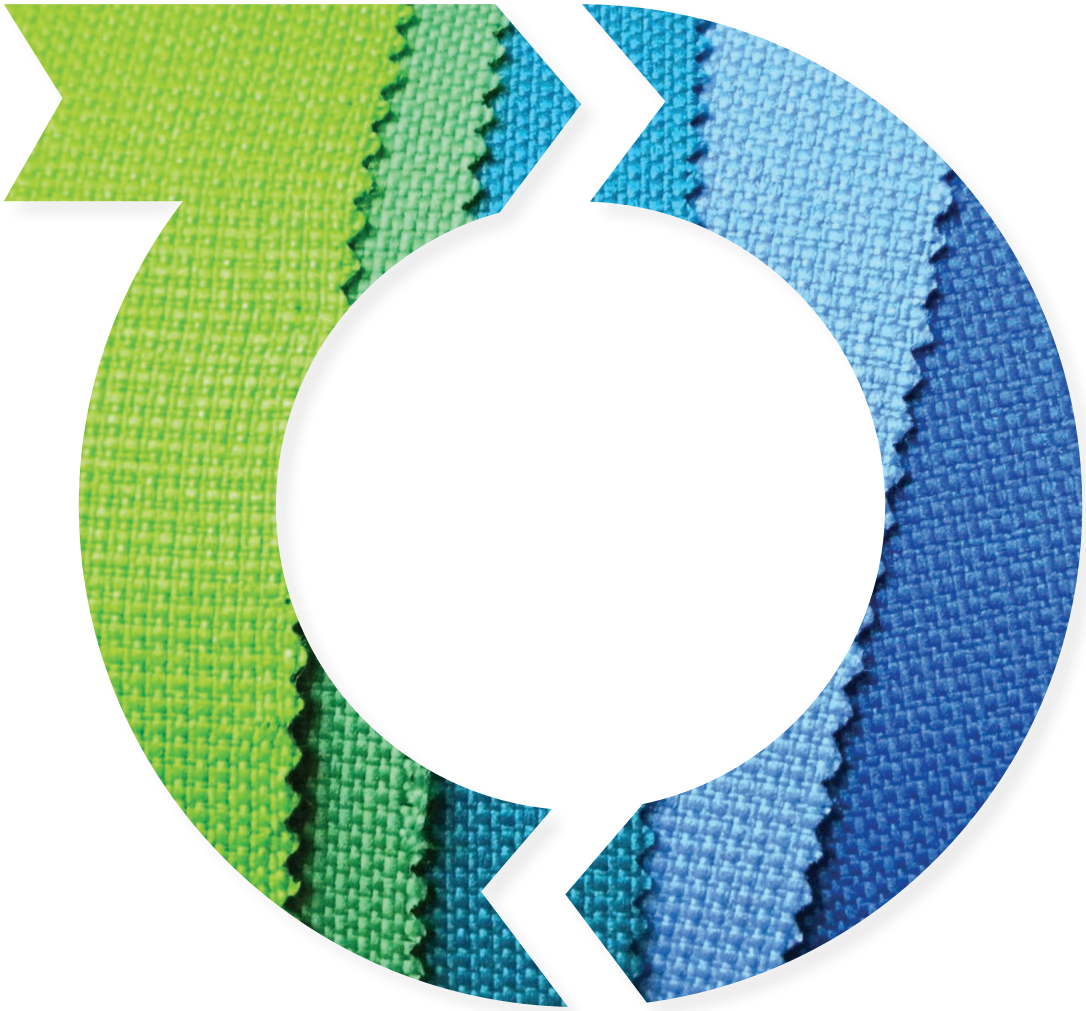

Chemical Recycling

Making Fiber-to-Fiber Recycling a Reality for Polyester Textiles

GREENBLUE®

ACKNOWLEDGEMENTS

GreenBlue would like to acknowledge the support and contributions of the following companies and people:

STUDY SPONSORS:

Patagonia, Steelcase

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Steelcase Inc.
Angela Nahikian
Jon Smieja
Heather Knight

