxygen-rich polymers, such as PET, are not considered suitable for pyrolysis. However, even plastic products made from PE and PS contain some oxygen, while metals and halogens are ubiquitous.

In a study by Zhou et al. (2015), both PE and PS had 2% oxygen, while PET had 33%. García et al. (2003) — who analyzed the pyrolysis products of PE, PVC, and PET plastic types — also detected large amounts of oxygen in the gas product of PE. It was also notable that high molecular weight PAHs formed from all plastic types.

In summary, though chemical recycling is touted with the unique selling point of being able to handle dirty and/or mixed plastic materials, independent authors disagree. Cook et al. (2022) concluded there is no evidence that this aspect has been realized and no evidence that chemical feedstock is being produced from post-consumer plastic in a commercially sustainable process.

2.5 CONSEQUENCES: WATER USE AND DISCHARGES

Water use is particularly high for many techniques, which use it for feedstock washing, process steam, and cooling. According to a news report, the proposed Encina plant in Pennsylvania plans to extract 2.5 million gallons of water per day to wash the plastic and cool the process, returning 60% to 70% of it amid concerns[26] about the release of pollutants termed “forever chemicals” (Bruggers, 2023).

To clean out the polar tar fraction from pyrolysis/gasification gas, water is used and large quantities are needed. In 2003, the Karlsruhe Thermoselect plant allegedly disposed of over 4 million cubic feet of wastewater into the Rhine, while officers at a similar plant in Italy were convicted of contaminating a lake with polluted wastewater (GHEJ/GAIA, 2006).

The problem is made worse because the specialized gas cleaning system will have to process higher amounts of tar and dust due to the many additives in plastics, as well as the higher ash, chlorine, and sulfur content in comparison to clean wood (Grootjes et al., 2016). Yet it is common for many environmental permit applications merely to default all cleanup to a nondescript black box wastewater treatment plant. This is not satisfactory.

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