U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Plastics for a Circular Economy Workshop: Summary Report

December 11–12, 2019
Golden, Colorado

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Acknowledgments

This report was prepared by Nichole Fitzgerald, Andrea Bailey, Jay Fitzgerald, Gayle Bentley, Melissa Klembara, and Kate Peretti. This workshop was made possible by the participation of the attendees and presenters.

List of Acronyms

AMO	Advanced Manufacturing Office
BETO	Bioenergy Technologies Office
BHET	bis(2-hydroxyethyl) terephthalate
BOTTLE	Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment
DOE	U.S. Department of Energy
GHG	greenhouse gas
HDPE	high-density polyethylene
MRF	material recovery facility
NREL	National Renewable Energy Laboratory
PBS	polybutylene succinate
PET	polyethylene terephthalate
PHA	polyhydroxyalkanoate
PLA	polylactic acid
quad	quadrillion (10^{15}) British thermal units
R&D	research and development
USDA	U.S. Department of Agriculture

Executive Summary

The Plastics for a Circular Economy Workshop, coordinated by the Bioenergy Technologies Office, the Advanced Manufacturing Office, and Mars, Inc., brought together stakeholders from industry, academia, and National Laboratories to discuss opportunities and challenges facing the development of new technologies to address plastic waste. This workshop was held as part of the Plastics Innovation Challenge, a comprehensive U.S. Department of Energy (DOE) program to accelerate innovations in energy-efficient plastics recycling technologies.[1] A series of keynote presentations, plenary presentations, lightning talks, and breakout sessions provided an interdisciplinary framework for sharing information and building collaboration. This document provides an overview of the content discussed in the presentations as well as a summary of each breakout session discussion. Diverse stakeholder perspectives were gathered and collectively provide an update on the state of the field. Key areas for consideration are discussed that may inform future research opportunities.

Problems resulting from plastic waste accumulation present an opportunity for innovative technologies to transform our approach to plastic material design and recycling. Real barriers exist that lead to poor recycling outcomes, as exemplified by the fact that only 2% of all plastic packaging is recycled into same- or similar-quality products. A lack of circularity has led to the accumulation in the environment of 80% of the 7 billion tons of plastic ever produced. This workshop provided a forum for interdisciplinary stakeholders to discuss the barriers to plastics circularity, how research and development (R&D) may overcome these barriers, and the highest-impact areas on which to focus efforts.

The workshop focused on four fundamental aspects of plastics recycling: recycling existing plastics using current methods, recycling existing plastics using new methods, developing new plastics and recycling using current methods, and, finally, developing both new plastics and new recycling technologies. A common framework for discussion was established by the keynote speakers. The plenary and lightning talk presenters provided their unique perspective on what barriers exist in these areas, potential solutions, and unintended consequences to developing new technologies to address plastic waste. Breakout sessions further enabled cross-pollination between research groups and organizations and helped to gather broad stakeholder input to help prioritize R&D goals (see Section 4).

By the conclusion of this workshop, interdisciplinary groups coalesced around the most critical challenges facing the development of a circular plastics economy, including the need for:

- Innovative deconstruction methods: Novel methods for deconstructing existing plastic waste provide a new value stream for plastics collected for recycling. These processes should tolerate high degrees of contamination in the waste stream.
- New materials and upcycling strategies: New materials that are recyclable by design provide a new value stream, an avenue to reduce environmental accumulation, and incentivize closed-loop collection. Alternatively, new materials that are biodegradable or compostable, particularly for flexible packaging, provide another material stream that may reduce environmental plastic persistence. New materials may require functional barrier properties and mechanical performance matching or exceeding the incumbent materials, constituting a major R&D challenge. Beyond new materials, new upcycling technologies are necessary, particularly for flexible packaging and multilayer materials which are currently not recyclable. New strategies for upcycling may further enhance the value of plastic wastes.
- Improved assessment and modeling frameworks: Standardized specifications for mixed recycled waste may enable more effective deployment of novel materials and recycling approaches. Further,

[1] U.S. Department of Energy. (2019). *Department of Energy Launches Plastics Innovation Challenge*. DOE, November 21, 2019. https://www.energy.gov/articles/department-energy-launches-plastics-innovation-challenge.

frameworks for assessing the energy and environmental impacts of new materials and new recycling approaches will support deployment of economically and environmentally viable processes. Improved standards for composting and biodegradability may also accompany the successful deployment of new materials, as well as environmental and toxicity modeling.

The information and feedback generated at this workshop will help guide programmatic decisions at DOE to ensure that investments in R&D address the most critical barriers to successful technology development. The DOE's Bioenergy Technologies Office and the Advanced Manufacturing Office, and Mars, Inc. would like to jointly thank all of the participants for their valuable input.

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1 Introduction

1.1 The Challenge

In the United States and across the globe, very few plastics are recycled. Labeling plastics with resin identification codes has implied to consumers that many plastics can be recycled, while in practice many recycling facilities can only cost-effectively recycle polyethylene terephthalate (PET) and high-density polyethylene (HDPE). Current recycling methods often do not allow for profitable recycling of commonly used plastics. As a result, only 14% of the 78 million tons of plastic packaging produced each year are collected for recycling, and only 2% are recycled into the same- or similar-quality applications.[2]

Without comprehensive plastics recycling, plastic waste builds up in our landfills and environment. Because the economic motivation to recycle is poor, plastics often "leak" into waterways, the ocean, and other parts of the environment. In fact, assuming the current rate of leakage and the projected growth in plastic consumption, the Ellen MacArthur Foundation predicts that by 2050, oceans will contain more plastics than fish by weight.

Re-X (recovery, reuse, remanufacturing, and recycling) strategies applied to plastics have significant potential to improve energy efficiency in chemical manufacturing. Efficiency benefits can be achieved by increasing the useful lifetime of the material (reuse) and by repurposing waste material and degradation products in another application (recycling). Both of these lower the embodied energy of plastics, reducing the roughly 8 quadrillion British thermal units (8 quads) of energy that is consumed annually in the United States to manufacture plastics, resins and synthetic rubber.[3] By shifting to energy efficient Re-X strategies, the United States can recover and reuse a large portion of energy that has previously been considered "waste."

Many plastics recyclers employ mechanical recycling strategies, a process that involves shredding, heating, and remolding plastic waste. While this process is more energy efficient than making a product from virgin material, mechanical recycling degrades the polymers and produces a less-valuable product. As a result, mechanical recycling is occasionally termed "downcycling." Furthermore, mechanical recycling often is not well suited to accommodate contamination and mixtures of a variety of plastic resins.[4] To make recycling more economically attractive, prevent leakage into the environment, and improve energy efficiency in plastics usage, there needs to be a society-wide shift away from downcycling towards true recycling or upcycling.

There are many possible solutions to minimizing plastic waste. Educating consumers on recycling best practices could go a long way towards decreasing contamination in recycling streams and increasing the value of recyclables. (A great example is the Atlanta, Georgia, "Feet on the Street" consumer education program, which in its 2017 pilot program of 5,000 residential homes increased the collection of valuable materials by 27% and decreased contamination of recyclables by 57%.[5]) New technologies for sorting mixtures of plastic waste, including robotics and artificial intelligence, could decrease contamination and make recycling more profitable. However, at the heart of the problem is that downcycling is not as attractive as same-cycling or upcycling. Therefore, this workshop focused on exploring new technologies for recycling that result in products that are the same or higher value and designing new plastics that are better suited for recycling than those that are currently widely used.

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[2] Ellen MacArthur Foundation. (2017). *The New Plastics Economy: Rethinking the Future of Plastics & Catalysing Action*. Cowes, United Kingdom: Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/NPEC-Hybrid_English_22-11-17_Digital.pdf.
[3] International Energy Agency. (2014). *World Energy Outlook 2014*. Paris: International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2014.
[4] Tullo, Alexander H. (2019). "Plastic has a problem; is chemical recycling the solution?" *C&EN*, October 6, 2019 (97:39). https://cen.acs.org/environment/recycling/Plastic-problem-chemical-recycling-solution/97/i39.
[5] The Recycling Partnership. (2019). *Driving Change – Impact Report June 2019*. Falls Church, VA: The Recycling Partnership. https://recyclingpartnership.org/impact-report-2019/.

1.2 Workshop Objectives

The objective of this workshop was to gather stakeholders from multiple sectors to discuss current technology challenges associated with plastics recycling.

New recycling technologies cannot be developed without a clear understanding of the plastics that need to be recycled. Many plastics in use today were introduced for consumer use almost a century ago and were not designed for recyclability. As such, there is growing interest in introducing new plastics that are more amenable to recycling. This workshop touched on elements of using current recycling technologies to manage current plastic waste (Figure 1, upper left quadrant), but the focus of the workshop was on developing new recycling technologies to manage existing plastics, developing new plastics to be better aligned with existing recycling technologies, and simultaneously developing new plastics and new recycling technologies for an idealized future.

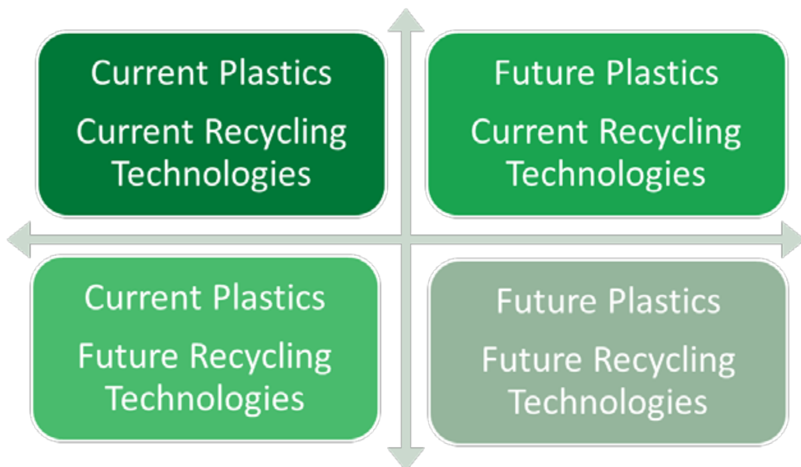

Figure 1. The workshop focused on developing technologies for four scenarios

BETO Mission

The U.S. Department of Energy's (DOE's) Bioenergy Technologies Office (BETO) establishes partnerships with key public and private stakeholders to develop technologies for producing cost-competitive advanced biofuels from renewable, U.S. nonfood biomass resources including cellulosic biomass, algae, and wet waste (e.g., biosolids). The key activities of BETO are aimed at developing a viable, sustainable domestic biomass industry that produces renewable biofuels, bioproducts, and biopower; enhances U.S. energy security; provides environmental benefits; and creates nationwide economic opportunities. Meeting these goals requires significant and rapid advances in the entire biomass-to-bioenergy supply chain—from the farmer's field to the consumer.

Parallels Between the Use and Deconstruction of Plastics and Biomass

BETO has historically invested in developing solutions to convert lignocellulosic biomass into fuels as well as value-added chemicals. The composition of this biomass poses the first challenge. Lignocellulosic biomass is composed of a heterogeneous mixture of polymers that were evolved in nature to be resistant to degradation in order to prevent plant material decay. Then, in the process of harvesting, aggregation, and transportation, the biomass can become dirty and contaminated, complicating technology development for processing and upgrading an already recalcitrant material. Plastics were similarly designed to avoid degradation for material durability and are often highly contaminated and dirty prior to recycling. Significant advances have improved our ability to degrade lignocellulosic biomass and to upgrade the derived monomers into value-added chemicals and fuels. We envision that capabilities built and lessons learned from biomass valorization programs may be leveraged to tackle the challenge of degradation and upgrading of plastics into new, functional, and intrinsically recyclable materials.

AMO Mission

The Advanced Manufacturing Office (AMO) at the U.S. Department of Energy supports the vision of a strong and prosperous America powered by clean, affordable, and secure energy. AMO is dedicated to improving the energy and material efficiency, productivity, and competitiveness of manufacturers across the industrial sector. Manufacturing plays an essential role as a driver of overall economic growth. Manufacturing accounts for 25% of total U.S. energy consumption, and manufactured products have a significant impact on energy use in every sector. AMO's mission is to catalyze research, development, and adoption of energy-related advanced manufacturing technologies and practices to increase energy productivity and drive U.S. economic competitiveness. This mission is achieved by bringing together manufacturers, nonprofits, research institutions, and National Labs to identify challenges, catalyze innovation, and develop cutting-edge materials, processes, and information technologies needed for an efficient and competitive domestic manufacturing sector.

Mars, Inc., Workshop Organizer – Mission

Mars was a workshop leader and coordinator for the Plastics for a Circular Economy Workshop. For more than a century, Mars, Incorporated has been driven by the belief that how business is done today affects the vision for tomorrow. This idea is at the center of Mars' role as a global, family-owned business. Today, Mars is transforming, innovating, and evolving in ways that affirm their commitment to making a positive impact on the world. Across diverse and expanding portfolio of confectionery, food, and petcare products and services, Mars employ 125,000 dedicated Associates who are all moving in the same direction: forward.

The Mars Sustainable in a Generation Plan addresses key areas of the United Nation's Sustainable Development Goals and features ambitious goals informed by science and rooted in The Five Principles. The plan focuses on three key areas—Healthy Planet, Thriving People, and Nourishing Wellbeing. Packaging plays a critical role in this plan as it allows Mars to deliver products and services that are of the highest quality and safety standards. Because Mars believes there is no such thing as a sustainable product in unsustainable packaging, Mars is investing in research and technologies to reduce the amount of packaging used, redesign packaging to significantly improve recycling rates, source sustainable materials used for packaging, and develop new technologies for collection and recycling. Their goal is to have 100% of their packaging be reusable, recyclable, or compostable and to decrease use of virgin plastic by 25% by 2025.

2 Workshop Structure

The Plastics for a Circular Economy Workshop ("the workshop") was held December 11–12, 2019 in Denver, Colorado. A total of 155 stakeholders attended from industry, National Labs, government agencies, research institutions, and universities. The breakdown of stakeholders is shown in Figure 2. Stakeholders represented both recycling facilities and entities interested in designing novel plastics.