Patagonia
Nellie Cohen
Elissa Loughman
Elena Egorova
Todd Copeland

Assets Unlimited
Frank Endrenyi

Association of Contract Textiles (ACT)
Janan Rabiah

Association of Plastic Recyclers (APR)
John Standish

Bentex Mills (a division of Burlington Technologies)
Rachel Marquardt

CARBIOS
Martin Stephan

Carpet America Recovery Effort (CARE)
Bob Peoples

Circle Economy
Traci Kinden
Gwen Cunningham

Cradle to Cradle Product Innovation Institute (C2CPII)
Annie Gillingsrud
Maura Dilley

Crypton
Hardy Sullivan

Designtex
Deidre Houget
Carol Derby
Susan Lyons

Ellen MacArthur Foundation - CE100
Joe Murphy
Francois Souchet

GreenBlue Institute
Nina Goodrich
GreenBlue Board of Directors

Gr3n
Maurizio Crippa
Matteo Bertele

H&M (Hennes & Mauritz)
Mutlu Toksoz
Cecilia STRÖMBLAD BRÄNNSTEN

Herman Miller Inc.
Lauren Zulli
Dan Broersma

I:CO
Chetan Gupta

L.A. Fiber
Ron Greitzer

Loop Industries, Inc.
Daniel Solomita
Giovanni Catino

lululemon
Robyn Kimber

Mohawk
Joe Foye
Mark Dye
Mike Sentha
Phil Stoner

National Council of Textile Organizations (NCTO)
Hardy Poole

Nikwax-Paramo Directional Clothing
Nick Brown
Gareth Mottram
Kim Paterson

Outdoor Industry Association (OIA)
Beth Jensen
Nikki Hodgson

Polartec, LLC
Jihad Hajjar

Resinate Materials Group
Kris Weigal

Shaw Floors
John Conyers
Troy Virgo

Sustainable Apparel Coalition (SAC)
Scott Miller
Amina Razvi

TEXTAID
Anna Pehrsson

Textile Exchange - rPET Working Group
Karla Magruder
Lisa Emberson
Brittany Moore
Donna Worley

The Renewal Workshop
Nicole Bassett

True Textiles
Alan Dean
Machell Apple

Unifi Manufacturing, Inc.
Chad Bolick

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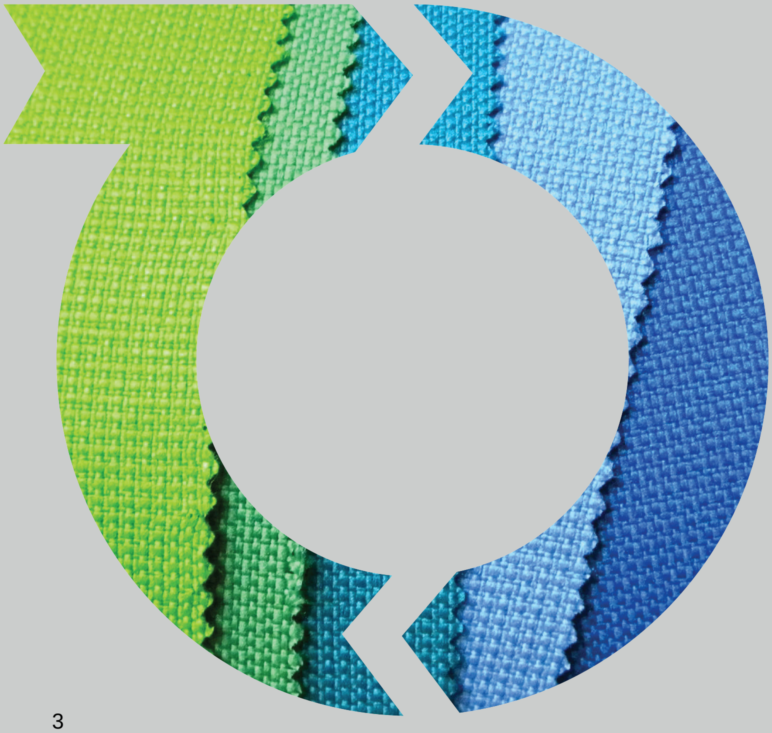


Executive Summary

Polyethylene terephthalate (PET) is a significant material in the global economy, and makes up about 18% of global polymer production. Approximately 65% to 70% of the PET produced is used for fiber applications, while 30% to 35% is used for solid-state resin applications. While recycling infrastructure is well-established for solid-state PET packaging materials, such as bottles, such infrastructure does not currently exist for PET fibers. It is challenging to recycle PET fibers using traditional mechanical recycling technologies due to the complexity of textile products, which often contain a blend of fiber types as well as a diversity of chemicals used for backings, surface treatments, dyes and pigments. As a result, PET textiles are often "downcycled" into lower value products or end up in landfills or incinerators.

