Chemical Recycling
Making Fiber-to-Fiber Recycling a Reality for Polyester Textiles
GreenBlue is a non-profit organization dedicated to the sustainable use of materials in society. Our mission is to foster the creation of a resilient system of commerce based on the principles of sustainable materials management (“SMM”). GreenBlue’s sustainable materials framework is anchored by three core principles:

**Material Sourcing**
Understand the origins of the materials being used to manufacture products. Identify and reduce any social or environmental impacts associated with extraction or agricultural cultivation of raw materials.

**Material Health**
Examine the “quality” of materials flowing through the materials economy or an individual company’s production system. Develop strategies to ensure that all inputs and outputs are as safe for humans and the environment as possible.

**Material Value**
Design products and systems to retain the embedded value of materials after each service life is completed so they can become feedstocks for future products. There are “levers” that create disruptive, positive changes or that can influence the direction and effectiveness of the material economy such as technology enablers, policy mandates and the creation of new financial and business models. Intelligent application of these levers can be used to create new opportunities or conversely may impose constraints on our capacity to build an effective and efficient circular economy. Some examples of effective levers are policy, such as feed-in tariffs for renewable energy or carbon taxes; technology, such as exponential increases in conversion efficiency of solar panels, data storage capacity or miniaturization of electrical circuitry; financing, such as micro lending, social profit investing, public-private partnerships; and new business models, such as legalization of benefit corporations, the sharing economy, and products as a service.

Occasionally, a new technology or a variation of an existing technology will emerge that fundamentally changes the economics of some aspect of production for a given industry sector. Recent innovations in chemical recycling processes for polyethylene terephthalate (PET) are a good example of how technology can be a lever that alters the cost/benefit equation for the reutilization of a commercially very significant material.

## PET – A Key Material in the Global Economy

PET makes up about 18% of world polymer production and is the third-most-produced polymer, after polyethylene (PE) and polypropylene (PP). The two primary uses for PET resin are for fiber to make polyester textiles and for solid-state applications such as bottles, containers, films and engineering-grade polymers. The approximate split between these major classes is 65%-70% fiber and 30%-35% solid-state resins. PET fiber represents about 55% of all textile fibers produced.¹

Global virgin PET production for 2015 was 72 million tons, of which 48 million tons was

¹ Interview, Chad Bolick, Unifi
amorphous PET used for fiber applications, 20 million tons was solid-state PET used for packaging applications, and 4 million tons was used for film. Note that additional post-consumer recycled inputs contribute to the total production of PET fibers and bottles.

Quality and Quantity - Both Important For Stable Recycling Markets

Creating stable recycling markets depends on the quality and quantity of material inputs and outputs available. Both are interdependent and achieving a balance between them is necessary to create a resilient marketplace capable of tolerating temporary disruptions to either variable. The quality of material inputs depends on the physical properties of feedstock materials, and is a major determinant of their cost. The quality of recycled outputs is measured by the ability of the recycled materials to meet the performance requirements of end products that use them. The quantity of inputs available also influences feedstock costs to recyclers as well as the scale, efficiency and profitability of their operations, and is governed by market demand for outputs.

An expression of the relationship between quality and quantity as it relates to healthy end markets might be:

\[
\text{Quality of Inputs} \times \text{Recycling Process} = \text{Quality of Recycled Outputs}
\]

There are qualitative differences between different grades of PET polymers based on their molecular weight or intrinsic viscosity (IV), optical appearance and common additive profiles. The intrinsic viscosity of a polymer reflects the material’s melting point, crystallinity and tensile strength. Differences in the physical properties of polymers have important implications for recycling PET and often are the primary determinant for matching feedstock materials with the performance requirements of the end products they are used to make. The intended application of the polymer dictates the IV required. The higher the specification for tensile strength, burst, impact or temperature, the higher the IV required. More crystalline forms of PET such as bottle resin have a higher IV than amorphous forms of PET used for non-specialty or lower performance resins, such as fiber.²

IV Values of Selected PET Polymer Grades

There are four major classifications of recycling – primary, secondary, tertiary and quaternary. The quality or physical properties of feedstocks is less critical the further out one goes on this recycling continuum. The degree of material transformation also increases as do the end application options for the recycled materials.

