A CIRCULAR SOLUTION TO PLASTIC WASTE

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INTRODUCTION

"We have met the enemy and he is us!"

Walt Kelly's memorable poster of Pogo standing at the mouth of a trash-filled Okefenokee Swamp marked the first Earth Day in 1970. The world's use of, and dependence on, plastics to simplify and enable modern lives has only increased in the 50 years since. And so inevitably has the amount of plastic waste—by some estimates, it's now ten times higher. Our methods to manage this waste have not keep pace, however. Today, we have the opportunity to turn the tide through circular-economy solutions that expand the scope of recycling methods, but doing so requires support from industry participants across the plastics value chain.

Plastics have become indispensable products that are both essential to modern life and a leading example of the complications that can be created by linear—make-use-dispose—economies. Plastics provide safe drinks, reduce food waste, and enable the storage and transport of medicines. They are essential for medical implants. Their light weight and durability aid in reducing carbon footprints along complex global-logistics value chains. We produce some 350 million tons of plastics every year. The problem is that about 250 million end up in landfills or the environment and 10 million in oceans.

A Big and Growing Problem

Environmentalists and NGOs have long warned about the impact of plastic waste on land, water, and air. Today, regulators, industries, and society alike recognize the need to limit plastic waste and identify new solutions to the problem. Many countries—some 60 so far, according to the UN—have responded with steps to constrain plastics consumption and environmentally detrimental means of disposal. Policymakers are increasingly restricting, and in some cases banning, single-use and flexible plastic products, such as shopping bags. They are also limiting disposal of plastic waste in landfills. Consumer companies, including restaurants and airlines, are cutting back on or entirely abandoning the use of plastic straws, plates, and cutlery. Although these actions have yet to materially reduce the volume of waste, they have sent a clear signal that the status quo can shift rapidly.

Reuse and recycling have proved effective at mitigating some types of plastic waste. Mechanical recycling (recovering plastic waste through mechanical processes) is common in some markets, but current technologies require a well-developed supply chain, including strong sorting, washing, and grinding capabilities. In addition, mechanical recycling cannot handle some of the most commonly used plastics or many advanced polymers designed to be resource efficient and mitigate climate change. Stronger efforts are needed to promote materials that are designed for recyclability, but current mechanical-recycling technologies will eventually reach their limits.

New Circular Technologies

Recent years have seen heightened interest in the potential of circular technologies to break, or at least mitigate the adverse effects of, the make-use-dispose model. Chemical recycling, in a couple of forms, has emerged as a feasible solution to provide decentralized and more broadly applicable recycling systems. One technique involves decomposition, or monomer recycling, in which a polymer is chemically converted back into its constituent monomers, making it a perfectly circular option that reverses the original polymerization process. The related process of conversion, or plastic-to-fuel (PTF) recycling, converts plastics into the equivalent of crude oil or petrochemical feedstock that can be fed into refineries or chemical plants, respectively.

Both of these chemical-recycling processes can be more fully described as plastics regeneration in circular-economy terms. (See Exhibit 1.) Several methods of both monomer recycling and PTF have been demonstrated at the lab scale, from pyrolysis to newer technologies such as hydrothermal liquefaction.[1,2]

The lower costs and ease of application of PTF technology provide a viable alternative for treating plastic waste until we are capable of fully closing the loop on all plastic materials. The most common PTF technology, pyrolysis, has the potential to fill a significant gap on the plastics disposal-reuse spectrum and provide a means of repurposing many types of plastic waste for which no feasible mechanical-recycling options currently exist. Moreover, as we describe in this

EXHIBIT 1 | An Overview of Chemical Recycling

PLASTICS REGENERATION

Decomposition or monomer recycling

- Chemolysis
- Hydrolysis
- Methanolysis
- Glycolysis
- Aminolysis
- Other methods

Conversion or plastic-to-fuel (PTF) recycling

- Pyrolysis
- Fluid catalytic cracking
- Hydrogen technologies
- KDV[1] process
- Gasification
- Hydrothermal liquefaction[2]
- Other methods

Some outputs of PTF recycling may be reconverted into monomers

Source: BCG analysis.

[1] German acronym for *Katalytische Drucklose Verölung*, or catalytic pressure-free conversion to oil.

[2] "Use of super-critical water for the liquefaction of polypropylene into water," Chen et al., *ACS Sustainable Chem. Eng.*, 2019:7;3749–58.

report, pyrolysis presents a promising business case, especially for chemical companies, which can adopt a new technology that is close to their core capabilities while simultaneously helping to develop smarter solutions for managing plastic waste.

The Business Case for Pyrolysis

BCG recently completed several comprehensive analyses of global waste markets, collection systems, recycling regulations, and business cases for mechanical recycling, as well as the economic viability of a number of conversion technologies. We chose pyrolysis as one example for further detailing, including the business cases and financial incentives for companies to invest in, build, and operate pyrolysis facilities. We examined the PTF value chain, the costs of the pyrolysis process, and its market potential. As part of the assessment, we looked at the environmental impact of pyrolysis, as well as its challenges, and studied how various factors and trends play out in three types of markets common around the world, ranging from those that are largely unregulated and immature with respect to plastics collection to those that are highly regulated with well-developed collection chains.

The analysis was reviewed with experts from the chemical industry, waste management companies, circular-economy organizations, and academia. (See the sidebar "Our Thanks to the Experts.")

Our main conclusion is that while the financial and business challenges vary, conversion technologies such as pyrolysis are economically viable in all the market types we studied. In some, pyrolysis can have an immediate and substantial impact—it has the potential to treat up

OUR THANKS TO THE EXPERTS

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Ladeja Godina Kosir, executive director, Circular Change

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Marc de Wit, CFO, Circle Economy

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to two-thirds of the plastic waste generated in Jakarta, for example. In others, the business case is feasible only if governments act to make inexpensive and environmentally detrimental means of disposal—principally landfills—less financially attractive.

Within the current hierarchy of solutions, pyrolysis can play an important role in mitigating the environmental impact of plastics in the near to medium term. The more companies, governments, and institutions invest in or support conversion technologies such as pyrolysis, the greater their ability to contribute to solving this global environmental problem.

NOTES

1. "Chemical recycling of waste plastics for new materials production," Rahimi and Garcia, *Nature Reviews Chemistry*, 2017:1;0046.
2. "Use of super-critical water for the liquefaction of polypropylene into water," Chen et al., *ACS Sustainable Chem. Eng.*, 2019:7;3749–58.

A CHALLENGE OF INCREASING SCALE AND COMPLEXITY

The problem is vast, global, and complex. Some estimates indicate that humans have manufactured more than 9 billion tons of plastics in the past century, most of it since the 1950s. In recent decades, the rising middle class in emerging markets has sent production soaring; half of history's plastics have been produced in the past 15 years. The top 20 countries account for 75% to 90% of the total global plastics consumption, most of it in the form of packaging. (See Exhibit 2.) Of the 9 billion tons of plastics produced, almost 7 billion have become waste. The UN predicts that under current consumption rates and waste management practices, approximately 12 billion tons of plastic waste will be dumped into landfills and leaked into the environment by 2050.