New chemical recycling technologies are now coming on to the market at various stages of development, and have the potential to disrupt the material economy for PET textiles. These technologies, from companies such as CARBIOS, Gr3n, Loop Industries, Resinate Materials Group, Worn Again, can typically accept a broad range of inputs, provided at least 70% to 80% of the material is PET, and have the potential to produce high-value outputs – so that PET fibers can be recycled back into virgin-quality fiber or even solid-state applications (bottles, containers, engineering-grade resins).

The terms "open-" and "closed-" loop recycling are frequently used to describe two different types of recycling in the circular economy. Typically, 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 flow to where there is the greatest demand and market value. An open- loop model offers the best chance for building a scalable, efficient and sustainable infrastructure for recycling PET textiles as well as other materials. Because chemical recycling can transform lower grade inputs and materials that are difficult to recover into higher grade outputs suitable for a variety of applications, it enables textiles to be part of a sustainable open loop recycling system, in which materials cascade up and down the quality ladder in response to market demand.

In the past, chemical recycling technologies for PET have struggled to become commercially viable, for reasons including higher capital and operating costs relative to mechanical recycling, lack of sufficient feedstock volumes to achieve economies of scale, and low prices for virgin materials, creating a weak market for recycled monomers or other outputs from chemical recycling facilities. The new chemical recycling technologies evaluated in this report have the potential to operate more efficiently as a distributed network of small-scale facilities near sources of PET feedstock. Additionally, many of the new technologies require relatively little energy inputs, potentially reducing operating costs. Some of the technologies can be co-located with PET resin manufacturers, and other recyclers have created partnerships with bottle and fiber manufacturers looking for high quality recycled PET resin. Both of these strategies can help assure a market for recycled outputs from chemical recycling facilities.

One approach to ensure that a chemical recycling facility receives enough feedstock for commercial viability is to con-

sider “PET wastesheds” within a geographical region. Because chemical recyclers can process a broad range of feedstocks, such as pre-consumer or post-consumer contract textiles, apparel, and carpet face fiber, as well as solid-state post-consumer PET packaging from materials recovery facilities, these materials can be aggregated to provide a recycler with sufficient feedstock material. GreenBlue conducted interviews and collected data from each of these sectors, and found that in general, the cost of PET textile scrap is on par with the cost of baled post-consumer PET bottles – and thus, could be both technically and economically viable as a feedstock for chemical recycling. More detailed information can be found in the PET Textile Sector Profiles of this report.

Many companies and other organizations are taking innovative approaches to solving the problem of textile waste: extending the life of textile products, making textile products more recyclable, and creating markets for recycled textiles – read more about this in our series of features. All of these efforts are important to help overcome the numerous challenges of creating a circular economy for textiles, where pre and post-consumer waste have the potential to be recycled back into high quality inputs for the textile industry. New chemical recycling technologies have the potential to create disruptive change in the PET economy, enabling all forms of PET to move freely through the economy in an open-loop recycling system without loss of material value.

Introduction

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.

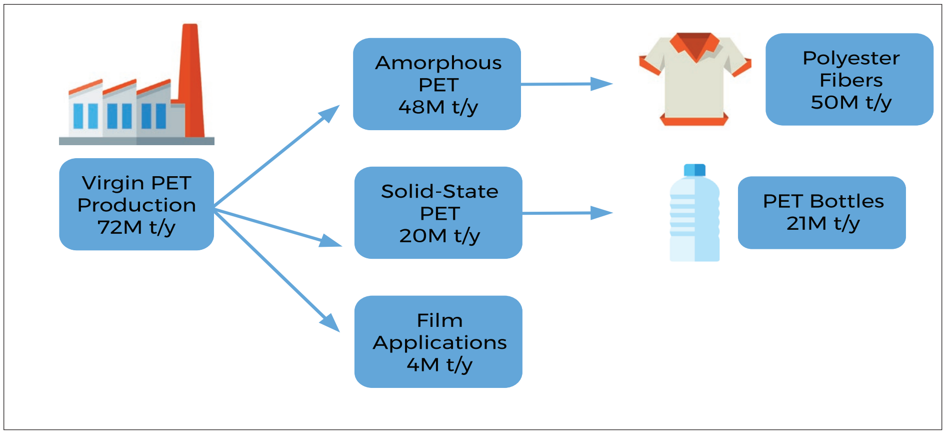
Occasionally, a new technology or a variation of an existing technology will emerge that fundamentally changes the economics of some aspect of production for a given industry sector. Recent innovations in chemical recycling processes for polyethylene terephthalate (PET) are a good example of how technology 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