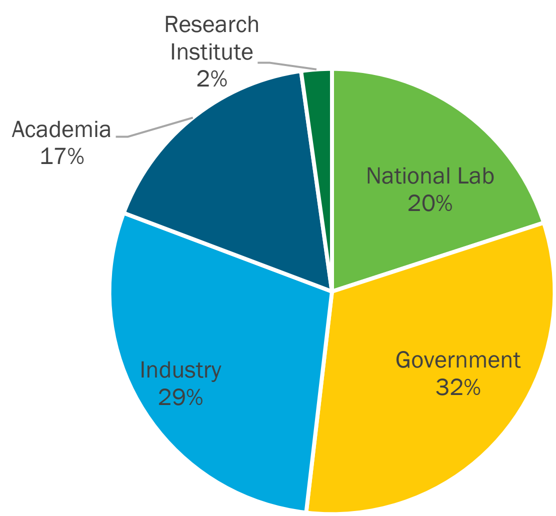

Figure 2. The breakdown of workshop attendees

The format of the workshop featured four types of sessions: presentations, lightning talks, breakout discussions, and networking breaks (Figure 3). The workshop began with a keynote presentation and a series of plenaries from industry representatives, the National Laboratories, DOE, and other government agencies. The plenaries were designed to introduce BETO's objectives for this workshop and to provide background information relating to plastics beyond participants' individual expertise. Because of the diverse backgrounds of attendees, the first goal of the workshop was to introduce a common language to facilitate discussions. Some of the critical concepts introduced included articulating the magnitude of the problem, highlighting the differences between technology solutions and policy solutions, and introducing possible solutions that are under consideration at large companies. Additional detail can be found in the individual plenary summaries.

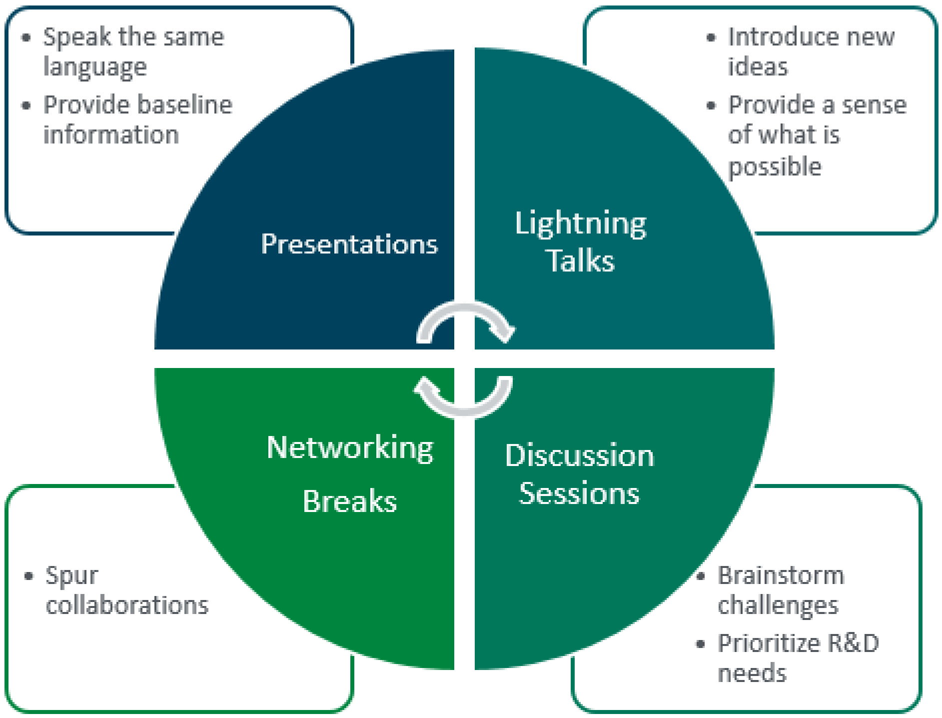

Figure 3. Workshop format

The plenaries on the first day were followed by 5-minute lightning talks in which speakers from industry, National Labs, and universities presented on innovative technologies both in the recycling and plastics space. These short presentations were meant to introduce new ideas and give participants a jumping-off point for the later breakouts. Descriptions of each presentation can be found in Section 3.

Day 1 ended with four simultaneous breakout sessions covering different recycling technologies and challenges related to introducing new plastics. The structure of the breakouts is described in more detail below. Day 2 began with additional plenary presentations and then ended with four simultaneous breakouts on some bigger-picture questions concerning the development of new recycling systems and new plastics.

A full agenda can be found in Appendix B.

Breakout Session Structure

Participants were able to choose which of the breakout sessions they wanted to attend on both days. In general, each session had between 30–40 attendees. Participants in each session were asked a unique set of questions related to the overall purpose of the breakout. A full list of questions that were asked in each breakout session can be found in Appendix C. At the conclusion of each breakout session, a volunteer presented a 5-minute overview of the conclusions from the session to all workshop attendees.

Sessions were facilitated according to the preferences of the individual facilitators and based on the makeup of the participants in each room. In general, participants were given a set of questions related to the session goal and discussed the questions in small groups of 5–7 participants before discussing with the entire room.

3 Presentations

A variety of presenters were invited to illustrate the key elements of this workshop. The presentations can be organized into five themes:

- Keynotes, which provided contextual data and concepts
- New plastics and materials to address recycling challenges
- Novel strategies for dealing with existing plastics
- Existing recycling strategies
- Analysis frameworks.

3.1 Keynote Presentations

3.1.1 Mike Biddle, Evok Innovations – Connecting the Dots: The Intersection of Plastics, Energy and Planetary Health

Dr. Biddle founded the company MBA Polymers to find a better way to recycle plastics. He presented his thoughts on the issue of plastic waste using four questions as a guide: Why are we here? Where do we want to go? How do we get there? Who will get us there?

Why are we here?

Dr. Biddle observed that there has been an explosion in plastic production in the past several decades. These new plastics have dramatically improved people's lives because they have excellent properties and myriad uses. Unfortunately, the benefits of plastics come at a cost that we are just starting to fully understand. Large amounts of plastics are found in a variety of marine life, washing up on beaches and causing visible ecological damage. In addition to this visible damage, microscale plastics can be found everywhere in our environment from arctic snow to the food we eat. The effects of human and animal exposure to these microplastics is just beginning to be understood.

Where do we want to go?

Dr. Biddle argued that we need to create more sustainable business models to address the externalities of plastic use but preserve the benefits.

How do we get there?

There has been a large push by environmental groups to ban plastics, but plastics are often the best choice of material from an environmental perspective. One study estimates that eliminating plastic and using the next-best alternative could increase the environmental costs of those materials by up to fourfold due to increases in production and transportation costs. Dr. Biddle suggested that what is needed is a simpler recycling infrastructure with fewer handling steps that creates a higher value.

Who will get us there?

Dr. Biddle argued that commitments from a variety of entities would be needed to realize this vision, including governments, non-governmental organizations, large companies, small companies, and individuals. Governments and non-governmental organizations have a role to play by helping to create policies that properly account for externalities and to fund research and development (R&D) to address critical problems. Dr. Biddle observed that some large progressive companies like Unilever have pledged to do things like double their size while halving their greenhouse gas (GHG) footprint. While these commitments are very important, they are relatively small on a per-employee basis, resulting in GHG reductions of only about 1 metric ton per year (Mt/yr) of CO_2 equivalent. Small companies exclusively focused on recycling can have a very large impact, with MBA Polymers estimated to have an impact of about 900 Mt/yr of CO_2 equivalent per employee.

3.1.2 Eric Klingenberg, Mars Incorporated – Rethinking Packaging for a Circular Economy

Dr. Klingenberg introduced Mars Incorporated's "Sustainable in a Generation Plan," which addresses sustainability through improving environmental impact, addressing human capital, and ensuring food safety and nutrition. Within the environmental impact component of this plan lies a circular packaging focus, which aims to "develop packaging that is 100% reusable, recyclable, or compostable while decreasing virgin plastic use by 25% by 2025." Dr. Klingenberg highlighted that when developing circular packaging, it's imperative that solutions are implemented globally and extend beyond recyclability.

Dr. Klingenberg described how we need to think about multiple options for making use of the waste plastic. There are a wide range of possibilities of how packaging can be recycled. Thinking more holistically about the package use, functionality required, and most probable end of life would enable improved material and package design to increase circularity. Specifically, he encouraged thinking beyond mechanical recycling and waste to energy to include new technologies like chemical recycling and biological recycling, i.e. composting or anaerobic digestion. Ultimately, creative avenues can and should be explored to redesign packaging and enable new recycling technologies to limit how much packaging ends up in the landfill.

Flexible packaging introduces unique challenges:

- Packaging needs to be durable
- It's often composed of multilayer materials
- Application-specific design and recycling mechanisms may be required
- Additives used in recycling processes must not introduce new contaminants.

Dr. Klingenberg discussed the philosophical approach to recycling. Currently, capabilities for recycling are evaluated as a tradeoff between investment and value outcome. However, to achieve a circular plastics economy, a new type of thinking may be required in which waste and recycling are seen as a resource and provide an opportunity for high-value products. It was emphasized that Mars does not believe that there is such thing as a sustainable product in unsustainable packaging. Reaching this goal for sustainability requires more than one solution, including holistic, fact-based approaches, environmental sustainability and recyclability, and using multiple technologies. Providing for a circular packaging economy will also require social change, as behavior is an essential element of proper disposal and collection.

3.1.3 Jill Martin, Dow – Plastics for a Circular Economy

Dr. Martin introduced Dow's approach to enabling a circular plastics economy. Dow has broken down their approach into four facets, outlined below, underpinned by Dow's innovation portfolio.

- **Design for recyclability** includes the design of nonrecyclable packages to become recyclable. This can be achieved by using a mono-material design, modifying protective coatings, introducing components that will increase compatibility with processing, developing film-orientation technology, simplifying the structure, and modeling package performance.
- **Developing tools to increase demand for mechanically recycled materials** focuses on developing a product market for mechanical recycling. This requires the integration of the collection system, from the consumer to the mechanical recycling facility, and producing material of marketable grade.

  - One idea discussed was the use of plastics in asphalt, which could potentially divert large amounts of plastic waste (approximately 420,000 pounds of plastic per 145 miles of road).
  - The Hefty® EnergyBag® has already diverted substantial waste from landfills by keeping hard-to-recycle plastic out of the environment.
- **Feedstock recycling solutions** address the generation of new feedstocks made from plastic waste, which can be used to produce new polymers.
- **Innovation and new business models** provide the commercialization space to develop and deploy new products and processes in the marketplace**.**

Overall, these processes face several challenges. Continuing to improve current systems and improving customer engagement will be critical to introduce this new platform. This will require identifying when package and recycling systems are compatible. Determining where scale will be advantaged is critical to identify. Closed loops are also a consideration; can new end markets be addressed or built while generating full circularity? Finally, consumers have shown that they are acceptant of paying more for more some, but not all, sustainable goods. Consumer buy-in will be critical if costs are higher than for traditional materials.

3.1.4 Gregg Beckham, NREL – Introduction to the BOTTLE Consortium

Dr. Gregg Beckham at the National Renewable Energy Laboratory (NREL) presented on the launch of the Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment (BOTTLE) consortium, for which Dr. Beckham serves as the primary investigator. BOTTLE is a multi-lab consortium that addresses plastic waste challenges by developing novel technologies for:

- Depolymerizing thermoplastics and thermosets
- Upcycling deconstructed waste plastics into higher-value materials
- Redesigning existing plastics to be "recyclable by design."

The BOTTLE mission is to develop robust processes to upcycle waste plastics and develop new plastics that are recyclable by design.

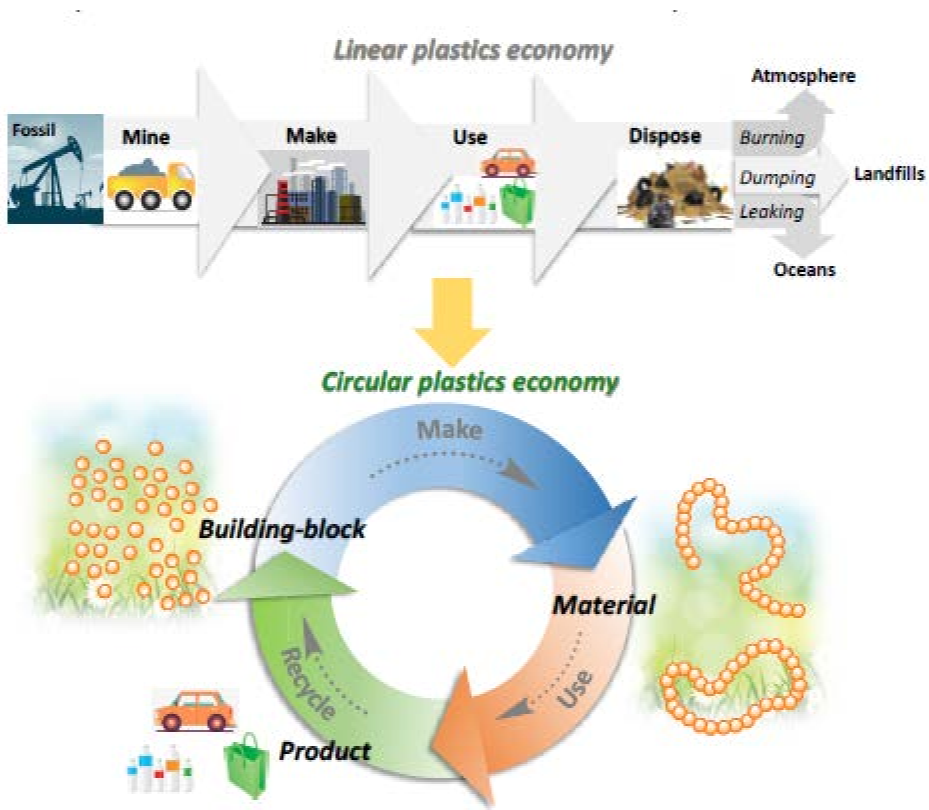

Figure 4. Visualizing the shift from a linear plastics economy to a circular plastics economy

Source: Gregg Beckham, NREL, and Eugene Chen, Colorado State University

The long-term goals of the BOTTLE consortium are to:

- Develop selective, scalable processes to deconstruct and upcycle today's commodity thermoplastics and thermosets
- Design new chemistries and associated processes for chemical recycling of tomorrow's plastics and composites that are inherently recyclable by design but maintain similar lifetime performance metrics
- Leverage AMO, BETO, and DOE investments in analysis-guided R&D, process development, biological and chemical catalysis, materials characterization, promoting secondary feedstock use, and modeling.