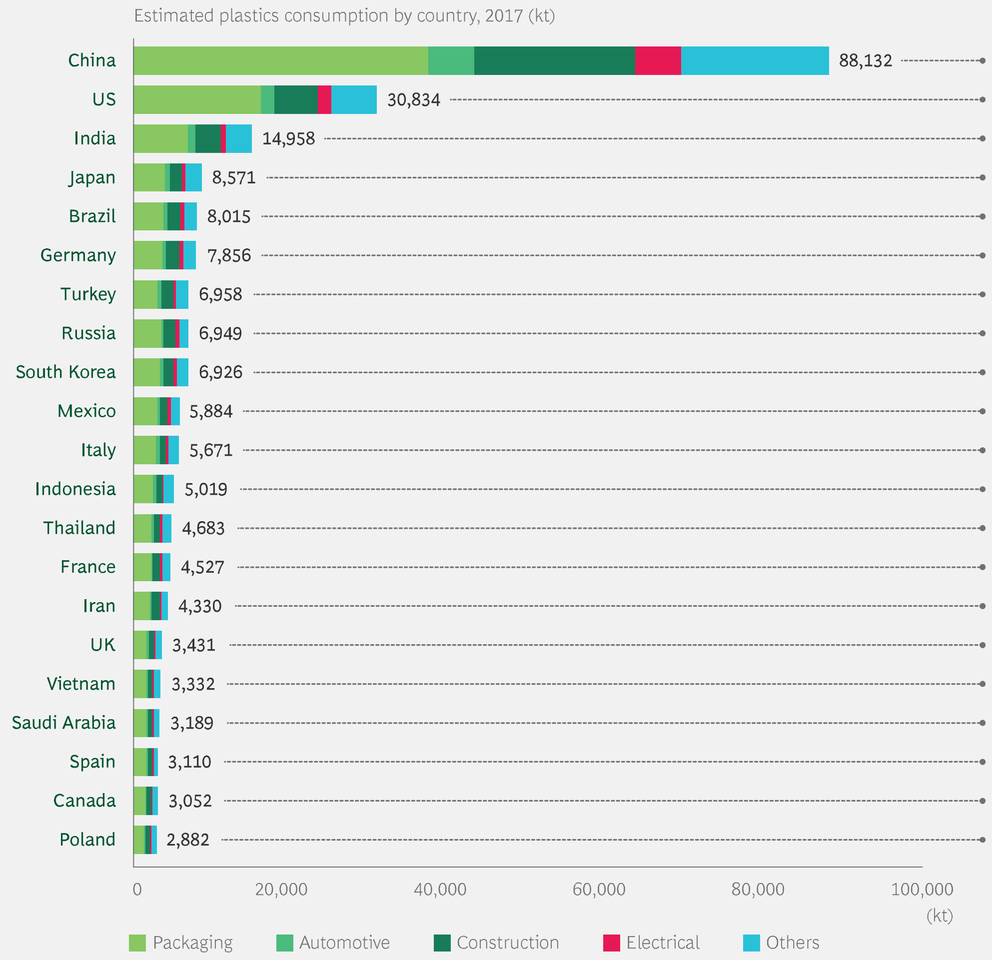
Flexible packaging accounts for about 50% of all plastics consumption.

Plastics exist in at least seven major forms, each with its own chemical composition and purpose. (See Exhibit 3.) Plastic types vary in their ability to be recycled. PET and HDPE, for example, lend themselves to reuse and mechanical recycling, whereas other plastics are disposed of after their intended use. Additives and adhesives make recycling even more challenging. Among plastics that are designed for disposal, the impact of a plastic material type depends on its time in use—some are made for single use while others are designed for longer-lasting applications, increasing their life cycle and reducing their environmental impact when considered over time.

Flexible packaging is one example of a single-use plastic that is typically disposed of after a short time. This material accounts for about 50% of all plastics consumption—and also for half of the total plastic litter in the ocean. Much of the flexible and mixed-layer plastic used in packaging is not suitable for mechanical recycling.

Additionally, because of behaviors and habits, as well as the absence of a well-developed sorting and recovery infrastructure and process, various types of plastic end up mixed together in municipal solid waste (MSW). These factors complicate existing mechanical-recycling efforts and often result in some waste being disposed of through a combination of industrial, commercial, and informal means and other waste accumulating in landfills or escaping collection systems entirely and leaking into the environment.

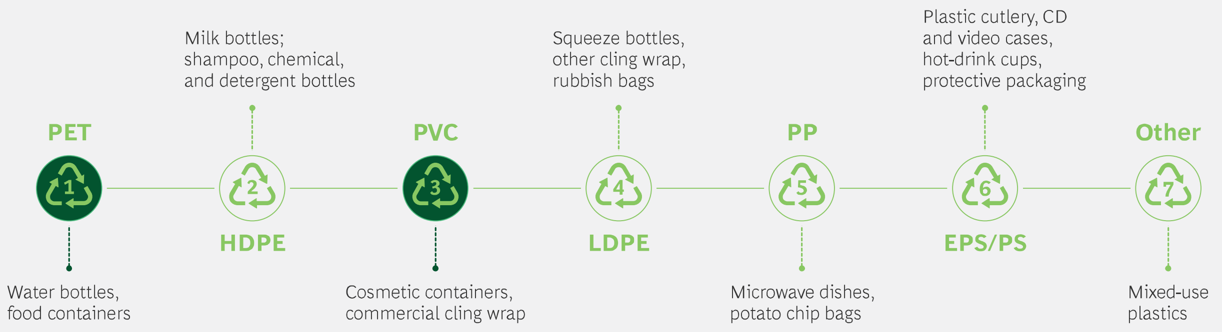
EXHIBIT 2 | The Problem: High Consumption and Low Recycling and Recovery Rates



Country	Estimated plastics consumption, 2017 (kt)	% Recycled	% Incinerated
China	88,132	10	40
US	30,834	10	15
India	14,958	N/A[1]	2
Japan	8,571	21	59
Brazil	8,015	2	5
Germany	7,856	38	61
Turkey	6,958	10	0
Russia	6,949	4	0[2]
South Korea	6,926	59	25
Mexico	5,884	10	14
Italy	5,671	27	33
Indonesia	5,019	2	5
Thailand	4,683	20	25
France	4,527	21	42
Iran	4,330	9	N/A
UK	3,431	29	31
Vietnam	3,332	8	20
Saudi Arabia	3,189	10	0
Spain	3,110	34	16
Canada	3,052	25	3
Poland	2,882	26	19

Sources: EPA; Plastics Europe; press search; VDMA; BCG analysis.
Note: Global plastics consumption was estimated at 250–350 million tons in 2017. Plastics comprise thermoplastics such as PVC, PE (HD-PE, LD-PE, LLD-PE), PP, PS (GP and HI), ABS, SAN, PET resin, PA (PA6 and PA66), as well as PC. Different countries use varying reporting criteria, so the numbers indicate the average of different types of plastic. Official recycling numbers are often overstated and are adjusted where possible.
N/A = not available.
[1] Official sources vary (15–60%); actual treatment is probably lower.
[2] The government plans to build five incineration plants by 2025.