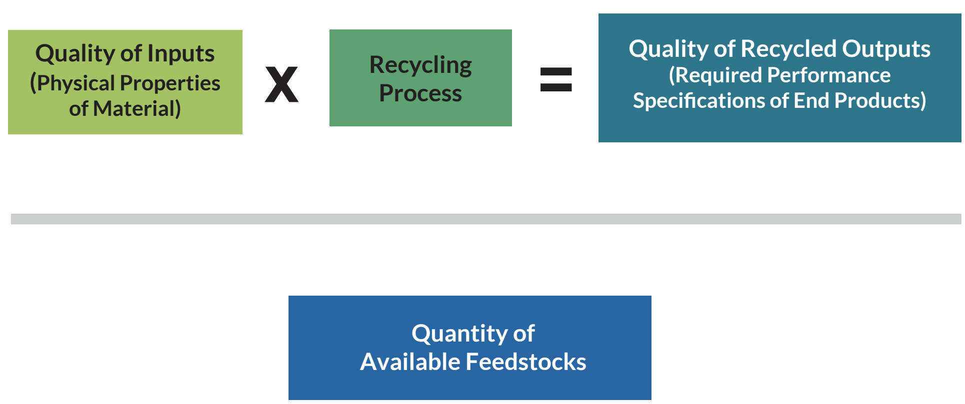
amorphous PET used for fiber applications, 20 million tons was solid-state PET used for packaging applications, and 4 million tons was used for film. Note that additional post-consumer recycled inputs contribute to the total production of PET fibers and bottles.

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.

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]

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



[2] "The Importance of Intrinsic Viscosity Measurement." AMETEK Sensors, Test & Calibration. http://www.ametektest.com/learningzone/library/articles/the-importance-of-intrinsic-viscosity-measurement.

Recycling Processes

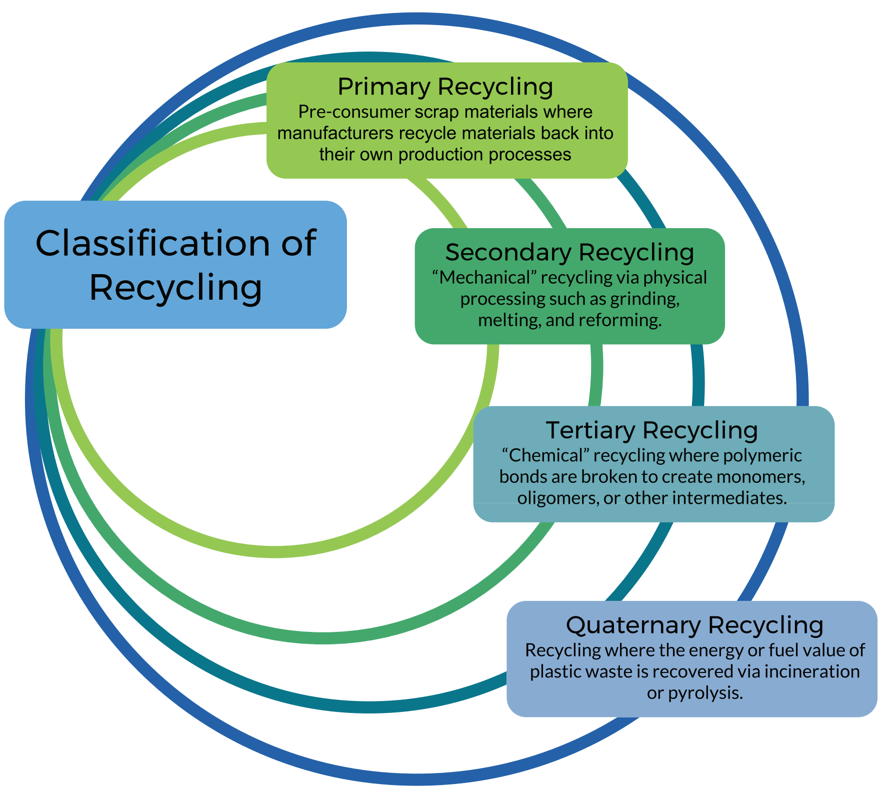
There are four major classifications of recycling – primary, secondary, tertiary and quaternary. The quality or physical prop-erties of feedstocks is less critical the further out one goes on this recycling continuum. The degree of material transformation also increases as do the end application options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

See illustration below.