R&D metrics for the BOTTLE consortium include:

- Greater than 50% energy savings relative to virgin material production
- Greater than 75% carbon utilization from waste plastics
- Greater than two times the economic incentive above the price of reclaimed materials.

A consortium approach was chosen because it will enable direct comparison of chemical and biological catalysis and cross-cutting analyses using consistent assumptions (economic, energetic, sustainability, and chemical/materials analyses) to be conducted for the important problem of plastics upcycling.

For more information about the BOTTLE consortium as it evolves, visit www.bottle.org.

3.2 Presentations on New Plastics and Materials to Address Recycling Challenges

Speakers from a variety of institutions were invited to give presentations about addressing the plastic waste problem via new plastic design. Presenters provided a range of solutions from currently available biodegradable and compostable plastics to new material concepts that address flexible packaging waste or are infinitely recyclable.

3.2.1 Matt Terwillegar, Danimer Scientific – Monomers and Polymers Derived from Biological Sources: Opportunities and Challenges

Dr. Terwillegar presented on the opportunities and challenges associated with using biobased plastics. To begin, Dr. Terwillegar addressed some common consumer misconceptions about "bio" plastics and categorized them into four different types: biorenewable plastics made from biomass, biorenewable plastics made via an organism, biodegradable plastics, and compostable plastics. A single material can fit into more than one of those categories. He emphasized that biodegradable is more important than biorenewable. Biodegradable plastics are broken down via microbes in various natural environments, including terrestrial and marine environments. Compostable plastics, either existing materials or novel materials, will not degrade in the environment and need to be decomposed in a municipal or industrial composting facility that provide inputs such as moisture and heat.

Dr. Terwillegar identified numerous challenges with introducing biobased plastics to consumers:

- Price-premium challenges: A new biobased plastic cannot be more expensive than an incumbent product, and "green" alone does not sell. In situations where a new biobased product both outperforms an incumbent and is competitively priced, there is still consumer resistance to change. This phenomenon further adds to the challenge of bringing biobased plastics to market.
- Recycling challenges: Many currently available biobased plastics like polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) will contaminate an existing recycling stream.
- Bio-sourced versus biodegradable: While there are environmental benefits of making plastics from biomass, at the moment there is little economic incentive to use them. The environmental benefits of biodegradable plastics, regardless of their source, are more tangible.
- Standards challenges: Many existing degradable plastics like PLA and polybutylene succinate (PBS) are sent to commercial composting facilities that use controlled environments to accelerate decomposition, yet the decomposition process can take up to 90 days. Many products are advertised as biodegradable, but in a practical sense they are not. There needs to be better standards for composting and biodegradability.
- Marine biodegradability challenge: Salt water poses a unique challenge to designing biodegradable or compostable plastics; it often acts as a preservative that prevents a plastic from degrading in marine environments. Plastic waste often ends up in the ocean if it does not make it to a landfill, recycling, or composting facility; as a result, it is important to address the challenge of how a plastic decomposes in a marine environment.
- Shelf-life challenge: Plastic films are often used to keep perishable foods fresh for as long as possible. Many have pointed to the disconnect between using an enduring material to protect a short-lived item like perishable food. However, Dr. Terwillegar pointed out that the common solution of using a biodegradable film to protect foods is not an ideal solution because food safety and longevity will be compromised.

The challenges that Dr. Terwillegar outlined in his presentation were enthusiastically agreed to by many attendees and were reiterated in several breakout sessions.

3.2.2 William Orts, U.S. Department of Agriculture (USDA) Western Regional Research Center – Agriculturally Derived Polymers and Composites Targeted Toward a Circular Economy

Dr. Orts presented numerous drivers for developing new plastics beyond addressing plastic waste. Depending on the driver that is motivating design, different products can result. For example, if the drive is to add value to agricultural products, manufacturing new plastics from biobased feedstocks might be the solution. If the motivator is to divert waste from landfills and mitigate litter, biodegradable or compostable plastics might be pursued. If maximizing recycling and reusing the carbon in the original product is a driver, new plastics designed for facile recyclability might be the answer. Other drivers include addressing regulatory actions and reducing GHG emissions in the plastic manufacturing process. The ultimate motivator, however, is making the best product at a good price. As many workshop speakers and attendees attested to, any new product introduced to market must have superior properties and a comparable price to an incumbent.

A big-picture problem illustrated by Dr. Orts is how to envision the future of the recycling industry as new plastics come online. In managing plastic waste, is there a preference for recycling over composting? Should one solution be prioritized over another, or should both be pursued simultaneously? What are the implications for infrastructure development? Issues with lack of consistency in waste handling and infrastructure make addressing these questions more challenging.

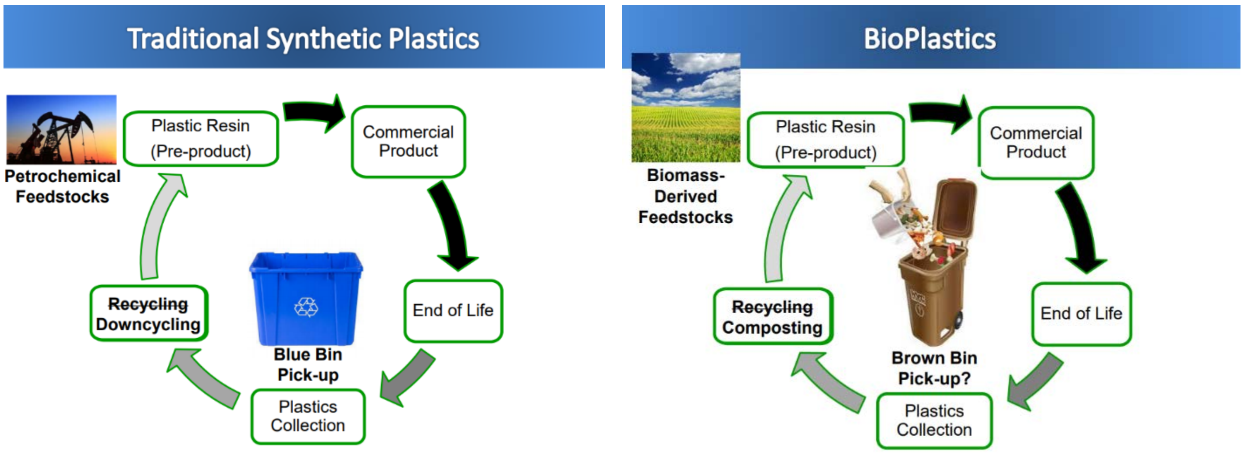

Figure 5. Comparing the life cycles of traditional plastics and biobased plastics

Source: William Orts, USDA

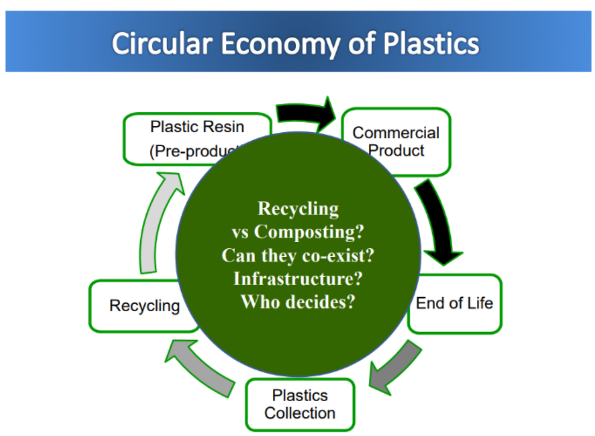

Figure 6. How do recycling and composting fit into the circular economy of plastics?

Source: William Orts, USDA

3.2.3 Shannon Pinc, NatureWorks – Lightning Talk

Ms. Pinc presented data from the U.S. Environmental Protection Agency that shows that food waste and yard clippings make up a significant portion (>28%) of municipal solid waste.

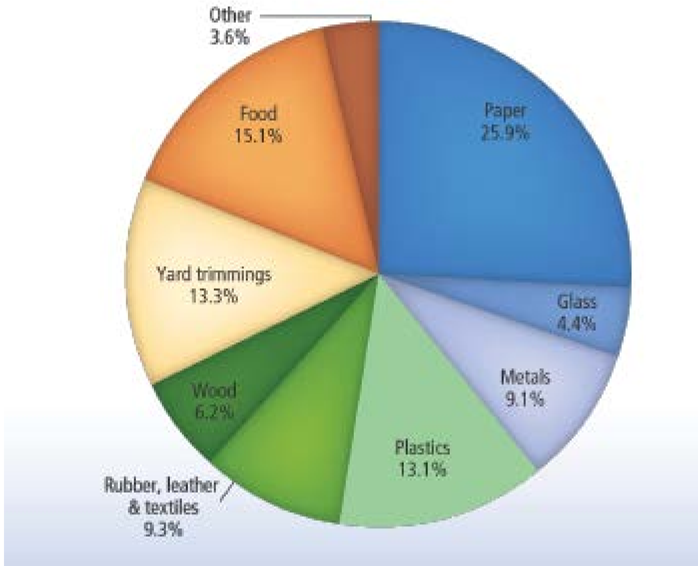

Figure 7. Total municipal solid waste generation (by material) in 2015 (total: 262 million tons)

Source: U.S. Environmental Protection Agency (2018)

Compostable products like to-go packages, utensils, and cups can play a role in addressing major global environmental issues such as climate change, food waste, and plastic litter. There are major challenges with widespread adoption of compostable products because they are often visually indistinguishable from non-compostable products. Consumer education is imperative to the success of compostable products and ensuring that they are actually composted, not contaminating recycling streams. This presentation highlighted a common theme at the workshop: better methods are needed to ensure that the right types of plastic waste have the right fate, be it a recycling facility, compost facility, or landfill.

3.2.4 Carson Meredith, Georgia Tech – Lightning Talk

One of the main contributors to waste accumulation is flexible packaging. While flexible packaging has played a major role in food safety and longevity, the fact that it is often extremely lightweight and made of thin layers of multiple polymers makes it very difficult to collect and recycle. Dr. Meredith presented on three technology challenges that, if addressed, could improve the end-of-life outlook for flexible plastic packaging:

- **Oxygen and moisture barrier properties in bioderived plastics**. A key property of multilayer flexible packaging is that it acts as a barrier to oxygen and moisture, keeping food inside from becoming stale or wet. Developing a biodegradable or chemically reversible plastic that has those desirable barrier properties could address the problem of excess flexible plastic packaging waste.
- **Reversible interfaces**. A challenge with multilayered flexible packaging is that the interface between the polymer layers is buried or inaccessible. By developing a chemical or physical approach to trigger reversal of multilayer adhesion, component polymers can be accessible to degradation mechanisms like chemical recycling or biodegradation. Proposed triggers include chemical, light, mechanical, or thermal triggers. Challenges with developing triggerable, reversible adhesion include wetting, transport, and kinetics in buried interfaces.
- **Multi-material depolymerization and integrated processes**. Mechanocatalytic reactions are driven by mechanical impact instead of thermal energy. This approach can be a cost-effective strategy for depolymerizing plastic waste. A key scientific and economic issue in chemical polymer recycling and upcycling is fractionating the resulting depolymerized crude mixture without energy-intensive, heat-driven separations. The resulting stream could be very complex, containing numerous components. This

problem is analogous to the challenges with deconstructing biomass via pyrolysis: the resulting biocrude is complex and individual compounds are found in very low concentrations. Clever solutions are necessary to funnel components of the crude mixture into different streams for upgrading.

3.2.5 Brett Helms, Lawrence Berkeley National Laboratory – Lightning Talk

Many of the most common plastics are recycled at very low rates in the United States, and when they are recycled, they are often recycled into lower-value products due to degradation of polymer properties resulting from mechanical recycling. Researchers like Dr. Brett Helms of Lawrence Berkeley National Laboratory are developing new plastics that can be recycled into pristine, same-value materials. Dr. Helms presented on the development of poly(diketoenamine)s, a next-generation plastic that can be used and reused without losing value.

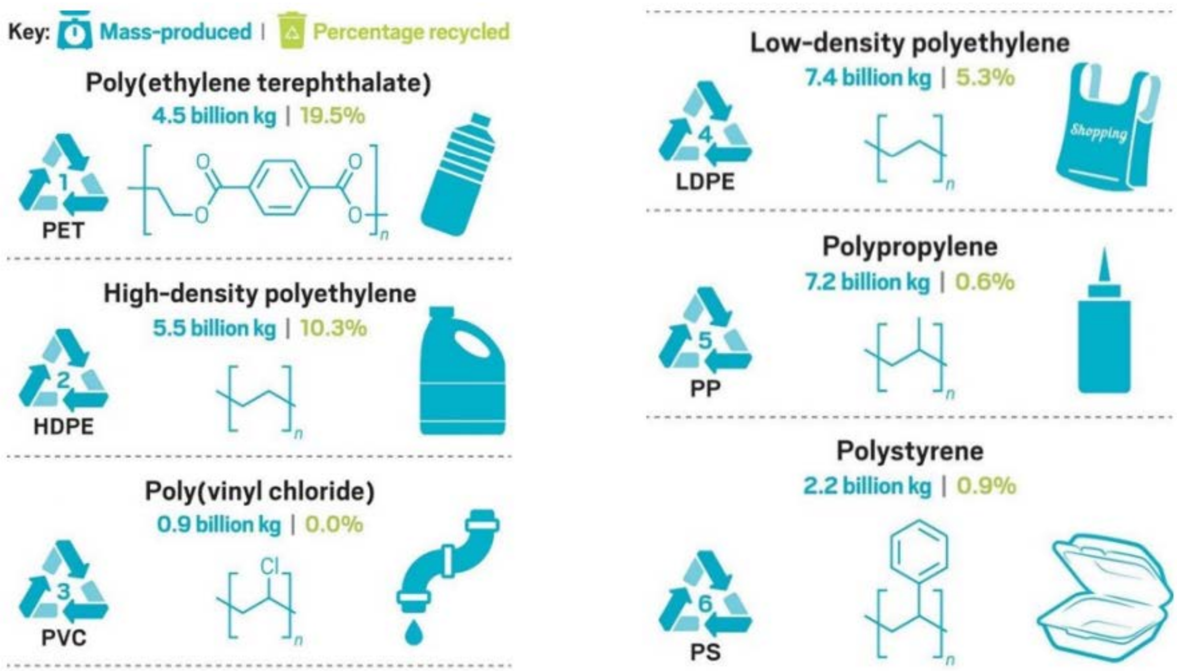

Figure 8. Common plastics and their recycling rates

Source: Lemonick (2018)

Dr. Helms explained how the new plastic recycling protocol ensures that the monomer stream generated after depolymerization is free from contaminants and colors, a common problem with chemical recycling of plastics.