EXHIBIT 3 | Plastic Types Have Different Uses and Makeups



PET and PVC are not optimal feedstock for a pyrolysis unit.

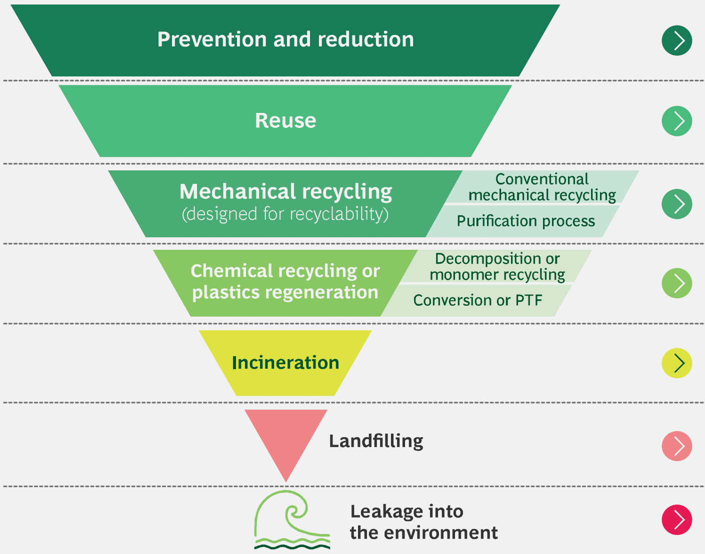
Source: *The New Plastics Economy: Rethinking the Future of Plastics*, World Economic Forum, 2016.

THE HIERARCHY OF WASTE

We use a pyramid of plastic waste management to describe the many ways of managing the plastic waste that we generate. (See Exhibit 4.) Outside of reducing the amount of waste generated, reusing plastics is the best alternative. Leakage of plastic waste into the environment is the least desirable, and disposal in landfills is only marginally preferable. Various stakeholder groups are actively pursuing initiatives to push waste management practices toward the upper end of the hierarchy. The immediate concern is to avoid plastics entering the environment, especially the oceans. For regions with established collection systems, an intermediate target is to find ways to reduce the use of landfills and incineration, which amplifies the critical role of reduction, reuse, recycling, and regeneration.

While the hierarchy of plastic waste management provides high-level guidance on which type of recycling is preferable, local specifications need to be considered on a case-by-case

Exhibit 4 | The Pyramid of Plastic Waste Management



- Prevention of plastic use where unnecessary
- Reduction of single-use and unnecessary plastics and packaging

- Production of reusable-plastic containers
- Design for long life and increased utilization

- Closing the loop of high-value materials (e.g., PET, PP, HDPE)
- Requirement for sorting technologies or separated collection systems

- Recycling of low-value materials (e.g., foils, blends)
- Value proposition in remote areas for decentralized solutions

- Energy recovery through burning of waste
- Only favorable as a last resource because possible only for one additional cycle

- Indefinite loss of raw material, which should be avoided
- Disposal in landfills or environment of about 250 million tons of the 350 million tons of plastics produced annually

- Worst-case scenario with waste leakage into the environment and eventually into the ocean

Source: BCG.

basis using thorough environmental- and societal-impact evaluations. In addition, a full life cycle assessment of the materials sometimes conveys surprising results. For example, materials that improve the environmental performance of a product, such as lightweight plastic for airplanes, may appear ecofriendly at first but are less so when analyzed in full because they are not extractable or recyclable. For materials such as these, a near-term solution is needed to effectively manage plastic waste.

Too many plastics are used for applications that are central to sustained development.

In early 2018, China upended the global recycling business when it stopped accepting imports of low-quality or highly polluting postconsumer plastic waste, citing purity issues. For years, China had taken up to 45% of the world's plastic waste imports for recycling, incineration, and landfilling. The ramifications of this decision are still being felt in markets worldwide.

Prevention and Reduction

Single-use flexible plastics have simplified our lives considerably, especially in the developing world, but they are also the most problematic aspect of plastic waste generation and management. Most single-use plastics are discarded after their first use, and far too many mar roadsides, forests, rivers, and seas.

The most effective solution is to reduce consumption. More than 50 governments have banned at least some types of single-use plastics. India and several other countries have imposed levies and taxes on the manufacture of such products. Governments can be expected to further incorporate sustainability considerations into their purchasing contracts. Industry players, led by consumer-facing companies, are starting to take steps to eliminate the use of plastic shopping bags and to develop other more sustainable solutions. Restaurants are promoting refillable cups and turning to renewable, recycled, or degradable materials for plates, cups, and cutlery, for example.

These are significant steps, but it is not realistic to expect near- or medium-term miracles. Plastics are too cheap and convenient, and the waste problem has yet to work its way to the top of the priority list in many jurisdictions. Moreover, even in the long term, too many plastics are used for crucial applications—such as health, safety, and sanitation—that are central to our sustained development and progress.

Reuse

After reducing consumption, reuse is the next best alternative. Reuse maintains the integrity and purpose of the product and has minimal environmental impact because washing is typically the only processing required. Manufacturers are producing an increasing number of reusable containers that are designed expressly for long life and increased utilization. But the application of reuse is limited, especially for containers that hold food, drinks, and chemical or toxic substances. Certain refillable hard plastic bottle systems are in use, but especially for applications such as food grade packaging, reusability is difficult to apply. A few countries are even witnessing a reverse trend: reuse is losing out to mechanical recycling.

Mechanical Recycling

A pillar of the circular economy, mechanical recycling provides both a viable business case for companies and significant societal and environmental benefits by reducing the amount of virgin plastics used and driving greater circularity. During mechanical recycling, waste is recycled into secondary raw materials without changing the basic structure of the material. Mechanical processes, including grinding, washing, separating, drying, regranulating, and compounding of used plastics, often create a closed-loop system. (See Exhibit 5.)

Demand for recycled materials has risen rapidly over the past few years, driven, among other factors, by consumer goods and other

EXHIBIT 5 | A Closed Mechanical-Recycling Loop

Sources: Dansk Retursystem; BCG analysis.

types of companies that have committed to using a certain share of recycled raw materials. In fact, for some high-value plastics—such as PP, PET, and HDPE—the demand for recycled resin has been greater at times than the current supply, and recycling has become a lucrative business. The profit margins for recycling used plastics for higher-value applications can reach 30% to 50%, depending on the type and color of the plastic; this presents a viable business model often linked with extended product responsibility (EPR) or deposit schemes, according to several examples we have seen.