Mechanical Recycling of PET

Mechanical recycling typically includes sorting, separation and removal of non-target materials or contaminants; reduction of size by crushing, grinding or shredding, or pulling fabric fibers apart for textiles; and then re-melting and extrusion into resin pellets. All thermoplastics, including PET, can be remelted to produce new plastics. As easy as that may sound, there are many challenges to mechanically recycling plastics into high quality materials capable of meeting the performance and cost expectations of higher value end products. One of the reasons that recovered PET is often downcycled to lower value uses is because it is difficult and costly to recycle materials with lower intrinsic viscosity (IV) into applications that require higher IV values. So,


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### Intrinsic Viscosity of PET Grades

<table>
<thead>
<tr>
<th>Application</th>
<th>IV Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fiber Grade</strong></td>
<td></td>
</tr>
<tr>
<td>Textiles</td>
<td>0.40-0.70</td>
</tr>
<tr>
<td>Technical</td>
<td>0.72-0.98</td>
</tr>
<tr>
<td><strong>Bottle Grade</strong></td>
<td></td>
</tr>
<tr>
<td>Water bottles</td>
<td>0.70-0.78</td>
</tr>
<tr>
<td>Carbonated soft drink grade</td>
<td>0.78-0.85</td>
</tr>
<tr>
<td><strong>Film Grade</strong></td>
<td></td>
</tr>
<tr>
<td>Biaxially oriented PET film</td>
<td>0.60-0.70</td>
</tr>
<tr>
<td>Thermoforming sheet</td>
<td>0.70-1.00</td>
</tr>
<tr>
<td><strong>Engineering Grade</strong></td>
<td></td>
</tr>
<tr>
<td>Monofilament</td>
<td>1.00-2.00</td>
</tr>
</tbody>
</table>

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### Four Classifications of Recycling:

- **Primary Recycling**
  Pre-consumer scrap materials where manufacturers recycle materials back into their own production processes

- **Secondary Recycling**
  "Mechanical" recycling via physical processing such as grinding, melting, and reforming.

- **Tertiary Recycling**
  "Chemical" recycling where polymeric bonds are broken to create monomers, oligomers, or other intermediates.

- **Quaternary Recycling**
  Recycling where the energy or fuel value of plastic waste is recovered via incineration or pyrolysis.
for example, post-consumer PET bottles are often recycled into fibers, but fibers are not recycled into bottles.

The more complex a material’s composition, the harder it is to mechanically recycle it back into materials of equal or higher value than the original material. A good illustration of complexity is PET bottles versus PET textiles. The majority of bottles come in two primary colors, clear and green. In addition to the catalyst used to make the polymer, there may be a small number of additional additives used to alter material properties. Common contaminants for bottle and container recycling include opaque colors, barrier layers for added performance, metal closures, rings, pump springs, PVC shrink sleeves, and adhesives used on paper labels.

Textiles, on the other hand, are vastly more complex in their construction and coloration. Most textiles are a blend of fiber types (e.g., PET/cotton or PET/elastane), contain multiple dyestuffs and may also have additional polymers and chemicals used as backings or as surface treatments. Unlike PET bottles and other containers, post-consumer textiles come in many forms to serve many applications – clothing, shoes, carpet, residential and office furniture, and automobile interiors to name but a few.

Mechanical recycling of pre-consumer PET textiles wastes for less demanding applications (what some call “downcycling”) happens quite frequently. Typical end uses are for “stuffing” or “filler” materials or nonwoven materials for furniture, mattresses, carpet pads, home or auto insulation, sound-deadening barriers and sediment erosion control to name a few. Certain pre-consumer wastes such as unused or damaged white (“greige”) fiber and yarns are routinely folded back into primary production. However, due to the degradation of polymers and contamination that occurs over multiple use cycles, mechanical recycling eventually degrades the value of the PET and often prevents it from recirculating into higher value applications such as fiber-to-fiber recycling.