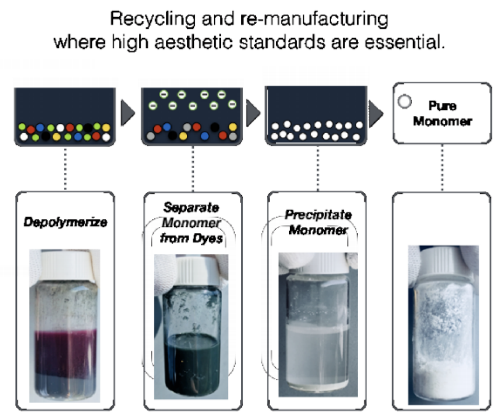

Figure 9. Ensuring that recycled plastics have the same appearance to virgin plastics is critical for many applications

Source: Christensen et al. (2019)

3.2.6 John Dorgan, Michigan State University – Lightning Talk

Professor Dorgan presented on how thoughtful, quantitative, and judicious application of polymer science can reduce costs, improve sustainable metrics, and enable the circular economy. He emphasized the importance of embracing active management of the global carbon cycle. Professor Dorgan showed how biobased PLA could be converted into large-scale composites, like those used in wind turbines. As the U.S. wind energy capacity continues to grow, the need for polymer resins to manufacture wind turbine blades will increase. Professor Dorgan explained research in his laboratory that demonstrated that it is possible to recover the resin from a wind turbine blade and reform it. He showed that turbine-to-turbine material circularity is possible.

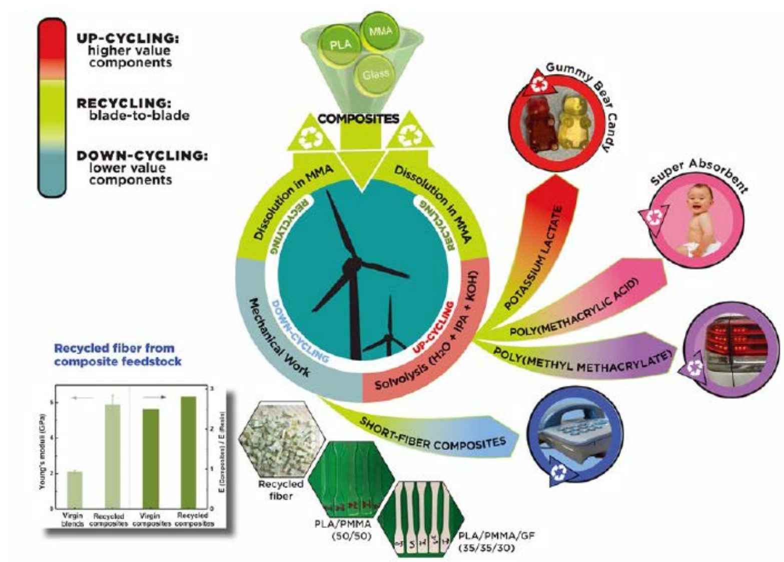

Figure 10. Different ways to make, recycle, and upcycle wind blades

Source: Professor John Dorgan, Michigan State University

3.3 Presentations on Novel Strategies for Dealing with Existing Plastics

Speakers from a variety of institutions were invited to give presentations to address novel strategies to tackle waste associated with existing plastics. Presenters provided a range of solutions, including biological and chemical recycling approaches.

3.3.1 Amy Waun, PureCycle Technologies – Recycled Resins with Virgin-Like Properties

Dr. Waun presented work conducted at PureCycle Technologies and Procter & Gamble to make plastic waste into recycled resins with virgin-like properties. Dr. Waun requested that the details of her presentation not be shared publicly.

3.3.2 Frederique Guillamot, Carbios – Carbios, The First and Only Company to Have Developed Biological Processes Based on Enzymes to Break Down Plastic Waste into Monomers

Dr. Guillamot presented a biological deconstruction strategy for PET waste that can transform PET into clean monomers at ambient pressure and low temperature (60°C–70°C) (see Figure 11). This work involves development of an enzyme recently reported to hydrolyze the ester linkage in PET, followed by subsequent enzymatic steps to make ethylene glycol and terephthalic acid.

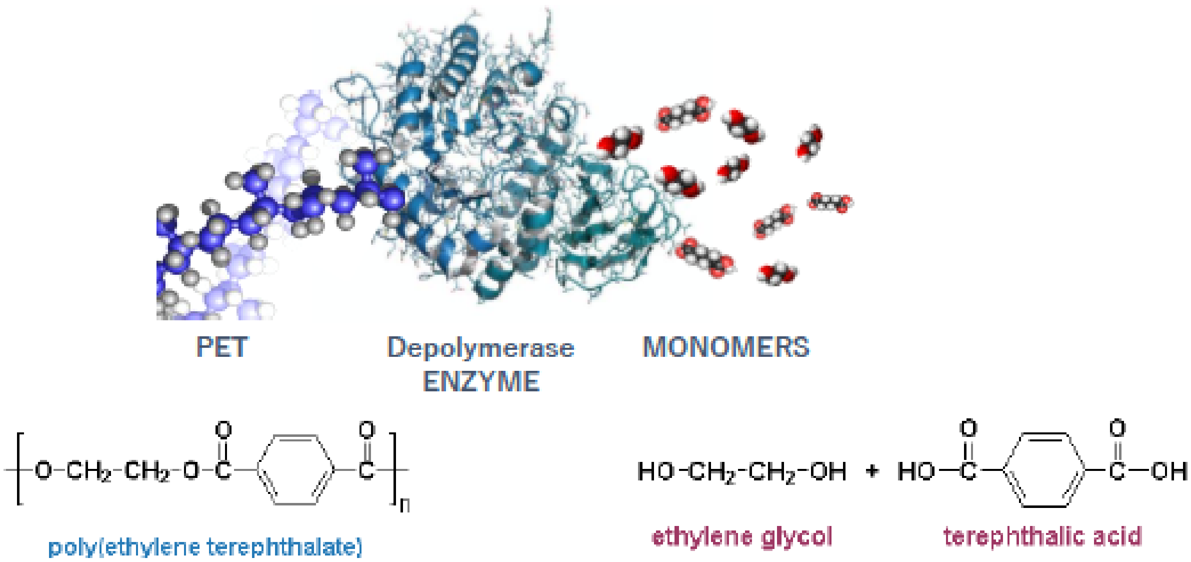

Figure 11. Biological deconstruction of PET

Source: Frederique Guillamot, Carbios

PET represents a large plastics market, with 70 million tons produced in 2017 and a 4% annual growth rate. The majority of this is used in textiles (60%), with an additional 40% used in various types of plastics. Although current strategies exist for recycling of PET in plastics, recycling of PET in textiles has been very challenging. Carbios' biological approach allows them to complement existing methods and address new streams like textiles, plastic trays, colored bottles, and complex plastics, which are not adequately processed in the current system.

Because plastics were introduced into the environment relatively recently, nature has had limited time to evolve enzymatic systems to efficiently break down plastics, though enzymes active on plastic substrates have been found. This presents an opportunity to use advanced protein engineering and evolution techniques to develop much more efficient enzymes than have been found to date in nature. Carbios has evolved one enzyme to break down >90% of a PET stream in 10 hours (see Figure 12).

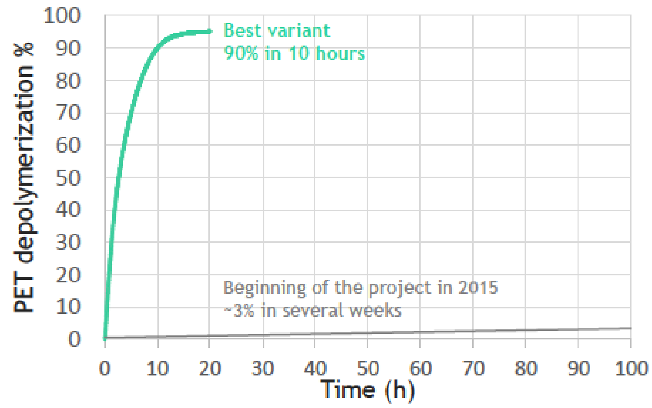

Figure 12. PET depolymerization via a Carbios-developed enzyme as a function of time

Source: Frederique Guillamot, Carbios

Dr. Guillamot also presented on other plastics with the potential to be good candidates for biological recycling. Plastics like PLA and polyamides offer strong possibilities due to their ester and amide backbone linkages, whereas plastics like polyethylene and polypropylene will be more difficult to tackle due to the lack of chemical handles.

3.3.3 Aaron Sadow, Ames Laboratory and Iowa State University – Lightning Talk

Dr. Sadow presented a 5-minute lightning talk on several novel chemical approaches for plastic upcycling under development in his laboratories at Ames Laboratory and Iowa State University. Dr. Sadow's approach focused on the largest volumes of plastic waste: polyethylene, polypropylene, and polystyrene, which together account for 55% of plastic waste. These polymers all have carbon-carbon linked backbones, which make them difficult to tackle through most recycling strategies other than mechanical recycling.

Dr. Sadow presented an example of the breakdown of HDPE into short-chain-length alkanes through the use of a Pt/$SrTiO_3$ catalyst using hydrogen. Using this method, the average molecular weight can be decreased by more than tenfold, forming a liquid product that can be processed for a variety of end uses.

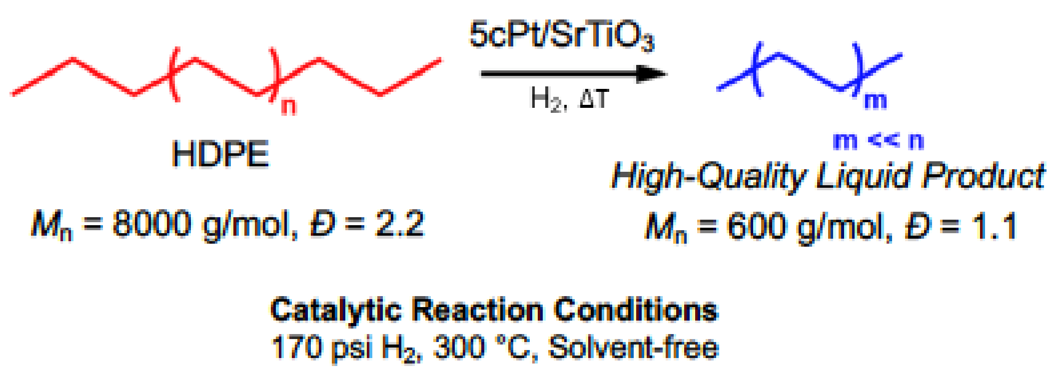

Figure 13. Deconstruction of HDPE into a high-quality liquid product

Source: Aaron Sadow, Ames Laboratory

3.3.4 Justin Siegel, University of California, Davis – Lightning Talk

Dr. Siegel presented on work done in his laboratory at UC Davis and in Ramon Gonzalez's laboratory at the University of South Florida. The biotech market is growing rapidly in the agriculture, health care, and industrial spaces, estimated at $350 billion in revenue in 2016. Part of this rapid expansion is due to the decreasing cost of DNA synthesis and sequencing. Because of these advances, Dr. Siegel argued that biotechnology has significant potential to address the problem of plastic waste.

The advantages of biotechnology solutions are the potential to utilize mixed feedstocks, operate at lower temperatures and pressures, and perform multiple transformations in the same pot. Several challenges must be overcome in order to effectively utilize biotechnology in this space, such as the need to develop robust and efficient enzymes and organisms, as well as the engineering of new pathways to utilize non-natural substrates.

3.3.5 Bob Allen, IBM Research – Lightning Talk

Dr. Allen presented on a chemical recycling approach developed at IBM Research. This technology uses a volatile amine catalyst (VolCat) to deconstruct PET into monomeric bis(2-hydroxyethyl) terephthalate (BHET), which can be repolymerized into new PET. This process is capable of handling dirty and colored materials, producing pure BHET. It can also leave other contaminating plastics intact, effectively “sorting” a mixed stream and resulting in pure monomer (see Figure 14). The BHET monomer can be easily crystalized, which helps to avoid a costly distillation step. Because of this and other processing advantages, this process results in greater than 60% energy savings for PET production compared to production from virgin material.

Figure 14. The IBM VolCat process selectivity deconstructs PET in the presence of other waste

Source: Robert Allen, IBM

3.4 Presentations on Existing Recycling Technologies

This set of speakers presented an overview of the current state of recycling and expanded both on what may need to be done to adapt current technologies to handle more types of plastic and how new technologies may be introduced to increase recycling. Speakers represented existing material recovery facilities (MRFs) and institutions performing early-stage research on novel recycling technologies.

3.4.1 Stacy Katz, Waste Management – Recycling: A Collector & Processor’s Perspective

Ms. Katz is Senior Manager of Materials Management & Quality at Waste Management, where she works on improving the quality of materials received and commodities produced at Waste Management facilities. She presented on Waste Management’s perspective of current collection methods and recycling technologies and how they can deal with novel plastic materials. She first introduced the pipeline for recycling. This pipeline is broken down into three components: material collection, mechanical and manual separation, and storage. After acceptable materials (paper, cardboard, PET bottles, HDPE bottles, cans, glass, etc.) are delivered, they are separated by size and shape using screens. Containers are separated mechanically or manually. Plastics are sorted optically or by people. After the material is separated, it is stored in a unique bunker so it can be baled for storage or moved to market.