Intrinsic Viscosity of PET Grades

	Application	IV Value
Fiber Grade	Textiles	0.40-0.70
	Technical	0.72-0.98
Bottle Grade	Water bottles	0.70-0.78
	Carbonated soft drink grade	0.78-0.85
Film Grade	Biaxially oriented PET film	0.60-0.70
	Thermoforming sheet	0.70-1.00
Engineering Grade	Monofilament	1.00-2.00 [3]

Four Classifications of Recycling



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,

[3] Al-Sabagh, A.M. et al. "Greener routes for recycling of polyethylene terephthalate." Egyptian Journal of Petroleum, vol. 25, issue 1, March 2016. http://www.sciencedirect.com/science/article/pii/S1110062115000148#b0035.

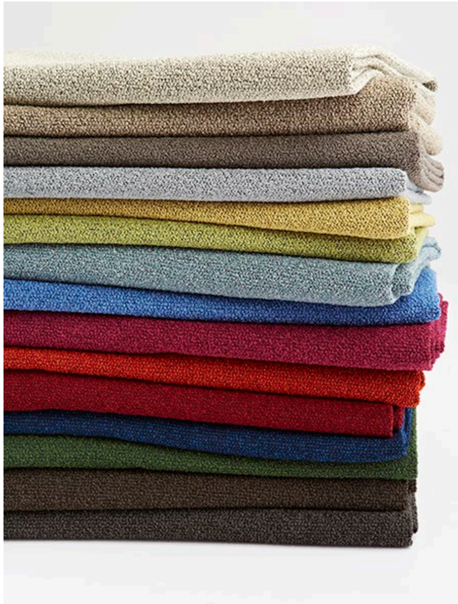
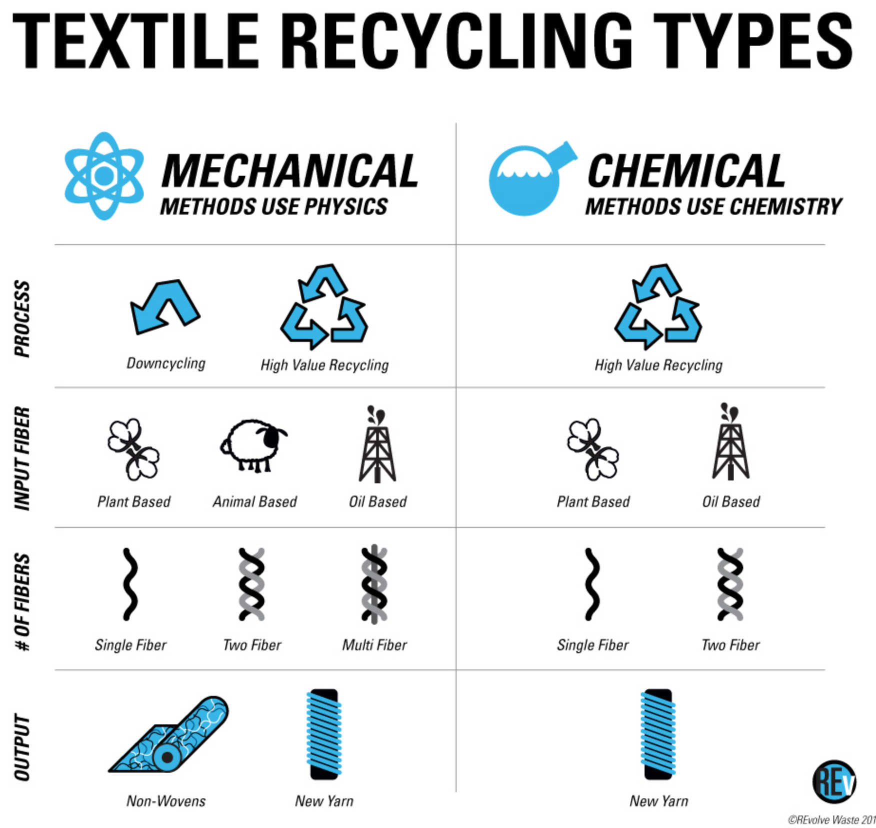


IMAGE COURTESY OF DESIGNTEX

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.