**Chemical Recycling of PET**

In chemical recycling, the PET...
polymer is typically broken down to create monomers, oligomers, or other intermediates. The most common methods for chemical recycling of PET include glycolysis, methanolysis, hydrolysis and ammonolysis. Depending on which process and depolymerization agents are used, chemical recycling produces various end products. The most common end products are PET's monomers, purified terephthalic acid (PTA) and ethylene glycol (EG), the necessary building blocks to make new, virgin quality PET resin. But chemical recycling is also used to separate PET from other materials and to remove colorants without actually depolymerizing it back to its monomers, or to create other end products that retain the material value of the polymer. For example, glycolysis will yield a mixture of polyols useful for the manufacture of polymers with properties quite distinct from PET, such as unsaturated polyesters, polyurethanes and poly-isocyanurates.

Occasionally, the term “chemical recycling” is used to refer to processes that convert polymeric materials into fuels or syngas. The term may also be used to refer to incineration of polymeric materials for their energy value. GreenBlue is using the term to describe a process that recovers the material value of polymers (in the form of monomers, oligomers or chemical intermediates to make other types of polymers) as opposed to harvesting PET’s energy value through the production of syngas, fuel or heat. Technologies for chemically recycling PET have been in existence for quite some time. However, these technologies have not become part of the mainstream of recycling due to several factors:

- Costs to build and operate chemical recycling facilities have traditionally been more capital and energy-intensive than mechanical recycling facilities.
- Historically, plants have been designed as large-scale operations, requiring significant volumes of feedstock materials to be profitable.
- There has been a persistent lack of infrastructure to collect feedstocks other than PET packaging (primarily bottles and containers) collected through materials recovery facilities (“MRFs”). There is not a similar collection infrastructure for PET textiles or other PET waste streams.
- Few regulations or government policies provide market incentives to collect and recycle PET textile waste and other PET materials.
- Low prices for gas and crude make it hard for recycled monomers or other outputs to compete with virgin sources. Weak or low-value end markets have been a barrier to entry for more expensive technologies.

For many in the textile community, the ideal recycling system is one where reclaimed textiles are converted back into virgin quality yarns to make new textiles, also often referred to as “fiber-to-fiber” recycling. Chemical recycling is the only technology that can truly achieve this vision because it is able to remove all unwanted constituents – non-PET fibers, colorants,

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catalysts, surface treatments, backing materials, and other auxiliary chemicals used in textile production.

Chemical recycling can also address one of the challenges of mechanical recycling: meeting higher IV requirements of certain applications. It hits the "reset" button to start the cycle over, producing virgin quality recycled resins that can be solid-stated to meet the IV necessary for any specific end application.

Another benefit of chemical recycling is that it is agnostic about the form or function the polymer serves. It does not matter if the polymer is in the form of a bottle, fleece jacket, compounding scrap, or an auto part. The process even allows for very high rates of contamination without negatively impacting the quality of the end product. However, the higher the contamination, the greater its impact on profitability and the number and types of by-products produced.

Results from our study indicate that the purity level required for economic feasibility is 70% to 80% PET content by weight for the technologies we evaluated. Chemical recycling also allows for "upcycling" PET materials whose physical quality is so degraded or contaminated that mechanical recyclers are reluctant to process them, successfully diverting these materials from landfills.