While there are strong markets for plastics accepted into recycling programs, the recycling industry can often not keep up with the development of new plastics, and there often isn't an existing market for these plastics to be sold into after the recycling process. Increased consumer education about exactly what plastics can be recycled in their local recycling infrastructure, as well as better communication between plastics developers and the recycling industry, will be critical going forward. New plastics that are incompatible with recycling technologies will not help solve issues with plastics in the environment even if they have superior properties to current plastics. She also noted that new plastics will likely have a very small market volume that may make it difficult to justify the economics of developing new recycling processes to handle them.

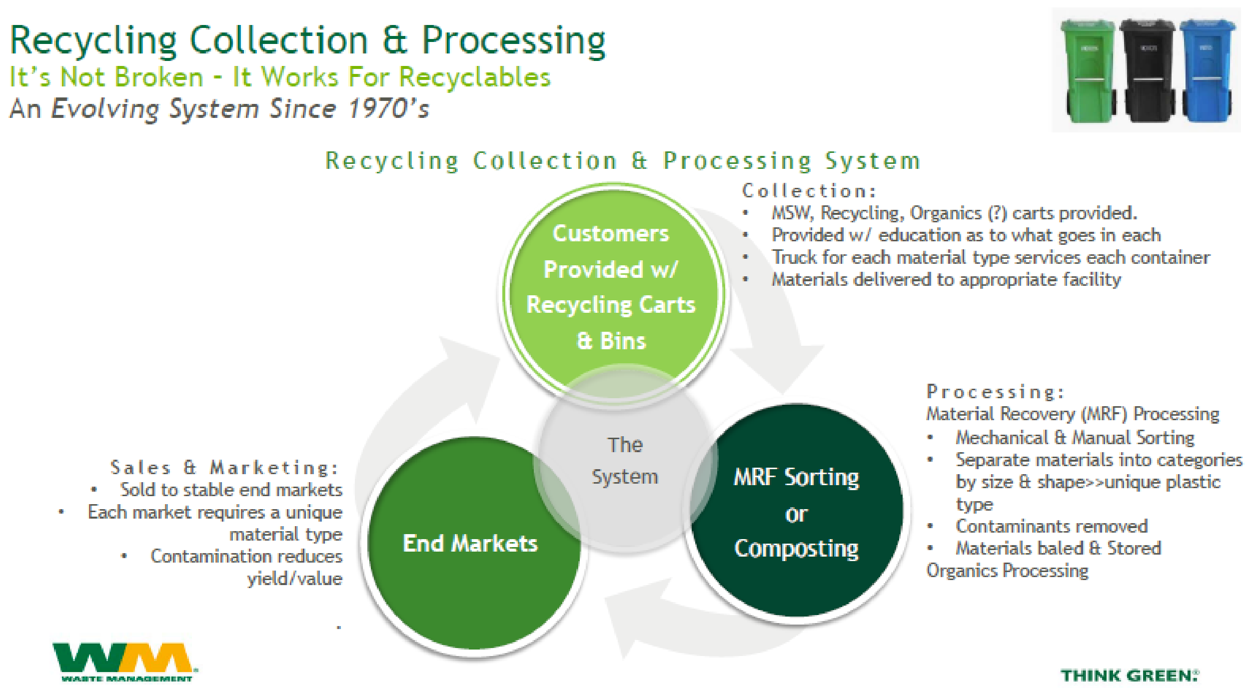

Figure 15. The recycling collection and processing system

Source: Stacy Katz, Waste Management

Ms. Katz outlined some specific problems that affect recycling. Clear communication and labeling are critical, and a lack thereof contributes to improper recycling, in which nonrecyclables are thrown in the recycling bin. For consumers, avoiding improper recycling is complicated because some items that have a recycling symbol are not recyclable. Of improperly recycled plastics, flexible-film plastic poses a major problem by preventing screens from working properly and by contaminating paper streams. Other nonrecyclable plastics complicate the recycling process by requiring additional people and equipment to eliminate them, at which point the material is sent to the landfill. Any improper plastic addition leads to a landfill fate, which is not an efficient use of a recycling system.

Specific challenges facing recycling were highlighted that may inform new plastics design:

- Speed of packaging innovation has outpaced recycling technologies

- U.S. recycling system does not have the capacity to meet demand for recycled goods: currently a one billion-pound annual gap between supply and demand for PET recycled bottles
- Limited investment in the U.S. recycling system, which is not universally available and is underfinanced as a public service.

Waste Management identifies several goals that may improve our recycling infrastructure: better consumer education (better labeling transparency and marketing), improved technologies to distinguish 2D and 3D materials to better separate containers from paper, and increase demand for recycled material. New technologies should also consider how they will interface with current recycling and how they will practically be collected.

3.4.2 Jason Locklin, University of Georgia – Assessing the Biodegradation and Compostability of Plastics

Dr. Locklin is an Assistant Professor at the University of Georgia, where he works on developing new polymers and assessing the potential for different degradation methods beyond traditional recycling. He presented on the potential for composting as a solution for plastic waste in the environment. The complex nature of many current plastics makes them very difficult to recycle. Composting processes may be able to handle more materials but would require additional research. It may require the development of new standards, and the applicability would likely vary across different regions due to differences in climate. Many local communities have already invested in composting facilities and education efforts, but there is substantial room to grow these efforts and to work with plastics producers to optimize the design of new plastics for composting.

3.4.3 Scott Farling, Titus MRF Services – Technology and Business Model Approaches for Maximizing Material Recovery

Mr. Farling is the Vice President of Business Development & Research for Titus MRF Services, where he works to develop secondary MRFs. He presented on technologies that can help maximize plastics recovery as well as the role that secondary MRFs can play in plastic collection. He echoed the point made by Ms. Katz previously, that it is difficult for most facilities to justify separating low-volume streams, making it difficult for facilities to deal with novel plastics. Technologies that are currently in use and show promise for increasing the value in recycled streams include optical sorting, robotic sorting, and digital watermarks that can be added to plastics and then scanned in sorting facilities. Combining technologies like this can increase the efficiency of sorting, but it may not be realistic to retrofit existing facilities to include new sorting steps. Secondary MRFs would be able to accept mixed streams of materials that existing facilities currently can't justify separating, such as plastics #3–7, and further sort them to meet industry specifications.

3.5 Presentations on Analysis Frameworks

This set of speakers discussed different analytical methods to predict the impact of new plastics and to measure the impact of keeping additional plastics out of the environment. Speakers in this area highlighted the importance of new analytical methods in helping plastics producers and recycling facilities avoid unintended consequences when trying to responsibly dispose of plastics. Speakers included representatives from National Labs and universities doing research in this area.

3.5.1 Cristina Negri, Argonne National Laboratory – Science to Shape a Bio-Benign Future

Dr. Negri is the Director of the Environmental Science Division at Argonne National Laboratory, where she works on integrating the concept of the circular economy into decision making and problem solving. She discussed the challenges associated with trying to increase the sustainability of processes across their full supply chain. Designing new materials to be bio-benign requires assessing environmental impacts involved in not only the manufacture of those materials, but also their use and disposal. There may be tradeoffs in the properties of the product itself if it is designed to have a minimal environmental impact over its full lifetime. Dr. Negri's group is working to develop a model that integrates environmental and sustainability impacts along with human health indicators to assess different plastic types. The hope is that with models such as this one, it will be easier to value the long-term impacts of avoiding negative environmental and human health impacts that currently aren't considered.

3.5.2 Birdie Carpenter, National Renewable Energy Laboratory – Lightning Talk

Dr. Carpenter is a member of the Resources and Sustainability Group in the Strategic Energy Analysis Center at the National Renewable Energy Laboratory, where she helped develop the Materials Flows through Industry tool. She presented a 5x5 lightning talk on the circular economy, and how to use the concept to avoid unintended consequences. The circular economy principle attempts to capture the value of recycling, reusing, and recovering materials, widening the scope of analysis to include a number of different sectors and timescales that may not show up in a traditional process analysis. Dr. Carpenter's presentation gave attendees a frame of reference for how difficult it can be to capture these factors in a single system analysis and posed questions for participants to consider about how technologies of interest may have unintended environmental consequences.

3.5.3 VeeAnder Mealing, Colorado School of Mines – Lightning Talk

Ms. Mealing is a Ph.D. candidate in the Landis Group at the Colorado School of Mines. She presented a 5x5 lightning talk on using different analytical models, including techno-economic analysis, life-cycle analysis, and material flow analysis, to develop a holistic decision-making process for which waste management processes to use. Some processes, such as composting, may appear environmentally preferred when only looking at certain metrics. Expanding analysis to include a broad number of environmental metrics including ozone depletion, acidification, eutrophication, and fossil fuel depletion for different plastics types can reveal that there may be unintended consequences to using these technologies. Similar to Dr. Carpenter's presentation, Ms. Mealing stressed that responsible and sustainable waste management needs to include a broad consideration of these consequences.

4 Breakout Session Summaries

There were eight breakout sessions, which covered a variety of topics. The objective of the breakout sessions was to bring stakeholders together to discuss technology challenges and opportunities.

Figure 16. Breakout session topics

4.1 Introducing New Plastics: Challenges and Opportunities

The objective of this discussion session was to catalog and prioritize R&D challenges and opportunities associated with designing and introducing new plastics to address plastic waste.

Many currently used plastics were not designed for recyclability or their post-consumer fate. The premise of this breakout discussion was that new plastics could be designed and introduced to address their post-consumer fate and by doing so, these new plastics could dramatically reduce plastic waste. The first questions posed to participants was, "Do you agree with the premise that introducing new plastics could reduce plastic waste? Why or why not?"

While all participants agreed that new plastic designs have the potential to reduce plastic waste problems, many stressed that there needs to be an abundance of caution when pursuing new designs to ensure that new or different plastic problems are not created. Participants stressed that while redesign of plastics is being pursued, development of recycling infrastructure and bolstering consumer education needs to happen simultaneously.

Takeaway message: Designers must be diligent about vetting ideas and performing supporting analysis to ensure that new solutions do not introduce new problems.

The second part of the discussion focused on the challenges and opportunities associated with designing new plastics. Participants emphasized the importance of articulating the problem before designing solutions. For example, it is important to distinguish between the plastic waste formed from a long-term use item versus a single-use item; designing for biodegradability might make sense for a single-use item that is likely to be leaked into the environment but not for a plastic item that is designed to be used for decades.

What new plastics or end-of-life properties should be introduced to address waste plastic accumulation issues? The four major properties or concepts that were discussed were:

- **Fit for purpose:** Participants stressed that each new plastic should not be overdesigned. Due to the diversity of applications for plastics, all requiring different properties, there will never be a "master plastic" that is used for all applications. As such, new designs should consider specific applications and target specific problems with waste in those applications.
- **Benign degradation products:** Participants emphasized that any plastic that is designed for biodegradation must produce biologically benign, nontoxic degradation products. Degradation products must be well characterized.
- **Reversible compatibilizers for multi-materials:** Compatibilizers are additives that are added to mixtures of resins that would not typically blend with each other to create a new product.[6] A compatibilizer could be used to blend two or more recyclable polymers together to create a new product with desired and/or tailored properties. A disadvantage of this approach is that the new product would no longer be recyclable; a reversible compatibilizer that could be triggered to release the original recyclable polymers could be advantageous.
- **Labeling systems:** Sorting is a major challenge to recycling complex mixed streams. Participants suggested that labeling systems that work with recycling facility machinery could be introduced when designing plastics. Possible labeling systems could include visible or invisible bar codes that could be scanned while being processed in a recycling facility.

[6] SPI: The Plastics Industry Trade Association. (2015). *Compatibilizers: Creating New Opportunity for Mixed Plastics, Version 1.0*. Washington, D.C.: SPI. https://www.plasticsindustry.org/sites/default/files/Compatibilizers%20Whitepaper%20(Version%201.0)_0.pdf.

Biodegradability as an end-of-life property: Many participants focused on the complex tradeoffs associated with biodegradable plastics. As an advantage, a material that degrades into benign components minimizes the risk of leakage of waste accumulation. Conversely, if a material degrades too easily, this introduces additional complications, including the contamination of recyclables and performance concerns. A degraded product could potentially generate unsightly residue or a toxic byproduct.

The final part of the discussion focused on the challenges and opportunities associated with the logistics of introducing new plastics to society.

The major challenges identified included:

- Managing huge design space for new molecules
- Understanding structure-function relationships
- Costs associated with bringing a new product to market
- Materials supply chain.

Conclusions

In all, the discussion covered a wide range of concerns and opportunities relating to the development of new plastics. Some of the main opportunities for research identified included the development of designer materials with optimal functionality, opportunities to incorporate sorting and recycling features into the material, development of reversible compatibilizers, and tuning degradability. Some challenges include avoiding unintended consequences, integrating into existing recycling infrastructure, tuning material properties, and cost. The outcomes of this discussion may provide useful context to direct and focus future research efforts.

4.2 Biological Recycling: Challenges and Opportunities

The objective of this session was to catalog and prioritize R&D challenges and opportunities associated with biological recycling of plastics. Any biological or hybrid biological and chemical process capable of taking a plastic waste and making a product was considered in the scope of the discussion. Plenary presentations helped to frame the discussion, specifically presentations from Frederique Guillamot at Carbios (Section 3.3.2), Justin Siegel from UC Davis (Section 3.3.4), and Gregg Beckham from NREL (Section 3.1.4). These plenary talks hit upon themes identified by DOE as areas where biology could play a role in tackling the issue of plastic waste, including biological recycling using selective chemistry, composting, and anaerobic digestion. Breakdown of plastics designed for biodegradability was discussed primarily in Flexible Packaging: Challenges and Opportunities (Section 4.7) instead of this session.

Participants were asked to discuss the following questions:

- Are there opportunities for biology to contribute to the problem of plastic waste, beyond biological recycling, using selective chemistry, composting, and anaerobic digestion?
- What are the R&D needs for biological recycling using selective chemistry, composting, and anaerobic digestion?
- What are the challenges with adding new biological recycling strategies to the current recycling system and to future systems?
- What are the top challenges identified with biological recycling?
- What are potential technology solutions and R&D needs to address the top challenges?