Many consumer goods companies have made recycling commitments. Evian water bottles will be manufactured with 100% recycled plastics by 2025. Unilever has pledged to make 100% of its plastic packaging recyclable by the same year. Walmart has announced that, by 2025, 100% of the packaging for its private-label products will be recyclable. Concurrently, testing and product development efforts are under way at chemical companies to improve the recyclability of materials.

Multiple large recycling systems or companies (including Veolia and Suez, founded in France and active globally; the DSD system in Germany; Renewi in Belgium, the Netherlands, and Luxembourg; and Reliance in India) have built strong businesses around recycling HDPE, PP, or PET products. Chemical companies are also increasing their efforts to diversify their recycling portfolios and adapt more plastics to mechanical recycling.

As recycling and the use of recyclable materials become more important, an increasing number of companies, such as Borealis, are putting greater emphasis on designing for recyclability. But this process involves significant technical challenges. Mechanical recycling cannot process blended materials, for example. Consequently, during the product design phase, the use of additives (such as glue) needs to be considered carefully. For some products, such as beverage containers and food grade packaging, design and material standardization has become the norm, but other types of plastics applications still lack explicit design standards for recyclability, which prevents mechanical recycling from achieving its full potential.

Newer technologies, such as purification, that go beyond conventional mechanical recycling are gaining traction. They work by dissolving plastics into solvents and separating the blends to purify the plastics through the extraction of additives and dyes, leaving a decontaminated polymer. These technologies focus on the same materials as conventional mechanical recycling, such as PET, HD, and PP, but they are still nascent technologies that have yet to see large-scale implementation. Outside of such material limitations, other factors also restrict the use of these new technologies. In the US, for example, the FDA must approve any postconsumer recycled HDPE and PP plastics that come into direct contact with cosmetics or food, which complicates further use of recycled material for containers.

Despite the many admirable efforts to improve mechanical-recycling processes, an effective mechanical-recycling system also requires an efficient collection system. The best collection systems separate waste at the source, which reduces cleaning requirements and saves water and energy. Industrial-sized sorting systems and mechanical-recovery facilities (MRFs) are increasing in efficiency and separating capability. But putting such a system in place takes time, investment, and often a fundamental change in consumer behavior.

> Pyrolysis feedstocks are types of plastic that have no value for present-day recycling operations.

A further shortcoming of mechanical recycling is that not all materials can be efficiently or economically recycled. For example, little demand exists for recycled pouches, foil, and other low-density plastic materials because they can rarely be recycled at a quality level similar to that of the original products. This is a serious problem, given that these mixed- or special-plastic materials provide crucial functionality but are difficult and extremely resource intensive to split apart for mechanical recycling—if the technologies exist to do so. The combination of cleaning, washing, recycling, and transportation costs often erases the economic and ecological viability of mechanical recycling.

The best case for these products frequently is that they are recycled into construction materials for roads and buildings or are used as fuel in industrial plants. They are typically loss makers for recycling companies, and these losses are expected to increase over time. Consequently, in some situations, these plastics are processed only when mandated by regulators or cross-financed by licensing systems or environmental pricing-reform schemes. Given the low demand and poor prices for these products in developed markets, it is unlikely that recycling programs in emerging markets can sustainably target these materials.

Additionally, because some materials degrade when heated, such plastics can be recycled only once or twice before the next option is “downcycling”—the conversion into a lower-value material use. Business solutions for this problem require cross-industry collaborations that are not common today. But keep in mind that even basic recycling is preferable to other options: one study in Italy found that each kilogram of recycled PET saved about 1,370 grams of crude oil, 430 grams of gas, and 390 grams of coal.

Chemical Recycling or Plastics Regeneration

Beyond mechanical recycling, several new chemical-recycling technologies are emerging that address limitations in material composition as well as the complexity of mechanical-recycling processes. These new methods can be broadly referred to as plastics regeneration. Monomer recycling is generally seen as a particularly circular method because it reverses the chemical composition of the plastics, transforming them back into stable monomer molecules that can then be combined to create the same grade and type of plastic as the original waste. Conversion into fuels or petrochemical feedstock is realized through a variety of technologies, the most common of which is pyrolysis.

Pyrolysis is based on the natural geological process that produces fossil fuels and uses heat to decompose materials in an oxygen-free (or oxygen-starved) environment, therefore emitting little greenhouse-promoting carbon dioxide. The outputs are synthetic oil and gas, which have greater energy value than coal and can be put to a variety of uses.

One big attraction of pyrolysis is that its feedstocks are types of plastic that have no value for present-day recycling operations, including shopping bags, product wrappers, and packing materials, which commonly end up in landfills or incinerators or—in the worst case—are just thrown away. (Note that PTF through pyrolysis is a single-generation solution, however; we discuss its shortcomings later in this report.)

Incineration and Landfilling—Big Steps Down

The steps down to the next levels of the plastic waste management hierarchy are steep, with significant environmental ramifications. While recycling has some adverse environmental impacts—related mainly to emissions and water use—these pale beside incineration and landfilling.

Incineration is a low-efficiency method of producing energy that comes with high environmental costs, including airborne particulates and greenhouse gas emissions. And not all incineration produces energy; some waste is simply burned as a means of disposal, especially in European countries that put a high cost, or a complete ban, on landfilling waste.

Because of low financial costs—especially in areas where space is plentiful—landfills remain popular, even if visually and environmentally injurious. According to an estimate in *Science Advances* in 2017, almost 80% of the plastic waste produced to date is now in landfills, dumps, or the environment. About 12% has been incinerated, while the rest has been recycled or remains in use.

Despite the severe environmental limitations of incineration and landfilling, these solutions are still preferable to the absolute worst-case scenario, where plastic waste escapes collection, ends up as litter on the ground, and eventually makes its way into rivers and the ocean.

PLASTICS REGENERATION FILLS THE GAP

PLASTICS REGENERATION CAN FILL a gap in the current plastic waste treatment spectrum through its use of conversion technologies. Pyrolysis, for example, the technology we explore here in depth, is adept at handling a variety of plastic types that mechanical-recycling centers typically reject. Although pyrolysis uses heat, it does so in an oxygen-free environment; hence, the only carbon dioxide it emits is from the energy source that generates the heat. As a result, its carbon footprint is much smaller than that of incineration.

The output from pyrolysis is 70% to 80% oil and 10% to 15% gas.