**Selected PET Chemical Recycling Technologies**

GreenBlue selected five chemical recycling technologies to feature in this report because they illustrate different types of chemical recycling processes and different end products that can be produced. These technologies are at different stages of development, but all are beyond bench scale engineering. A few are scaling from pilot to demonstration plants, while others are entering into the early phases of commercialization. GreenBlue attempted to understand how these technologies were substantially different than many of the PET depolymerization technologies that preceded them. Based on responses of interviewees, the chief differences seem to be:

1. Facilities are designed to operate at smaller scales within smaller footprints, presumably requiring less capital to build and operate and potentially allowing them to be located closer to available feedstocks.
2. Most of the companies also claimed that their technologies require less energy to operate than previously designed facilities. All of them have also conducted life cycle analyses (LCA) on their processes to demonstrate that they have a lower carbon footprint than manufacturing PET resin from virgin feedstocks.
3. Worn Wear and Resinate Materials Group are not fully depolymerizing PET into monomers, possibly affording them even greater energy savings that can be applied to lower operating costs or lower priced products.

The following technologies are included in this report:

- **CARBIOS - "Using Enzymes to 'Biorecycle' PET"**. A process for using enzymes to depolymerize PET into its monomers.
- **Gr3n - "A New Approach to PET Chemical Recycling"**. Using microwave radiation to accelerate the depolymerization of PET.
- **Loop Industries - "Recycling PET Waste into High-Quality Resin"**. PET depolymerization to create branded recycled resins instead of monomers.
- **Resinate Materials Group - "Turning PET Waste into High Performance Polyester Polyols"**. Using glycolysis to digest PET into oligomers to manufacture high performance polyols.
- **Worn Again - "A Solution for PET/Cotton Blended Fabrics"**. A dissolution process to separate and recycle fibers from cellulosic and polyester blended fabrics.

**Markets for Recycled PET**

While the collection infrastructure and end markets are not well organized and for the most part still nascent for PET textiles, the market for PET rigid containers is much more mature. Observing this fact, most of the chemical recycling companies covered in this report are assuming that a significant portion of their feedstock will come from PET container bales and/or recycled PET (rPET) flake. Rigid PET bale prices set a benchmark price to which chemical recyclers will compare.
the costs of acquiring PET textile feedstock. In the U.S., there has been a steady decline in rigid PET bale prices since a high in 2011 of $0.38/lb (East Coast). By late 2015, prices had dropped to under $0.10/lb. Realizing that global production of PET fiber resin is much larger than container resin, chemical recyclers are already forecasting PET textile feedstock as part of their acquisition strategy and planning. Approximate price parity with rigid PET feedstocks will help to unlock the potential of this mostly unexploited source of PET. Interestingly, market prices for container bales are roughly aligned with those of pre-consumer PET textile waste according the survey data Green-Blue obtained. Across all industry sectors evaluated, the sales price for pre-consumer PET textile waste ranged from a low of $0.02/lb to a high of $0.16/lb. It is unclear if these prices are what collectors or brokers pay or if they are paid directly by recyclers. Also, several producers of textile goods reported paying to dispose of textile waste if they were unable to find recyclers who would pick up free of charge.

Open- and Closed-Loop Recycling of PET Textile Waste

The terms “open-“ and “closed-“ loop recycling are frequently used to describe two different types of recycling in the circular economy. Their definition can vary, but most often they are used to describe the quality of end products made from recycled materials. Open-loop recycling presumes that materials will be cascaded to lower value uses due to degradation in quality, whereas closed-loop recycling presumes to keep materials flowing within the same product value chain (e.g., bottle-to-bottle, fiber-to-fiber). However, in reality materials (virgin or recycled) flow to where there is greatest demand and economic value. An open-loop model offers the best chance for building a scalable, efficient and sustainable infrastructure for recycling textiles (or any other material). Ideally, the entire materials economy would flow in an open loop where all materials have economic value defined by the end markets creating demand for their use. Two things are necessary to make an open-loop system more efficient and effective: 1) “reprogramming” cultural norms to see all materials as inherently valuable, leading to a societal commitment to build the infrastructure necessary to maximize the value of all materials flowing through the economy, and 2) enabling materials to cascade “down” or “up” within an open system to uses that best fit their physical properties with the least amount of processing, making downcycling and upcycling irrelevant concepts. Innovations in recycling technologies can help move materials up or down the quality ladder to more efficiently respond to market demand.