Are there opportunities for biology to contribute to the problem of plastic waste, beyond biological recycling, using selective chemistry, composting, and anaerobic digestion?

Participants agreed that biology could potentially contribute to multiple aspects of the plastics problem. There was broad agreement that biology should be used where it was best equipped to make an impact and not force fit into certain areas. Generally, though, the participants thought that the categories outlined were the most promising areas for biology to contribute.

What are the R&D needs for biological recycling using selective chemistry, composting, and anaerobic digestion?

- **Selective chemistry:** Selective chemistry for biological recycling employs enzymes to catalyze the depolymerization reactions. Improved enzyme efficiency and enzyme selectivity for desired materials and depolymerized products may both advance this R&D challenge.
- **Hybrid approaches:** Participants noted that hybrid biological and chemical methods would likely be needed to overcome the challenges as opposed to just biological methods alone. This is particularly true when discussing the problem of more recalcitrant plastics such as polyethylene, in which crystallinity and strong carbon-carbon bonds prevent biological breakdown at ambient temperatures at industrially relevant rates. Improving the titer, rate, and yield of hybrid biological and chemical systems through co-design was seen as an opportunity.
- **Biological funnel:** Participants noted that there was a large opportunity to utilize a biological funnel approach in which mixed plastic streams could be broken down into intermediates, accessible to biology, which could then be used by an organism to make a single product. The ability to produce a single product was seen as a main advantage to biological processing versus purely thermal or chemical methods.
- **Composting and anaerobic digestion:** Participants noted that improving compostability of materials is an attractive R&D target. Additionally, anaerobic digestion could be used to degrade materials with an opportunity for coproduct generation. Testing the functional degradation of the novel materials in either environment will be a critical R&D metric.
- **Fundamental understanding:** Participants noted that although composting and anaerobic digestion are practiced at industrial scale, the actual biology is not well understood and represents a basic science need. In particular, which microbes are responsible for which functions in the system needs further study, as opposed to simply cataloging what organisms are present. In addition, the impacts of plastics on soil quality is not well understood and is key to determining if composting of plastics makes practical sense.
- **Public testing infrastructure:** Participants noted that there is not good public infrastructure to do reproducible studies for degradation of plastics in these systems. There are a few facilities, mostly at academic institutions, that can do this testing, but they are not widely available to the community at large. Because these tests can be very sensitive to process parameters including things like plastic particle size, humidity, soil quality, etc., results are not easily replicable across laboratories.

What are the challenges with adding new biological recycling strategies to the current recycling system and to future systems?

Participants pointed out several potential difficulties in incorporating biological processes into current recycling infrastructure.

- **Timeframes:** Biology generally requires longer timeframes than mechanical processes to process similar amounts of material. This means that more space will need to be dedicated to biological steps to have multiple parallel reactors. Additionally, advances will be needed in enzymatic reaction rates to make these more compatible with current processing technologies.

- **Infrastructure:** Companies that specialize in recycling generally are not familiar with biological systems and may not have the specialized support required to service biological systems. Because of these potential incompatibilities, participants noted that biological processes may have to take place in separate facilities from primary MRFs that could process presorted material.

What are the top challenges identified with biological recycling?

- **System integration:** Because practicing biological recycling at scale will be quite different from traditional recycling, one of the top challenges is integration into the current system. Designing the proper handoff points to ensure that everyone along the value chain can profit from integration of biological recycling is critical. Communication between collection companies, MRFs, and purchasers of MRF-sorted material will be critical to incorporation of these new technologies.
- **Titer, rate, and yield:** Current public enzymatic systems for plastic breakdown are too slow and inefficient for commercialization, so additional R&D is required to improve titers, rates, and yields for these processes. There is significant opportunity in this space, though, as the enzymes discovered in nature have shown large improvements to date in engineering approaches like that of Carbios.

What are potential technology solutions and R&D needs to address the top challenges?

- **Role for government:** There was broad agreement that the government has a role to play in addressing this issue. Participants thought that the consortia approach of bringing multiple complementary capabilities and sets of expertise together to address the problem was the correct approach. There was also agreement that more publicly available infrastructure for testing of new plastics, particularly for the ability to be composted or degrade in the environment, was needed.

4.3 Chemical Recycling: Challenges and Opportunities

Chemical recycling technologies use chemical processes to break plastic waste down into smaller polymer and individual monomer components, which could then be upgraded back into the original plastic or into new novel materials. These technologies are not currently widely used by recycling facilities due to large capital costs and high energy-input requirements.[7]

This session was designed to allow DOE to gain a better understanding of the potential of chemical recycling technologies, both through a survey of the current technologies that are available and a discussion of potential new technologies. The session aimed to understand whether chemical recycling technologies show specific promise when compared to other methods, and if their use should be increased. If participants felt that they should increase in use, DOE wanted to understand if chemical recycling technologies could be integrated into the current recycling infrastructure.

Participants were asked to identify specific R&D needs to advance chemical recycling and to identify specific parties that should be involved in addressing needs related to chemical recycling.

Session Outcome

To start this session, participants were asked to identify a number of different chemical recycling technologies as a group. After this list had been generated, they were asked to list the R&D challenges associated with that

[7] Rahimi, A. and García, J. (2017). "Chemical recycling of waste plastics for new materials production." *Nat Rev Chem* (1:0046). https://doi.org/10.1038/s41570-017-0046.

technology. A summary of the technologies that were identified and the associated challenges is presented in Table 1.

Table 1. Chemical Recycling Technologies and Associated Challenges Identified by Participants in Breakout 1c

Technology	Associated R&D Challenges
Solvent dissolution	• Preprocessing incoming waste. Participants felt that current MRF industry would likely be unable to supply a stream that would be appropriate for this technology due to a higher required purity of incoming materials. One solvent of interest may be able to dissolve different polymers under different conditions, but in general, complex mixtures will be hard to deal with. • Plastic producers need to be willing to alter acceptable properties • Downstream separations will be required, depending on the desired final product. Participants specifically identified ultra-filtration technologies. • Developing and identifying new solvents.
Upcycling to new polymers	• Ultra-filtration technologies to improve separations • Downstream separations will be required, depending on the desired final product.
Pyrolysis and other catalyst-controlled reactions	• Better preprocessing, including sorting and separations of incoming waste upfront. Pyrolysis may be better suited to addressing a complicated mixture of plastics. • Difficulties associated with material handling related to introducing plastics to a reactor • Reducing the associated energy intensity of the process • Catalyst and reagent design to improve selectivity and functionality of the process • Improving catalyst regeneration and mitigating catalyst deactivation • Additional upgrading and posttreatment of the resulting pyrolysis oil. Participants also noted that pyrolysis may be a good front end for other biological upgrading processes. • Downstream separations, depending on the desired final product. Participants specifically called out ultra-filtration technologies.
Gasification	• Better preprocessing, including sorting and separations of incoming waste upfront • Identification of potential oxygen sources • Downstream separations will be required, depending on the desired final product • Higher capital cost associated with gasification.

Some common challenges that appeared across technologies include preprocessing of incoming waste streams to deal with seasonal and geographic variations in feedstocks, dealing with contaminants, and downstream separations.

Many of the participants pointed out that new analysis related to the economics and sustainability metrics (such as techno-economic analysis and life-cycle analysis) was a need for all of the technologies that were listed. A better understanding of the economic implications of chemical recycling technologies in general is needed. It is not clear in many cases how the composition of the products of chemical recycling compares to the current state of the art. It is important to model the full process in question so that added costs related to factors such as disposal of waste streams generated by chemical recycling are factored into decision-making processes.

To close out the session, participants were asked about how they felt DOE should balance prioritizing developing new plastics that would be more amenable to chemical recycling processes versus adapting chemical recycling technologies to better handle existing plastics.

Participants in this session felt that it is important to consider the difficulties associated with introducing new plastics to the marketplace due to how well established the current plastics industry is. Any new plastic would likely comprise a very small percentage of the total plastic waste stream to start, and this would only add to the sorting challenges that were identified above. Because many chemical recycling options are not already in place in recycling facilities, there is likely less market resistance to making changes in the recycling space.

Policy mandates for recycled content in Europe require extensive plastic recycling, which may not be possible to meet with mechanical recycling alone. Chemical recycling may further increase the recycling capacity and product value beyond what is achievable using mechanical recycling alone. This was discussed as a short term challenge in Europe, and one that may generate a broader opportunity space for additional plastics upcycling technologies in the long term.

Conclusions

- Chemical recycling technologies show promise but would require additional investment in R&D related to preprocessing and separations to expand in use
- There is likely more near-term promise in focusing on how chemical recycling technologies can process existing plastic waste streams than in developing new plastics that would break down favorably under chemical recycling.

4.4 Composite Recycling: Challenges and Opportunities

This session aimed to identify potential opportunities to impact and enable recycling and upcycling of composite materials.

The overarching objective of this breakout session was to identify the key challenges and opportunities that are unique to composite recycling. The composite materials that pertain to this session are made up of a polymer matrix that has been reinforced by a solid material to provide property benefits. Although this encompasses a wide range of materials from tires to wind turbine blades, this session focused on high-performance, fiber-reinforced composites due to the growing volume and number of applications they are being used in.

State of Technology

The majority of fiber-reinforced composites are glass fiber and are not recycled due to the low cost of virgin glass fiber. There is a greater incentive to recycle carbon fiber due to higher costs, but current recycling efforts reduce the length, surface properties, and resulting performance of the fibers. Because most composite applications have strict performance requirements, it has been a challenge to find an appropriate application space for recycled fibers.

Some countries have considered adding composites to cement kilns to reclaim the embodied energy. The practicality of this in the United States is unclear but is being tested. Another potentially viable route is to retain the material for repurposing for other uses.

Key Challenges and Considerations

Composite recycling faces unique challenges due to their applications, the cost of materials, and the logistical hurdles required for transport. As mentioned above, fiber-reinforced composites are typically highly engineered for a specific application. Therefore, repurposing that material for a different application is difficult. Furthermore, the quality of fibers reclaimed from recycling processes is generally lower than virgin material or in a format that is difficult to use, further limiting potential application space. To retain fiber qualities and value, processes should be designed around retaining fiber length and properties, which can complicate reclamation procedures.

Recycled products must be of sufficient value to motivate collection and recycling efforts. However, the highest-value component is the fiber, which is degraded in current recycling approaches. Glass fibers are relatively low cost and even the cost of carbon fiber is coming down, which reduces the incentive to reclaim and recycle. Volume is another consideration that motivates collection and recycling. Because composites are currently produced at much lower volume than commodity plastics, the incentive to collect and recycle are lower and the market for recycled products is low.

Transportation of material can be costly and challenging, especially for large composites such as wind turbine blades. To circumvent transportation challenges, modular solutions may be the only practical option but can present additional technological challenges. The size of composite materials such as wind blades may also lead to recycling infrastructure issues, requiring specialized equipment. Additionally, the physical properties that make composites valuable to use, such as strength and toughness, also introduce challenges to deconstruction and recycling.

The majority of composites manufactured today are made using a thermoset polymer matrix, which is more difficult to recycle than most thermoplastics. A thermoset plastic is chemically crosslinked during curing into the final form and maintains mechanical properties under high heat. In contrast, a thermoplastic is not crosslinked during curing and can melt under high heat, making it more recyclable. One topic of discussion was whether thermoplastics could replace thermosets as the polymer matrix in some applications. Thermosets typically have low viscosity and epoxies offer easy control of rheology, which is critically important in many composite manufacturing approaches. However, if thermoplastics were properly designed to account for composite mechanical properties, resin and adhesive performance, healing properties, and end-of-life considerations, it could possibly replace the thermoset. For instance, thermoplastics may actually have an advantage in automotive-related stamping applications. In general, thermosets and thermoplastics have inherent properties necessary for specific applications and it is not easy to replace one with the other.

Although thermoplastics are thought to be more easily recycled, isolation from the reinforcing fibers may require solvolysis, which is not practical in many composite applications due to size of the parts (wind blades, boat hulls, etc.) and the desire to maintain fiber length and surface properties. Furthermore, reversible cross-linking and polymers that are designed for recycling may enable more facile deconstruction of plastics, including thermosets, and allow for retention of desirable properties of reinforcing materials such as fibers.

Opportunities

The unique nature of composites and their application poses certain challenges to recycling, but also offers potential opportunities that don't apply to commodity plastics. Several opportunities to enhance recycling and reuse of composites were identified. For instance, designing new materials for specific applications will diversify the recycling "pool" and make sorting and recycling processes more complex. This is true for post-consumer processing, but post-industrial processing manages more uniform streams and could utilize novel techniques for deconstruction. Similarly, capturing materials from high-volume applications, such as wind turbines and automotive parts, may allow for similar isolation of post-consumer streams.

Due to the high value of many composites, repair strategies that can extend the useful life of composites should be considered. Repair strategies utilizing adhesives (thermosets) or thermal welding (thermoplastics) could work. In addition, downcycling may provide acceptable incentive, but appropriate end products need to be identified and/or coproducts from degradation developed. Construction materials were identified as a potential application space for recycled and downcycled composites, including drywall and cement, where rigorous cleaning of fibers would not be needed.

To address the issue of the small size of the composites market relative to other plastics, it may be useful to identify what high-volume streams composites and composite decomposition products could be added to in order to make it worth the trouble to recycle them.

Recommended R&D Areas of Focus

There was broad agreement that this problem is complex and the challenges are multifaceted. To address this, the recommendation was to take a system-level approach to designing the polymer through the entire life cycle. In addition, multiple disciplines will need to work together to develop actionable solutions.

The R&D areas that were identified as most promising were:

- Catalyst development to break down thermosets
- Understanding the fundamental interfacial chemistry of composites to enable new material design, including "triggerable" chemistry for decomposition, reversible cross-linking, and vitrimer chemistry
- Development of processes that will retain fiber size and properties
- Methodologies that can quickly and cost-effectively verify the recovered fiber properties
- Mechanism development for internal heating that would allow post-forming and reforming of composite sheets.

In the short-term, R&D should focus more on reuse pathways, with system redesign as a longer-term investment. In addition, tools that can evaluate the life cycles of different composites should be utilized and further developed.