SOURCE: REVOLVE WASTE 2017, TRACI KINDEN, HTTP://REVOLVEWASTE.COM/

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. With intention and considerable effort, some manufacturers are also collecting and recycling colored fabric waste from their operations back into first quality goods. 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.

+ READ ABOUT DESIGNTEX

Chemical Recycling of PET

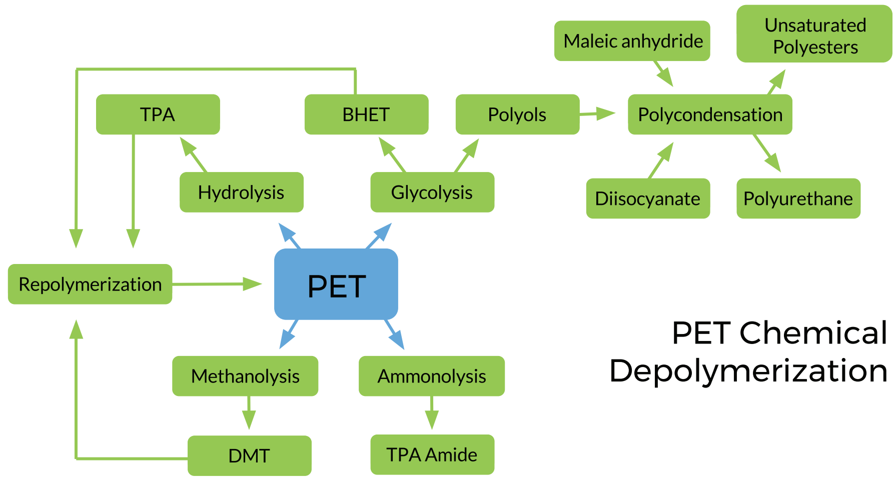
In chemical recycling, the PET

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.[4] 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.

+ READ ABOUT WORN AGAIN

+ READ ABOUT RESINATE

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



PET Chemical Depolymerization

SOURCE: AGUADO, JOSE AND DAVID P. SERRANO. *FEEDSTOCK RECYCLING OF PLASTIC WASTES.* 1999.

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,

[4] J. Aguado and D. Serrano. Feedstock Recycling of Plastic Wastes. 1999. p. 32.

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

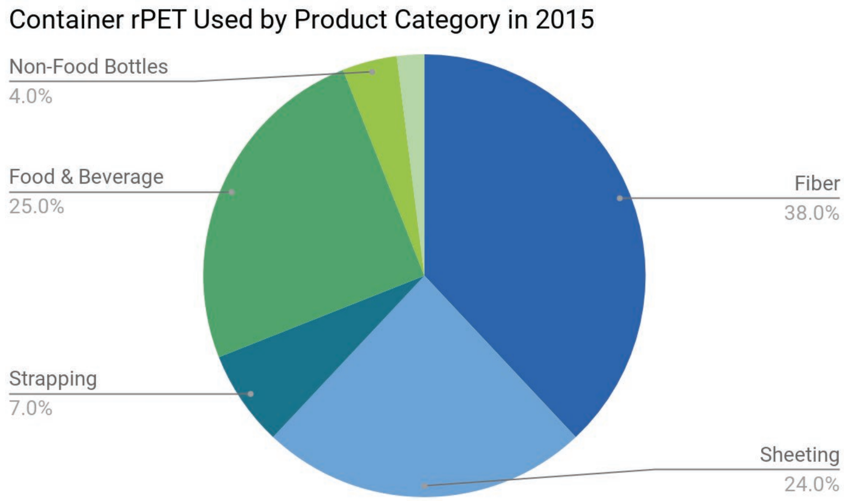
While the collection infrastructure and end markets are not well organized and for the most part still nascent for PET textiles, the market for PET rigid containers is much more mature. Observing this fact, most of the chemical recycling companies covered in this report are assuming that a significant 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)[5]. By late 2015, prices had dropped to under $0.10/lb.[6] 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 GreenBlue 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 to create

[5] Powell, Jerry. "A quick review of PET and HDPE market conditions." Resource Recycling, 2015.
[6] "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.