Depending on the mix of inputs—and that can vary substantially—the output from pyrolysis is 70% to 80% oil, which can be used for a number of purposes, and 10% to 15% gas, which is usually recycled to provide the pyrolysis heat. Only about 10% to 15% of the output is char, an inert solid that is typically recycled for roads or sent to landfills, although some usage of char as a fuel has also been demonstrated. Using the liquid output from pyrolysis as fuel or inputs for petrochemical plants prolongs the original plastics' life cycle to at least a second round in the case of the former and to potentially several more in the latter, depending on the ultimate usage and disposal.

In the past two decades, a handful of companies have piloted pyrolysis as a for-profit way of turning otherwise nonrecyclable plastics into fuel. (Active companies include Agilyx, RES Polyflow, Brightmark Energy, RTI, and Klean Industries.) In 2000, Klean Industries and Toshiba built a pyrolysis plant in Sapporo, Japan, that produced 40 to 50 tons a day; it operated until 2012, producing about 9 million liters a year of light oil (used as a chemical feedstock) and medium fuel oil (such as diesel) as well as about 4 million watts a year of electricity. BP and RES Polyflow are constructing a US pyrolysis plant in Indiana that will produce 100 kilotons a year and is expected to begin operations in 2019. BP will purchase all the diesel fuel produced by the facility.

In addition to these commercial efforts, pyrolysis has also been the subject of a number of academic and industry reports.[1]

Like any chemical process, pyrolysis has its challenges. The biggest are scale and operational complexity. Pyrolysis reactors require regular maintenance, and the downtime is costly. A plant typically comprises multiple reactors, with additional reactors added in parallel to increase capacity. Some players are exploring smaller continuous-process reactors to gain scale.

Another major issue is that pyrolysis requires a sustained and consistent amount of quality feedstock in order to function effectively; providing this steady flow of input can be challenging because the plastics must be sorted and cleaned in advance to avoid contamination (although the cleaning and processing standards are less stringent than those required for mechanical recycling). These and other issues raise a key question with respect to whether pyrolysis can contribute in a meaningful way to plastic waste solutions: Is it economically viable?

Note

1. See, for example, Conversion Technology: A Complement to Plastic Recycling, 4R Sustainability, for the American Chemical Council, April 2011; 2015 Plastics-to-Fuel Project Developer's Guide, Ocean Recovery Alliance for the American Chemical Council, June 2015; and Energy and Economic Value of Municipal Solid Waste (MSW) and Non-Recycled Plastics (NRP) Currently Landfilled in the Fifty State, Themelis et al., Columbia University Earth Engineering Center, July 2014.

THE ECONOMICS OF PYROLYSIS

FOUR FACTORS DIRECTLY DETERMINE pyrolysis's economic viability, and they vary considerably by region and market. They include the addressable volume of plastic waste, feedstock acquisition and treatment costs, the capacity and operating expenses of pyrolysis plants, and potential revenues from the sale of pyrolysis gas and liquids.[1] In addition, several structural and environmental trends shape the impact of these factors and the feasibility of pyrolysis in each market. (See Exhibit 6.)

To assess the financial viability of pyrolysis as a business—particularly for energy and chemical companies—BCG researched eight markets, each with its own distinct characteristics. The markets can be divided into three representative categories:

- **Mature markets** have established and well-developed collection systems, limited landfill use because of regulations or space constraints, near-term recycling targets with stringent monitoring, as well as near- and medium-term plans to reduce single-use-plastics consumption. Our study included Singapore and Seine-Maritime, a province of France.

EXHIBIT 6 | The Factors Affecting the Economic Viability of Markets

The addressable volume of plastic waste

- The quantity of plastic waste generated each day
- The volume of plastic waste feedstock available through cost-effective channels

Feedstock acquisition and treatment costs

- The cost of acquiring plastic waste from various channels
- The cost of cleaning and processing plastic waste into pyrolysis feedstock

Pyrolysis design capacity and operating costs

- The design throughput capacity of the pyrolysis unit
- The associated operating and capital costs

Revenues from the sale of pyrolysis liquids

- Available markets for the pyrolysis liquids
- The estimated price point of each barrel of pyrolysis liquid product

Structural and environmental trends

- Current and future regulations that could affect the volume and cost of feedstock
- Social perceptions and views on waste management

Source: BCG analysis.

- **Moderately developed markets** have established waste collection systems, little pressure on reducing landfill use because of favorable economics, and some long-term recycling goals in place (including data collection to support them) but no firm regulation aimed at reducing plastics consumption. We studied the five US coastal states along the Gulf of Mexico as an area that is representative of these markets.

- **Nascent markets** have inadequate plastic waste collection systems, few recycling targets, and no firm regulation for reducing plastics consumption. We looked specifically at a few regions of Indonesia (Jakarta, Ambon, and Batam) and two provinces in China: Guangdong and Zhejiang. Overall, China spans the nascent and moderate categories: many cities have developed formal collection systems, and incineration of waste to generate electricity is common.

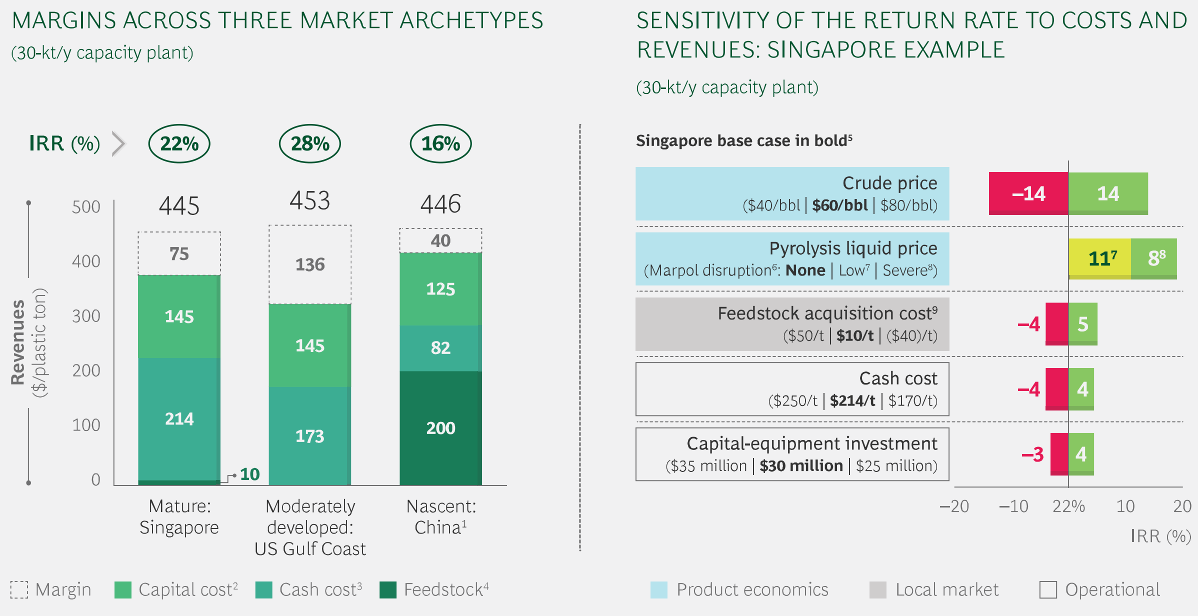
In each market, we used two criteria to determine economic viability:

- **Volume.** Estimated number of 30-kt/year plants that can be run given the addressable volume of plastic waste in the market.