4.5 End-of-Life Considerations: How to Match Use with Material Design? What Are Potential Unintended Consequences?

The objective of this session was to catalog and prioritize plastic "design for end of life" problems, solutions, and unintended consequences. Participants were asked to discuss: What is the ideal fate of plastic waste? How can we ensure that we are making good decisions when are designing for the future? When are there instances of solutions not being well suited for solving a problem?

The discussion was organized around three facets of designing new plastics: (1) What are the problems we are trying to solve when we design for end of life? (2) What are possible solutions to solving these problems? and (3) What are potential unintended consequences? To illustrate the objective of the discussion session, the following example of a problem, solution, and unintended consequence was given: A problem is plastic waste leaking into the environment. A potential solution to this problem is to replace plastics that have a high likelihood of being leaked with a biodegradable alternative. A potential unintended consequence is that plastics degrade into undesired or unpredicted chemicals.

Circularity and the Problem with "End of Life"

Before the discussion could begin, attendees debated the merits and flaws of the term "end of life." It was noted that when designing for circularity, a product should not have an "end of life." Further, many products have multiple functions, so it is difficult to define which "end of life" is the most relevant. Several terms were brainstormed, including:

- Post-consumer fate
- End of intended life
- Post-application use
- Post-intended use
- Post-functional use
- **Post-application fate**.

Participants coalesced around the term "post-application fate" to best describe the fate that should be designed for.

With the new term in hand, the attendees began brainstorming potential problems to solve when designing for the post-application fate of a plastic, their potential solutions, and potential unintended consequences of these solutions.

Problems to solve with plastic design:

- Ensuring that a plastic is designed to be compatible with multiple fates, including recycling, incineration, and environmental leakage
- Addressing the formation of microplastics and their degradation products and understanding their fate and impact
- Addressing the fate of plastics that leak into the environment
- Addressing consumer education and lack of understanding of recycling nuances
- Designing to minimize the overall life-cycle carbon footprint of the plastic, including its transportation costs
- Addressing social issues such as where and how recycling infrastructure is employed
- Ensuring that a new plastic matches or exceeds the performance of existing plastics
- Ensuring that a product is reusable and has multiple applications
- Addressing unique issues of plastics leaking into waterways and oceans and understanding how plastics (existing and novel) degrade in those environments
- Addressing the variability in definitions of biodegradability and coming up with standards and metrics that define how long and under what conditions must a material biodegrade.

Potential solutions:

- Minimizing the number of plastics that we use in order to make recycling or other post-application fates easier to manage
- Designing long-lasting plastic products to incorporate and sequester CO_2
- Introducing chemical bonds or other entities that trigger degradation of a plastic at a defined time
- Introducing chemical linkages that are reversible
- Introducing barcodes or other labels to facilitate sorting at recycling facilities
- Develop technologies for "one-pot recycling"
- Instead of using plastics to address the problem of preventing food spoilage, maybe look at other solutions like improving transportation logistics so that food does not need to be packaged in plastic to avoid spoilage
- Designing for composting and biodegradability to result in products that improve the environment.

Potential unintended consequences:

- Inadvertently changing the ecosystem or biodiversity due to the degradation of biodegradable plastics
- Inadvertently changing the ecosystem or biodiversity due to leakage of novel enzymes or microbes from recycling facilities (if biobased approaches to recycling are embraced)
- Inadvertently decreasing food safety and hygiene when getting rid of single-use plastics
- Inadvertently increasing GHGs associated with making and using new plastics
- Losing functionality/performance when embracing a new plastic that is designed for recyclability or biodegradability.

Conclusions

When designing a new product for its post-application fate, it is imperative to consider possible unintended consequences. Addressing one issue might exacerbate another. Future proposals for new plastic designs should include:

- Life-cycle analyses that addresses the GHG and other emissions associated with the production and use of the proposed plastic
- Risk analyses that address the environmental and societal implications of introducing a new material and a corresponding mitigation plan.

4.6 Redesigning a Recycling System for the Future

The objective of this session was to identify potential challenges and opportunities that would arise as new types of plastics are designed and introduced along with novel recycling technologies. Any biological or hybrid biological and chemical process capable of taking a plastic waste and making a product was considered in the scope of the discussion. Plenary presentations helped to frame the discussion, specifically presentations from Scott Farling of Titus MRF Services, Stacy Katz of Waste Management, and several talks on new plastics and new recycling strategies.

Participants were asked to discuss the following questions:

- What are challenges and opportunities with redesigning plastics and recycling technologies at the same time?
- To what extent is system redesign already being handled by MRFs?
- In an ideal future, are there fewer plastic types to facilitate easier sorting or more plastic types with better matched use cases and recycling strategies?
- What should we optimize for in an ideal recycling stream?

What are challenges and opportunities with redesigning plastics and recycling technologies at the same time?

- **Distinct communities:** Plastic manufacturers are often large multinational corporations, whereas recyclers are more regionally or locally based. Because of this, recyclers respond to the components of waste streams that enable them to be economically viable, and until new plastics are widely enough used for them to be an economic opportunity, participation from MRFs may be challenging. Bringing together these two distinct communities—recyclers and plastic producers—will be a critical step in redesigning plastic recycling.
- **Avoiding silos:** If new plastics are designed without input from MRFs, there is a danger that these new materials, even if they are more easily recyclable using new methods, may create difficulties in current recycling systems. For example, if a new plastic were introduced that current systems could not separate easily from PET, the PET stream could become contaminated and less valuable to many current facilities.

To what extent is system redesign already being handled by MRFs?

- **Business case:** MRFs are currently operating at large scale. Without a supply of and market for new materials, they have very little incentive to create new infrastructure. There was consensus among participants that if DOE supported the applied research to develop and pilot new technologies, MRFs would then be more likely to adopt those technologies versus engaging in R&D and piloting themselves.
- **Secondary MRFs:** Participants noted that potential early adopters might be secondary MRFs that could justify the added expense of new technologies for smaller-volume plastics if they could aggregate them from multiple sources.

In an ideal future are there fewer plastics types to facilitate easier sorting or more plastic types with better matched use cases and recycling strategies?

- **Sorting:** Fewer types of plastics are always easier to handle from an MRF perspective if they can be efficiently separated. There is some potential for introduction of more plastic types if they either do not require additional sorting or if the sorting methodologies are very simple. The biggest opportunity in this space would be to introduce new plastics with compatible recycling strategies that can all be grouped by a primary MRF and then processed elsewhere.
- **Barcodes:** If new plastic types can be barcoded, there may be more potential for simpler implementation into current systems. Participants noted that even if barcoding were successful, there would still need to be demand for the sorted material and space to store additional material types, which may be limiting.

What should we optimize for in an ideal recycling stream?

Participants noted that there are a variety of key factors for optimizing a new system:

- **Maximizing:** economic value, material recovered, flexibility, and reuse
- **Minimizing:** GHG emissions, land use, water use, energy use, and leakage into the environment.

Broadly speaking, participants agreed that economic value must be maximized to make any of the other goals possible, because processes that are not economical will not be implemented by the industry. Second to this was minimizing leakage and maximizing material recovered.

4.7 Flexible Packaging: Challenges and Opportunities

This session was designed in collaboration with Mars Inc. to investigate issues surrounding flexible packaging. The goals of the session were to:

- Identify challenges and opportunities related to collecting flexible packaging
- Identify challenges and opportunities related to recycling flexible packaging
- Identify potential design elements that should be targeted in a redesign of flexible packaging.

As Mars covered in their plenary presentation (Section 3.1.2), flexible packaging made up 40% of the total plastic waste stream by units sold in 2017.[8] While the number of units is fairly large, the actual weight of material is quite low. The low weight of flexibles makes them difficult to collect, and their current composition makes them hard to recycle, resulting in these materials being landfilled or incinerated. Mars has a high interest in improving the recycling of flexible packaging due to the large number of Mars products that require this packaging format. Eric Klingenberg was the co-moderator of this session.

In this session, participants were asked to respond to each of the three main questions above in small groups and then discuss with the full room.

Session Outcome

Collection Challenges: Participants cited the lack of incentive for both recycling facilities and consumers to invest in sorting and collecting flexibles due to the issues pointed out above as major challenges. Because flexibles are designed for single use and are cheap to manufacture, consumers have little incentive to change their use patterns.

Some participants noted that the move of many municipalities towards plastic bag bans and other efforts to limit flexible packaging would impact the economics of collecting flexibles in those areas. Because there is currently a lack of infrastructure for flexible collection, reducing the amount of flexibles that would need to be collected would hurt efforts to establish anything. Flexibles are currently considered a contaminant by most collection facilities.

A number of different sectors use flexibles (participants brought up food and beverage, cosmetics, and cleaning products), which leads to a wide variety of potentially contaminating substances in residues on the plastic waste that facilities would need to deal with.

Collection Opportunities: Most of the feedback that participants had on opportunities for improving collection of flexibles related to improving sorting methods, both through consumer education and improved technologies. If possible, standardizing what different recycling systems will accept in different areas will help in both of these areas. Participants identified better sensors and improvements in mechanical processing as R&D needs for this area. An organized data collection effort that identifies the key properties that recycling facilities should consider when designing their collection systems was also suggested. Many of the suggestions

[8] PlasticsEurope. (2018). *Plastics – the Facts 2018: An analysis of European plastics production, demand and waste data.* Brussels, Belgium: PlasticsEurope. https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf.

related to consumer education would rely on changes to policy, which is not within DOE's mission space. These suggestions will not be covered in detail here.

Some participants also proposed that packaging could be redesigned so that it could be recycled alongside other materials or composted along with food waste. This would eliminate sorting concerns but would require considerable investments in upfront R&D, especially due to restrictions surrounding materials that are used in food packaging.

Recycling Challenges: Several of the challenges related to recycling were similar to the collection challenges that were previously identified. Because flexibles are used for packaging in multiple sectors, they will require considerable front-end processing to remove a variety of contaminants. This adds to an already challenging economic case for recycling these materials. The strict standards surrounding food packaging was again brought up as a major challenge. These standards, in areas such as shelf life and sterility, make it more difficult to design new materials for food packaging. New materials will need to pass through approval processes by the U.S. Food and Drug Administration and other similar international bodies.

Several of the challenges that were identified related specifically to composting systems. Localized factors such as humidity and temperature that impact composting make it difficult to come up with a universal process, which is what participants believe would be desirable for recycling flexibles because they are so widely used.

Recycling Opportunities: Participants thought that concepts such as the barcoding described in Scott Farling's plenary will help to generate more data about what materials consumers are making an effort to recycle. Integrating this concept into flexibles would be desirable. Getting researchers increased access to existing recycling data from recycling facilities in general was also cited as a way to help start addressing some of the more complex challenges identified earlier. Participants felt that current efforts in this area are diffuse and would benefit from a structure that brings multiple parties together.

Participants identified a number of R&D needs for recycling, regarding both the design of new plastics and different recycling technologies. These included catalyst design to target different plastic types in a single stream, designing new packaging that can easily be separated into different components, and redesigning multilayer polymers to achieve the same functionality with a single layer. Identifying new recycling methods that minimize sorting, which is very energy intensive, was also brought up as a priority. Accordingly, better sensors and imaging technologies were also identified as R&D needs in this section.

In the area of composting, participants suggested bioprospecting for naturally occurring organisms that can break down plastics would be important. Similar to other recycling systems, making any current data on composting flexibles available to the research community was also suggested.

Many of the suggestions in this section also related to changes in policy and behavior. For the reasons mentioned above, these will not be covered in detail in this report.

Conclusions

- Flexible packaging is a large opportunity space due to the number of units of packaging, but the known issues related to its diffuse nature and use in a large number of sectors will make developing a recycling strategy difficult.
- Actions that would assist with the collection of flexible packaging include better sorting, imaging, and preprocessing methods that can eliminate a variety of common contaminants.
- Actions that would increase recycling of flexible packaging include an increased access to data from recycling facilities to better understand the problems around flexibles in current systems, new catalysts,

new enzymes that can digest flexibles, and redesigning flexibles to be easier to break down under milder conditions.

- Actions to improve recycling of flexible packaging associated with food include assisting in the development and scale of biological recycling for food waste, designing better materials for food packaging to be comingled with food waste, avoiding sorting requirements, and improving biological recycling technologies.
- Some behavioral and legislative actions would also likely assist with increasing recycling of these materials.
- Development and scaling of alternative recycling options would be enablers for flexible packaging, see sections 4.2 Biological Recycling and 4.3 Chemical recycling of this report.

4.8 Manufacturing Recycled Content: Challenges and Opportunities

The second manufacturing-focused breakout session aimed to better understand what research and development is needed to enable greater use of recycled plastics in the manufacturing sector.

State of Technology

PET is a high-volume plastic with several viable routes to recycle, repurpose, and degrade PET. For example, recycled PET can be used to supplement virgin PET to make new PET containers, or it can be repurposed into other applications such as carpet and clothing fibers. Despite having the best-established supply chains for recycled plastic, and with companies looking for ways to use recycled plastic in their products, barriers still remain to effectivity utilizing all of the potential PET waste resource. These include the quality, contamination levels, and collection of waste streams containing large amounts of PET.

Companies are working on solutions to purify streams of contaminated and mixed plastics to produce products that are suitable for reuse in a variety of applications. Two examples of this type of technology are VolCat[9]—an IBM process that degrades polyester in blended fabrics to intermediates that can be used to manufacture new plastics—and a PureCycle technology that takes waste polypropylene and restores it to a virgin-like state to be used in any application in which virgin polypropylene could be used.[10]

Key Challenges and Considerations

The main challenge facing manufacturers interested in using recycled polymer feedstock is quality. Secondary feedstocks inherently have a broader range of properties, which can complicate manufacturing processes that were designed for specific and often narrow tolerances. Quality, consistency, and safety of recycled streams are critical to enabling their use, particularly in applications related to consumables. To ensure product quality, more analysis of recycled feedstocks is needed. For very sensitive applications, this may include traceability to its source.