Closed-loop recycling (i.e., materials being recycled back into the original products they served) is largely a reaction to a poorly designed open system. Most examples of successful closed-loop recycling happen because one or more manufacturers make a concerted effort to intervene in existing markets or to create

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their own markets for securing recycled materials for use in future products (e.g., “products as a service”). These product manufacturers are relying on closed-loop recycling as an interim strategy, a necessary stepping stone towards building a more efficient open-loop system that allows them to exert more influence over keeping these materials flowing within their own supply chains.

The use of recycled PET bottle flake to make PET yarns is a good example of successful open-loop recycling. PET yarn producers have long been using recycled PET bottle flake to create recycled yarns. According to a joint report by the National Association for PET Container Resources (NAPCOR) and the Association of Plastic Recyclers (APR), approximately 38% of rPET stream is consumed by the PET fiber industry for recycled yarn production.\footnote{“Post-consumer PET Container Recycling Activity in 2015.” NAPCOR and APR, October 13, 2016. https://napcor.com/wp-content/uploads/2017/02/NAPCOR_2015RateReportFINAL.pdf.}

Clearly, the textile industry provides a reliable market for rPET but unfortunately, this open loop is not reciprocal. The combination of low prices for virgin PET resin and excess capacity in global PET resin production provide little economic incentive for mechanical recyclers to invest further in upgrading the resin to meet higher IV specifications that would allow rPET from textile waste to be used for PET rigid containers or engineering-grade resins or even back into yarn production. Therefore, these materials logically cascade “down” into end markets where required physical properties are less stringent.

However, often a consequence of materials flowing into other value chains is that the materials keep cascading to lower levels of quality until they are considered valueless and are landfilled or incinerated with or without energy recovery. Another consequence is that once these materials are “re-routed” into non-adjacent value chains, they become highly dispersed, making collection for future cycles of recycling potentially cost prohibitive and unlikely. Chemical recycling has the potential to hit the “reset” button, moving degraded or lower molecular weight materials back up the quality ladder, allowing them to flow within the same value chain from which they came or to other end markets if demand is greater.

**“PET Wastesheds” - Creating More Stable Markets for PET Textile Recycling**

If chemical recycling is to be used as a mechanism to keep used textiles in the material economy, a key question to be answered is what fraction of the textile waste stream is capable of meeting the 70% to 80% PET purity required by the chemical recycling technologies covered in this study. Across all textile sectors, pre-consumer sources have a greater chance of achieving cost effective, high quality recycling in an open system than is currently possible for post-consumer sources. They are easier to sort by predominant fiber type at the point of generation, ensuring a level of purity sufficient to meet quality specifications of end users. The economics of collection to aggregate sufficient quantities of material are also much more favorable than for post-consumer sources. However, pre-consumer textile feedstocks may not be enough to achieve economies of scale that typically characterize stable markets. Therefore, the ability of chemical recyclers to aggregate PET waste materials from a variety of sectors will be
critical for them to obtain the volume of feedstocks necessary to sustain their businesses. For example, PET waste streams that are difficult for mechanical recyclers to process such as off-spec resin, “fines” (very small pieces of processed PET that are often contaminated with dirt or other contaminants), white colored or opaque bottles, crystalized black food-grade trays, blister packs and thermoforms (e.g., clamshells, cups, tubs, lids, boxes, trays, egg cartons) could find higher value end markets through chemical recycling.

Analogous to the concept of a watershed where water flows to a common basin determined by its regional topography, PET recycling markets can be organized as “wastesheds” where recyclers can aggregate multiple forms of PET feedstocks available within a given region. Such an approach reduces the transport of material and could significantly improve the economics of recycling PET. With this idea in mind, GreenBlue combined locations of selected textile waste generators in the eastern U.S. with locations of MRFs for rigid containers to observe what potential there is to aggregate PET materials across different sectors within that region. Chemical recyclers might also find other types of PET materials not represented in this map but flowing in quantities sufficient to collect and process economically, such as scrap X-ray film, flexible films, straps, converter scrap, mattress ticking and batting, retail window display fabrics, etc.