- **Margin.** Revenues from the sale of pyrolysis liquids minus the costs to acquire feedstock, the cash costs of operation, and capital expenditures.[2]

We set the size of the pyrolysis unit at 30 kilotons per year accounting for scalability issues commonly seen in pyrolysis reactors. We established an arbitrary nominal internal rate of return (IRR) hurdle of 12% as the minimum return that a company would need to justify investment. Our analysis indicates that, of the eight markets, six exceed this IRR, and four do so substantially, including one nascent market: Jakarta. (See Exhibit 7 for examples.)

EXHIBIT 7 | Pyrolysis Has a Positive Investment Outlook in All Three Market Categories



MARGINS ACROSS THREE MARKET ARCHETYPES

(30-kt/y capacity plant)

SENSITIVITY OF THE RETURN RATE TO COSTS AND REVENUES: SINGAPORE EXAMPLE

(30-kt/y capacity plant)

Sources: Expert interviews; industry reports; BCG analysis.
Note: Consumers may be willing to pay a premium on goods from recycled content, which may result in higher revenues from pyrolysis liquids.
Bbl = barrel.

[1] Estimate for a single province (either Guangdong or Zhejiang), not a combined value for both.
[2] Capital cost of installing pyrolysis plant as well as sorting, cleaning, and pretreatment facilities if required are valued at a 12% hurdle rate.
[3] Cost to prepare and process pyrolysis feedstock, including labor and utilities, transport of feedstock, and shipment of pyrolysis product.
[4] Cost of acquiring plastic feedstock.
[5] Base case uses Singapore economics.
[6] For more information, see "Just How Disruptive Will IMO 2020 Be?," BCG article, May 2019.
[7] Assumes that price of fuel oil with sulfur content >0.5% drops to $20/bbl, with value of pyrolysis liquid at about $95/bbl.
[8] Assumes that price of fuel with sulfur content >0.5% drops to $5/bbl, with value of pyrolysis liquid at about $110/bbl.
[9] Cost of acquiring feedstock independent of cleaning and sorting costs.

Here's how the economics play out for selected markets in each category, with particular emphasis on two of the four factors cited above: the addressable volume of plastic waste and the feedstock acquisition and treatment costs, which are often the most significant variables with the broadest range. (See also the sidebar "The Yangtze River: A Big Need, a Complex Problem," which presents a particularly tricky and troubling case with some challenging economics.)

Mature: Singapore and Seine-Maritime—the Challenges of Volume and Market Structure

Two very different markets illustrate the opportunities and challenges for pyrolysis in mature, regulated markets. Singapore and the Seine-Maritime province in France have attractive IRRs (more than 20% and 25%, respectively), but these high rates are based on extremely different business cases. In Singapore, the market offers an ample supply of mixed-plastics feedstock, but the high cost of collection and cleaning can have a big impact on profitability. In Seine-Maritime, feedstock is relatively inexpensive, but quantities are limited, which undermines one of the prerequisites of a profitable pyrolysis facility: the ability to operate continuously.

Singapore generates some 2,200 tons a day of plastic waste, about 50% of it from residential sources. Most of this (about 1,800 tons a day) goes straight to incineration centers. Only about 12% to 20% enters recycling sorting facilities, and just half of this is actually recycled, with the balance rejected principally because of contamination.

With the potential for 120 to 300 tons a day of discarded plastics from sorting centers, Singapore could provide ample feedstock for a 30-kt/year pyrolysis plant. (Regulatory changes that favor pyrolysis could divert additional plastic waste from incineration and offer even greater supply.) The municipal waste stream is poorly segregated, however, and substantial cleaning and sorting are required to convert plastic waste to usable feedstock, which drives up costs. Pyrolysis operators would need to partner with the four companies that control waste collection in Singapore. Our analysis indicates that they could expect to pay almost $170 a ton for mixed-plastic waste, leading to a total operating cost of $370 a ton and a profit margin of about $75 a ton, or nearly 17%. (See Exhibit 8.)

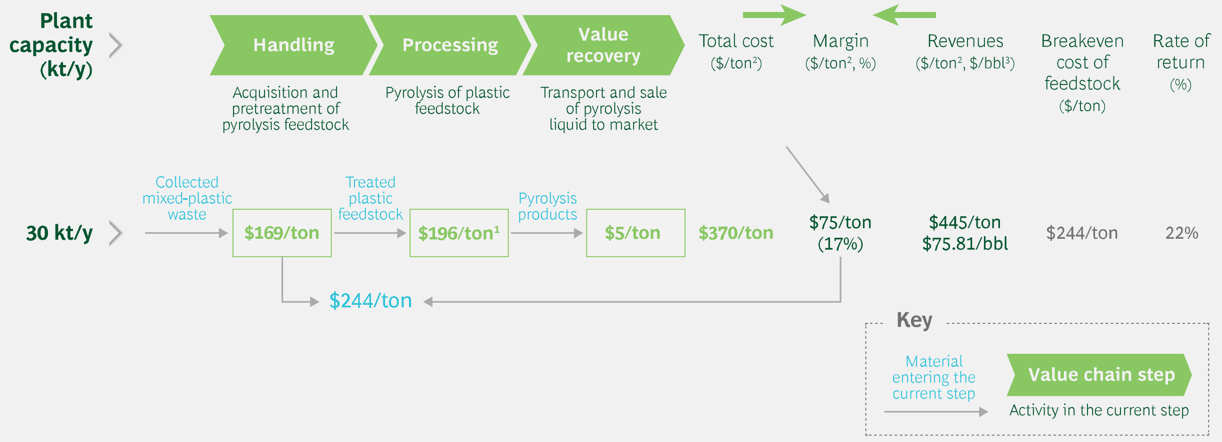
In Seine-Maritime, feedstock costs are substantially lower—less than $120 a ton, resulting in total costs of about $320 a ton, almost 15% lower than in Singapore. A pyrolysis operator could expect to achieve a profit margin of almost $130 a ton, or close to 30%. But Seine-Maritime generates only about 150 to 190 tons of municipal solid waste (MSW) a day, most of which (110 to 160 tons) goes to

THE YANGTZE RIVER

A Big Need, a Complex Problem

Ten rivers account for some 85% of global plastic waste carried to the ocean—the Yangtze River alone carries 50%, or some 200 tons a day of plastic waste, into the East China Sea. But collection technologies aimed at recovering usable plastics from the water, while innovative, so far take the form of small-scale pilots or concepts that lack funding and technological support. More-effective efforts to clean up the Yangtze, potentially through partnerships, could have a huge impact on the problem of global marine plastic waste, especially because PTF technology can be used to dispose of the waste cost-effectively once it is collected. Small, portable, and modular pyrolysis reactors, such as the ones being tested by RTI (with an annual capacity of approximately 5 kilotons to 7 kilotons), could be trucked to, and operated at, waste collection sites and may pave the way forward for treating riverine plastic waste.