Related to quality, a challenge secondary feedstock suppliers have is that specifications are often process-dependent and different for different applications (blown film, casting, etc.), which fragments the market. Low-volume applications that may have lower purity requirements and would allow greater utilization of contaminated plastic resources are difficult for recyclers to identify and so are underutilized. In addition, producers may not be willing to share specifications broadly, making it difficult for recyclers to know what potentially valuable streams they ignored. These types of considerations can often prohibit use in certain applications with nonstandard requirements. One example shared was from a toy manufacturer that needs to consider that toys are sometimes chewed, resulting in toxicity requirements similar to food products. In

[9] IBM. (2020). "Plastic Surgery: A radical new recycling process will breathe new life into old plastic." https://www.research.ibm.com/5-in-5/trash/.
[10] PureCycle Technologies. (2019). "PureCycle Technologies Celebrates Successful Run of Groundbreaking Plastics Recycling Technology." *PureCycle Technologies News*, September 25, 2019. https://purecycletech.com/2019/09/successful-run-of-feedstock-evaluation-unit/.

general, there is a lack of basic understanding of how common contaminants impact properties and limit application in final products and how sorting and cleaning can impact those contaminants.

Another challenge is that manufacturers that want to incorporate additional recycled feeds into their products often find that switching to recycled feedstocks requires retooling due to property changes. Retooling can be expensive, and the added cost may be unjustified.

Finally, the life-cycle impacts of using secondary feedstocks must be considered. The incentive to use recycled feeds cannot only be diverting waste. Companies also want to ensure there is a carbon and energy life-cycle benefit. The more "touches," including collection, sorting, and purification needed to deliver a suitable product, the more diminished the carbon and energy life-cycle benefits become.

Research Opportunities and Recommendations

There are several potential solutions to address product quality concerns. The optimal solution will be tailored to the process and product. From a manufacturing point of view, there are some applications where a broader product quality distribution is actually valued, but this depends on the end use. Designing equipment to accept broader tolerances in material properties could be a good value proposition for many companies and not only for the use of secondary feedstocks. The extent to which low-value streams could be aggregated or not separated in the first place to generate a higher-volume stream should be considered.

There were several recommendations to better understand contamination and how contamination impacts product quality and performance. In general, better analysis of secondary feedstocks and their contamination is needed. Making composite recycled materials with virgin feeds requires understanding the compatibility with secondary feedstocks, which could build off fundamental analytical work. A taxonomy of secondary feedstock properties should be created to match with potential applications. It could be that secondary materials are perfect "primary feedstocks" in other applications, such a park benches and decking materials. Similarly, there is not currently a market for oligomers/vitrimers even though a lot of current research is exploring how to decompose these materials. Research should be conducted to understand what the market size could be before identifying it as a promising solution.

Much of the separation into small, higher-quality waste streams occurs in secondary MRFs. Technology that would enable secondary MRFs to be more effective, including modeling tools, would be impactful due to the complexity of the streams they are handling. Basic science development in separation of materials and decomposition are also needed. International collaboration may be particularly useful due to Europe's earlier focus in this area. In all of this research, limiting unit operations ("touches") should be a focus to reach a pure/clean stream in an energy and cost-efficient way.

Inks, dyes, and compatibilizers were highlighted as key contaminants in most secondary polymer feeds. Interestingly, they also have high value, so extracting and recycling them could be economically viable. Inks often contain metals, which impart potential toxicity in products, so their removal is critical to reuse in certain applications. Research in this area is needed to easily separate and isolate these materials from polymers.

Use of additive manufacturing to increase use of secondary feeds was an area of interest the breakout groups were asked to consider. To address the added cost of retooling, additive manufacturing may be a low-cost solution, particularly for prototyping the change. Beyond that, the groups saw little benefit to additive manufacturing for this application because:

- The size of the market for additively manufactured goods relative to the amount of plastic waste is small
- The narrow window of materials that are able to be used in additive manufacturing further reduces the potential impact on plastic waste and increases the technical complexity

- Diversion of waste to additive manufacturing could compete for other dispositions, potentially lowering the value proposition for both due to the impact of volume on economics.

For additive manufacturing to play a larger role in utilizing secondary feedstocks, initial applications should be focused on creating a closed-loop system in which polymers designed for additive manufacturing are recycled back into additive applications. The distributed nature of additive manufacturing could be a potential opportunity. If it could be co-located at MRFs, for example, that could drive a value proposition. Overall, the life-cycle analysis impact seems low, but analysis should be conducted to understand what opportunities exist.

5 Conclusions

The Plastics for a Circular Economy Workshop brought together stakeholders from industry, academia, and National Laboratories to discuss opportunities and challenges facing the development of new technologies to address plastic waste as part of the Plastics Innovation Challenge. The workshop featured several robust breakout sessions where participants brainstormed challenges and solutions to a variety of topics. While numerous specific technical challenges and potential solutions were outlined in the previous sections, there were several overarching themes and future directions identified. Future research needs include:

- Innovative deconstruction methods:
  - New methods for deconstructing existing plastic waste, which are essential for ensuring that plastics collected for recycling can be transformed into products of higher value
  - Robust processes that can tolerate high degrees of contamination often found in collected or post-consumer materials.
- New materials and upcycling strategies:
  - New plastics that are recyclable by design, which will maximize the economic value of waste plastics streams, incentivizing their closed-loop collection
  - Biodegradable solutions for thin, flexible plastic packaging that do not compromise food safety and longevity, including improved oxygen and moisture barrier properties
  - New recycling and design solutions for flexible plastic packaging, including multilayer materials, which are currently not recyclable
  - New strategies for upcycling, which are essential for converting waste plastic into valuable new materials, enhancing the value of plastic wastes.
- Improved assessment and modeling frameworks:
  - Development of specifications for mixed recycled waste so that processors can balance feedstock loads similar to oil refineries
  - Frameworks for assessing energy and environmental impacts of plastics during their manufacture and disposal.
  - Better standards for composting and biodegradability, providing access to researchers to conduct extensive degradation studies under standardized conditions
  - Predictive environmental and toxicity modeling, which is necessary for informing new plastic recycling solutions, including plastics that can degrade in the environment or compost facilities.

DOE would like to thank workshop participants for their time and input on this topic. DOE will consider workshop feedback when developing programmatic plans in support of the Plastics Innovation Challenge.

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Appendix B: Agenda

Day 1

Time	Topic	Speaker
8:00	Registration	
9:00	Welcome and Introduction	Nichole Fitzgerald, DOE BETO
9:10	Connecting the Dots: The Intersection of Plastics, Energy and Planetary Health	Mike Biddle, Evok Innovations
9:50	Monomers and Polymers derived from Biological Sources: Opportunities and Challenges	Matt Terwillegar, Danimer Scientific
10:10	Agriculturally derived polymers and composites targeted toward a circular economy	Bill Orts, USDA ARS
10:30	Break	
10:45	PureCycle Technologies Overview – Recycled Resins with Virgin-like Properties	Amy Waun, Procter & Gamble
11:05	Carbios, the first and only company to have developed biological processes based on enzymes to breakdown plastic wastes into monomers	Frederique Guillamot, Carbios
11:25	Introduction to the BOTTLE Consortium	Gregg Beckham, National Renewable Energy Lab
11:45	5x5 Lightning Talks	Bob Allen, IBM Brett Helms, Lawrence Berkeley National Lab Shannon Pinc, NatureWorks
12:00	Lunch	
1:00	Recycling: A Collector & Processor's Perspective	Stacy Katz, Waste Management
1:20	Assessing the Biodegradation and Compostability of Plastics	Jason Locklin, University of Georgia
1:40	Technology and Business Model Approaches for Maximizing Material Recovery	Scott Farling, Titus MRF Services
2:00	5x5 Lightning Talks	Alberta Carpenter, National Renewable Energy Lab VeeAnder Mealing, Colorado School of Mines Carson Meredith, Georgia Tech Justin Siegel, UC Davis Aaron Sadow, Ames National Laboratory John Dorgan, Michigan State University
2:30	Break	

3:00	Breakout discussions: Session 1a: Introducing New Plastics: Challenges and Opportunities *(Keystone)* Session 1b: Biological Recycling: Challenges and Opportunities *(Golden Ballroom Salons F-G)* Session 1c: Chemical Recycling: Challenges and Opportunities *(Telluride)* Session 1d: Composite Recycling: Challenges and Opportunities *(Aspen/Snowmass)*	Moderator: Nichole Fitzgerald, DOE BETO Jay Fitzgerald, DOE BETO Andrea Bailey, DOE BETO Melissa Klembara and Kate Peretti, DOE AMO
4:30	Report outs from each breakout room	
4:50	Day 1 Wrap-up	Melissa Klembara, DOE AMO

Day 2

Time	Topic	Speaker
8:00	Registration	
8:30	Day 2 Introduction: The future of plastics recycling: new technologies for plastics designed with end-of-life in mind	Jay Fitzgerald, DOE BETO
8:40	Rethinking Packaging for Circularity – A Mars, Inc. Perspective and Workshop Motivation	Eric Klingenberg, MARS Advanced Research Institute
9:00	Science to shape a bio-benign future	Cristina Negri, Argonne National Lab
9:20	A Plastic Producer's Approach to The Circular Economy	Jill Martin, Dow
9:40	Break	
10:00	Breakout discussions: Session 2a: End of Life and Unintended Consequences *(Keystone)* Session 2b: Re-designing a Recycling System for the Future *(Golden Ballroom Salons F-G)* Session 2c: Flexible Packaging: Challenges and Opportunities *(Telluride)* Session 2d: Manufacturing recycled content: Challenges and Opportunities *(Aspen/Snowmass)*	Moderator: Nichole Fitzgerald, DOE BETO Jay Fitzgerald, DOE BETO Andrea Bailey, DOE BETO Melissa Klembara and Kate Peretti, DOE AMO
11:30	Report outs from each breakout room	
12:00	Workshop Wrap-up	Kate Peretti, DOE AMO

Appendix C: Breakout Session Questions

Breakout Questions:

1a. Introducing New Plastics:

- Do you agree with the premise that introducing new end-of-life plastics could reduce plastic waste? Why or why not?
- What new plastics or end-of-life properties should be introduced to address waste plastic accumulation issues?
- What are the technology solutions/R&D needs associated with developing these new plastics?
- What are the biggest challenges associated with introducing new plastic materials to existing systems?

Additional Questions:

- Can new plastics be effectively introduced without disruption to existing systems? Are there processes that need to be developed for better collection and separation?
- What are the key performance hurdles for compostable, flexible plastic packaging?
- Are there analysis tools that would speed up deployment?
- In an ideal system, are there fewer types of plastics or more with better-matched uses?
- What manufacturing challenges exist for incorporating new polymeric materials into existing applications?

1b. Biological Recycling:

- Are there opportunities for biology to contribute to the problem of plastic waste beyond biological recycling using selective chemistry, composting, and anaerobic digestion?
- What are the R&D needs for biological recycling using selective chemistry, composting, and anaerobic digestion?
- What are the challenges with adding new biological recycling strategies to the current recycling system and to future systems?
- What are the top challenges identified with biological recycling?
- What are potential technology solutions and R&D needs to address the top challenges?

1c. Chemical Recycling:

- What chemical recycling technologies are currently available?
- Should use of these technologies be increased?
- Can they be integrated into the current recycling infrastructure or do systemwide changes need to be made?
- Can they work with existing plastics, or would they rely on the design of new plastics?

- Should chemical recycling become more prevalent? What are the drawbacks?
- Advantages of novel chemical recycling techniques over current state of the art?

1d. Composite Recycling:

- Do you agree with the premise that introducing new materials such as thermoplastic resins could reduce composites waste? Why or why not?
- What new materials or end of life properties are needed to address composites waste?
- What are the technology solutions/R&D needs associated with developing new composites and/or recycling strategies?
- What can be done to incentivize recovery, recycling, and reuse of composites (in the absence of new prescriptive regulations)?

2a. End-of-Life Considerations:

- What is the ideal fate of plastic waste?
- How can we ensure that we are making good decisions when we are designing for the future?
- What problems are we trying to solve when we "design for end of life?"
- What are possible solutions when designing plastics and applications for end of life?
- When are there instances of solutions not being well suited for a problem?

Additional Questions:

- Should recycling strategies for durable applications vs. consumable applications be considered differently?
- In an ideal system, are there fewer types of plastics or more with better-matched uses?
- Is biodegradability really a solution for leakage into the environment?
- Are there unintended consequences with biodegradability?
- Are there toxicity (health and environmental) concerns of degraded products that should be considered in the design of novel biodegradable polymers?
- Will additive technologies that degrade traditional plastics lead to unintended consequences?
- Is upcycling or downcycling enough, or do we need to strive for circularity?
- What are the lessons learned from Europe?

2b. Redesigning a Recycling System for the Future:

- What are challenges and opportunities with redesigning plastics and recycling technologies at the same time?
- To what extent is system redesign already being handled by MRFs?

- In an ideal future, are there fewer plastics types to facilitate easier sorting or more plastic types with better-matched use cases and recycling strategies?
- What should we optimize for in an ideal recycling stream?

2c. Flexible Packaging:

- What are the challenges with collecting flexible packaging waste? What are the opportunities?
    - Is there segregation that is needed in package types that would help collection, sorting, and the best recycle stream?
    - If the output of any reprocessing stream is weight-based, is there enough weight/volume in flexible packaging for mechanical, chemical, or other recycling processes to be economically viable without subsidies?
- What are the challenges with recycling flexible packaging waste? What are the opportunities?
    - Is there one specific recycling technology that shows the most promise for flexible packaging?
    - Can mechanical recycling processors afford artificial intelligence and robotic sorting of flexibles?
    - Are there analysis tools that would speed up deployment?
- Should flexible packaging be redesigned? What design elements are critical?
    - Can new plastics be effectively introduced without disruption to existing systems?
    - What are the top R&D needs for redesigned flexible packaging?

2d. Manufacturing Approaches for Recycled and Upcycled Streams:

- What are the key manufacturing challenges posed by using recycled/upcycled feedstocks?
- What are the technology solutions/R&D needs associated with addressing the top challenges?
- What opportunities do additive manufacturing technologies bring to the table?
- What are the research challenges for additive manufacturing of plastics (existing and new)?
- Will additive technologies that degrade traditional plastics lead to unintended consequences? Is there any evidence?

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