### Polymer Textile Sector Profiles
In 2016, GreenBlue contacted Loop Industries to inquire whether their process could successfully depolymerize PET textile waste. The company had not previously run any trials on textile materials, so GreenBlue sent some weaving fabric waste to Loop to process. The first trials were performed on post-industrial fabric scrap from contract textile mills. These materials traditionally have 80%+ PET fiber content, making them excellent feedstock for most chemical recycling processes. The fabric waste depolymerized very efficiently and increased Loop’s interest in waste textiles as a possible feedstock. GreenBlue sent some weaving fabric waste to Loop to process. The first trials were performed on post-industrial fabric scrap from contract textile mills. These materials traditionally have 80%+ PET fiber content, making them excellent feedstock for most chemical recycling processes. The fabric waste depolymerized very efficiently and increased Loop’s interest in waste textiles as possible feedstock. GreenBlue conducted two more trials – one for carpet and one for post-consumer garments. Trials done on post-consumer apparel and outdoor sporting goods were a mix of different fiber types and materials. Results for these materials were not considered economically viable due to a low ratio of PET to other material types. Conclusions from the depolymerization trials were that 1) PET textile waste is a viable feedstock for Loop’s process and 2) a minimum content of 80% PET is required to make recycling textiles economically profitable for Loop.

After confirming that chemical recycling of PET textile waste is technically feasible using Loop Industries’ system, GreenBlue set out to answer the following questions:

- How much PET textile waste is being generated by industry sectors where PET is a primary fiber?
- Where are sources of pre-consumer waste located relative to Loop’s two plants scheduled for construction in the U.S. and Europe?
- Where are these sources of textile waste currently going – recyclers, incineration,
landfill?
• What are the most common end markets utilizing recycled textile wastes?
• What is the average revenue earned from the sale of these materials?
• What other design or technology innovations support more effective recycling of PET textile materials?

GreenBlue focused on the following industry sectors to collect representative data to attempt to answer some of these research questions:
• Apparel manufacturing
• Contract textile mills
• Carpet manufacturing
• Contract office furniture manufacturing

Primary methods of data collection were phone and email interviews and survey responses. Data collection for all of these sectors was limited mostly to U.S. manufacturing locations. Apparel was the exception; we combined data from a small group of brands with suppliers located in the U.S., the U.K., Turkey, China, Thailand, Sri Lanka, the Philippines, Vietnam, and Korea. GreenBlue also attempted to obtain aggregated data from the Sustainable Apparel Coalition (SAC), which had just recently completed an update from suppliers reporting data into the Higg Index Facilities Module. However, the SAC reported that the data currently does not differentiate waste by fiber type, though the SAC expects to obtain fiber-specific waste information in future revisions of the Facilities Module.

Our goal was to collect representative data to illustrate the potential for chemical recyclers to use PET textile waste as a commercially significant feedstock for their business, rather than to conduct a study based on comprehensive, statistically valid sampling methods. A more robust quantification of PET textile feedstock would be a valuable contribution to building a more efficient recycling infrastructure. We hope this study will provide some useful guidance for those efforts.

Although this study did not include a full inventory of potential PET textile feedstocks, we identified over 20 million pounds of pre-consumer PET textile scrap generated per year by the companies in these sectors that supplied data. This suggests that the total volume of PET textile scrap potentially available for recycling is likely much larger. Though textile scrap is generated globally, certain sectors are concentrated in particular geographical regions. For example, carpet manufacturing in the U.S. is concentrated in the Southeast, particularly Georgia, while much apparel manufacturing takes place in Asia. The responses to our survey confirmed that much of the PET textile scraps generated, when they are recycled, are sold at a relatively low cost to recyclers that use them for lower-value purposes, such as nonwoven materials (e.g., carpet padding, insulation). Chemical recycling has the potential to convert a significant fraction of this textile waste into yarns to produce new woven textiles.
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