EXHIBIT 8 | Example: The Pyrolysis Value Chain for Singapore



Sources: Osiris calculations; BCG analysis.
Note: The pyrolysis liquid price was estimated by valuing Brent crude at $60/bbl and estimating the price in Singapore. For other Asian markets, the price of crude is the price of crude in Singapore plus the costs of shipping crude to the respective markets.
[1] $196/ton includes the cost of operating the pyrolysis reactor and the capex hurdle rate at 12% per year.
[2] Value per ton of plastic.
[3] Value per barrel of pyrolysis liquid.

incinerators or landfills. Only approximately 25 to 30 tons is recycled, and current EU regulations favor mechanical recycling over pyrolysis. To ensure sufficient supply for a 30-kt/year plant, an operator would need to either look beyond the Seine-Maritime province to other regions for supply or use plastics extracted from landfills, which would require cleaning and sorting. Either solution adds costs. A variety of planned and potential regulatory initiatives—including steps to reduce plastic waste, redirect waste from landfills, expand sorting, and improve sorting efficiency—contribute to a somewhat fluid cost and supply picture for the foreseeable future.

Moderately Developed: The US Gulf Coast—Sufficient Quantities, Low Costs

The five states of the US Gulf Coast (Alabama, Florida, Georgia, Louisiana, and Texas) constitute a high-potential market for pyrolysis. Plastic waste is both ample (about 25,000 tons a day) and inexpensive (approximately $125 a ton). Of the five states, only Florida recycles a significant percentage of its MSW (37%); the other states are in the single digits, with 90% or more of their MSW going to landfills. We estimate that pyrolysis plants in the Gulf Coast states could operate with a profit margin of about $135 a ton, or 30%. Continued fallout from China's decision to restrict imports of recyclables adds to the addressable volume and reduces costs for potential operators.

Improved sorting efficiency could cut costs further because of lower contamination. (The US state of Rhode Island, for example, saw contamination levels drop 20% in one year after it promoted standardized labels for recycling bins and increased efforts to address consumer confusion about recyclables sorting.) Once recycling efforts produce streams of well-sorted, very clean plastics, mechanical recycling becomes a viable option in the region, however.

Nascent: Guangdong and Zhejiang—High Volumes, High Costs

The provinces of Guangdong and Zhejiang share similar characteristics. A small group of cities in each generates 80% of the plastic waste (nine cities produce 25,000 tons a day in Guangdong; six cities create almost 20,000 tons a day in Zhejiang). Private companies manage waste collection and processing, but mechanical recycling depends on an informal network of waste pickers, collectors, and traders. The regions have the potential to produce an ample supply for pyrolysis facilities, but the cost of feedstock acquisition is high: more than $200 a ton in both regions. This results in total operating costs of more than $400 a ton. Estimated margins are about $40 a ton, or 8% to 9%.

Pyrolysis prevents plastic waste leakage from collection systems and diverts plastics from landfills.

The regulatory outlook is only mildly negative for volume, but potential regulatory changes could easily drive feedstock prices higher, which would imperil already thin prospective margins. In Guangdong, the government is piloting sorting programs in some cities, and the government in Zhejiang is taking measures to promote sorting at the source. Both these actions could have a positive impact on the quality of supply and therefore the overall cost.

The Environmental Impact of Pyrolysis

Like most industrial processes, pyrolysis has positive and negative effects on the environment. On the plus side, it is a relatively efficient way to reuse raw materials that have already been taken out of the planet. It is not as efficient, in many instances, as mechanical recycling, but mechanical recycling—at least today—is not economically viable for all plastics. Pyrolysis increases flexibility because plants can be built close to sources of waste (and some are even portable), reducing long transportation distances to central recycling centers. While pyrolysis requires energy and produces some emissions, it also has the significant benefits of preventing plastic waste leakage from collection systems around the world and diverting plastics from landfills.

A 2017 study by Argonne National Labs of a pyrolysis-based PTF technology compared the energy, water consumption, and greenhouse gas (GHG) emissions of ultra-low-sulfur diesel (ULSD) fuel made from pyrolysis with conventionally produced ULSD. The study concluded that “the GHG emissions [from pyrolysis-derived ULSD] would likely be reduced up to 14% when it is compared to conventional ULSD … [Pyrolysis]-derived ULSD fuel could therefore be considered at a minimum carbon neutral with the potential to offer a modest GHG reduction. Furthermore, this waste-derived fuel had 58% lower water consumption and up to 96% lower fossil fuel consumption than conventional ULSD fuel in the base case.”[3]

The paper also compared the production of pyrolysis-derived fuels with alternative scenarios for managing plastic waste such as landfilling and incineration (power generation) and concluded that the negative environmental impact of pyrolysis was far lower than that of other plastics regeneration alternatives.

Additional Challenges

Despite the advantages of pyrolysis, some important limitations and risks also have to be addressed. The most immediate shortcomings are the current small scale (explored more in the next section) and the challenging technical operations. Furthermore, unintended consequences must be considered. Several chemical companies are putting major efforts into research and development of plastic products that have a greater ability to be mechanically recycled. Promoting pyrolysis, a means of plastics regeneration, could eliminate the incentives for these R&D efforts. In addition, the conversion from plastics to fuel allows for only one additional use of the initial plastic as opposed to a completely circular solution, which leads to several life cycles of the polymer.

Pyrolysis development could have socioeconomic consequences as well: in some regions, the informal subsector of collecting and sorting waste provides a livelihood for millions of people. (See the sidebar “The Collection Conundrum.”) Large sorting centers or collection systems with at-the-source separation would have a detrimental effect on such subsectors.

When deciding on the best recycling option for a given plastic material, a full life cycle assessment must be conducted, taking into account all factors—economic, environmental, and social—to determine the preferred solution.

NOTES

1. Profitability is affected by the price of oil and the demand for various types of fuel (such as gasoline, kerosene, and jet fuel). If Marpol (International Convention for the Prevention of Pollution from Ships) regulations shift to favor more ultra-low-sulfur fuels, that could provide a boost to sales of pyrolysis liquids because the principal output is low-sulfur oil.

2. During the analysis of the business cases, a broad variation in the quality of the resulting pyrolysis liquids was assumed, given the wide variation of ingoing feedstock.

3. The full-length research article is "Life-cycle analysis of fuels from post-use non-recycled plastics," Benavides et al., *Fuel*, 2017:203;11–22. Five companies provided pyrolysis product yields and material and energy consumption data that were processed using a proprietary GREET (Greenhouse Gases, Regulated Emissions and Energy Use in Transportation) model.

THE COLLECTION CONUNDRUM

In most nascent markets, the informal economy looms large in waste collection. In Jakarta, for example, which has little enforcement of laws mandating the sorting of household waste, an informal network of pickers collects trash door-to-door and transports refuse to some 1,100 temporary waste stations, where it is sold to middlemen. All waste is eventually collected at a single landfill facility, where it is sorted by 3,000 to 5,000 pickers, according to some estimates. Recyclables are sold through a chain of intermediaries to recycling plants. This long collection chain increases the market price (by a factor of three to five) and provides feedstock of variable quality. Major companies are reluctant to engage with such informal networks, yet these markets provide perhaps the only source of employment for thousands of uneducated, unskilled workers.

ACHIEVING PYROLYSIS AT SCALE

Pyrolysis offers energy and chemical companies the opportunity to explore profitable, new business models while simultaneously improving their environmental, social, and governance (ESG) performance. (BCG research on companies' total societal impact shows that companies that do well on nonfinancial ESG measures also deliver a better financial performance and command a disproportionately higher valuation.)

Pyrolysis can have an immediate and significant impact in immature markets.

Pyrolysis (and other plastics regeneration technologies) can also act as a complement to mechanical recycling, reducing waste volumes that go to less efficient and environmentally adverse incineration facilities and cutting substantially into the amount of plastic waste that goes to landfills or is simply dumped.

This potential expansion of waste management methods should prompt government interest. Pyrolysis can have an immediate and significant impact in immature markets such as Jakarta (where pyrolysis could handle more than half and potentially up to two-thirds of all plastic waste), Guangdong (a quarter of all plastic waste), and Zhejiang (one-fifth of all plastic waste). Pyrolysis is also economically viable in many mature markets, but in regions such as the US Gulf Coast, where it competes on cost with ample landfill capacity, governments need to decide whether they want to use their legislative and regulatory authority to discourage landfilling and incentivize alternatives.

In all markets, the biggest single challenge for pyrolysis is to achieve the scale necessary to have a significant impact on the plastic waste problem and generate sufficient revenues and profits to justify investment. All members of the ecosystem can help facilitate progress. Industry players and governments especially should take action.

Industry

Companies in the energy and chemical sectors are the likely lead actors. Some have invested in mechanical recycling, and most chemical companies are designing bioplastics or plastics with enhanced recyclability. Several companies are also exploring, or at least monitoring, monomer recycling and PTF technologies. The market case exists in plenty of places for stepping up their efforts.

Numerous startups experimenting with pyrolysis and other conversion technologies may find the prospects of a large corporate partner attractive. For example, Bin2Barrel, which was recently acquired by Integrated Green Energy Solutions of Amsterdam, is constructing a pyrolysis plant for the port of Amsterdam that will process 100 tons of plastic waste a day. In May 2018, Recycling Technologies of the UK announced agreements worth €65 million to sell the oil output from its patented PTF technology. Also in the UK, ReNew ELP is constructing a PTF plant, using Australian technology, that can process up to 20,000 tons of plastic waste annually. The company has announced plans to build three additional plants once the first is up and running.

Resource scarcity and high commodity costs have long led the chemical industry to put resource efficiency and output maximization at the core of its operations. Setting up viable opportunities for plastics regeneration through pyrolysis would require that chemical companies partner with firms in other sectors (such as packaging, consumer goods, and waste management) along the plastics manufacture, usage, and waste management value chain.

Such partnerships are opportunities for packaging and chemical companies to develop new products, for consumer companies to adopt sustainable-packaging solutions, and for waste managers and haulers to set up collection and processing systems—all efforts that may result in potentially superior growth rates and a positive societal impact. While these partnerships might constitute a new paradigm, closing the loops and creating a truly circular solution to manage plastic waste is a critical need that calls for new models and solutions.

Government Regulations

Mandates at the government level can incentivize the development of plastic waste solutions through the promotion of and investment in new processes and technologies as well as by regulating usage and disposal of plastics. Europe has been a leader in the latter regard. In recent years, the EU has:

- Promoted reuse and recycling with plans to integrate 10 million tons of recycled plastics into new products by 2025 and reduce reliance on landfills and incineration
- Encouraged producer responsibility through member state regulations and discussion of fees on manufacturers to subsidize waste collection and recycling
- Moved to improve rates of household plastics recycling by as much as 60% by 2020

Governments need to shape policies such that they create guiding frameworks that can help define a clear waste management hierarchy and incentivize recycling of all types of plastic. These frameworks can aid in the development and successful implementation of innovative product design, waste management infrastructure, and mechanical recycling, as well as plastics regeneration technologies. All levels of government can play a role, from local and regional legislative bodies to national assemblies, executives, and agencies.

Finally, the role of governments in changing behaviors and habits through education systems, incentives, and their own sourcing standards should not be underestimated. Clearly, governments have a broader role to play that can provide long-term benefits to society.

A VIABLE SOLUTION—NOW AND INTO THE FUTURE

To tackle the colossal societal and environmental issue of plastic waste, we need proportionally meaningful efforts from the private and public sectors as well as society at large that encompass behaviors and habits. The ultimate solutions will involve a combination of judicious consumption and disposal measures as well as the development of cost-competitive and environmentally friendly alternatives. Most observers would agree, however, that these changes are years away. In the meantime—over the next decade or two—we can implement circular solutions to reuse or repurpose plastic waste in the most efficient way. Plastics regeneration technologies such as pyrolysis will also play a part in these efforts and are technologically and financially viable alternatives.

A cross-value-chain collaboration to realize the full benefits of plastics regeneration is almost certainly an imperative. An industry coalition has taken a first step with the founding of the Alliance to End Plastic Waste. More than 40 global and regional chemical companies, packagers, consumer goods manufacturers, and waste managers (supported by BCG) have pledged to invest up to $1.5 billion in plastic waste management infrastructure in Southeast Asia, where the plastic litter and leakage problem is most acute. This move clearly signals that the private sector is ready to scale up efforts to combat one of the most pressing environmental issues of our times. While this is a credible start that may yet catalyze further investments in the cause, we still have a way to go before we find a comprehensive, definitive solution.

FOR FURTHER READING

BCG publishes regularly on the subjects of sustainability and total societal impact. Some previous publications include the following:

What Companies Can Learn from World Leaders in Societal Impact
A report by Boston Consulting Group, April 2019

The Economic Case for Combating Climate Change
A report by Boston Consulting Group, September 2018

The Role of Green Projects in Scaling Climate Investments
An article by Boston Consulting Group, February 2018

Ten Steps Toward the Circular Economy
An article by Boston Consulting Group, February 2018

Total Societal Impact: A New Lens for Strategy
A report by Boston Consulting Group, October 2017

NOTE TO THE READER

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