SOURCE: POST-CONSUMER PET CONTAINER RECYCLING ACTIVITY IN 2015, OCTOBER 13, 2016; NAPCOR AND APR

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.

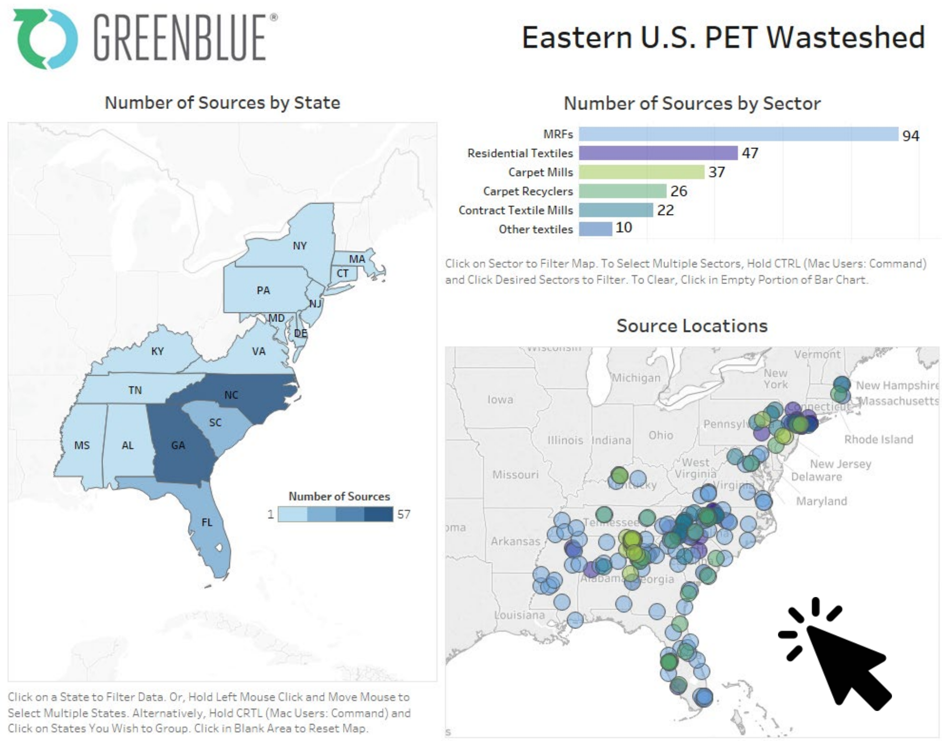
The use of recycled PET bottle flake to make PET yarns is good example of successful open-loop recycling. PET yarn producers have long been using recycled PET bottle flake to create recycled yarns. According to a joint report by the National Association for PET Container Resources (NAPCOR) and the Association of Plastic Recyclers (APR), approximately 38% of rPET stream is consumed by the PET fiber industry for recycled yarn production.[7] 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

[7] "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.

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. This 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, strapping, converter scrap, mattress ticking and batting, retail window display fabrics, etc.

Polyester 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 fab-ric waste depolymerized very efficiently and increased Loop’s interest in waste textiles as a possible feedstock. GreenBlue conducted two more trials – one for carpet and one for post-con-sumer 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.

Apparel Sector

Much has been written over the past five years about the social and environmental impacts of the apparel and footwear sectors. Both the mainstream and sustainability media have informed consumers about a multiplicity of issues related to the production and consumption of textiles, ranging from significant environmental pollution from contract manufacturing operations in Asia, to synthetic microfibers in potable water supplies, to humans subjected to unjust and dangerous work environments. The advent of fast fashion has put even more pressure on the textile industry, exacerbating the global challenges the industry faces.

Global consumption of apparel garments is rising exponentially. Between 2000 and 2014 garment production doubled, and by the mid-2010s consumers were keeping their clothing only half as long as they did at the end of the 20th century.[1] An estimated 62 million tons of apparel and footwear were consumed in 2015, and global consumption is expected to increase 63% to 102 million tons by 2030 due to a rising population and a rapidly growing middle class in China and India. An estimated 64% of the fiber used by the apparel industry in 2015 consisted of polyester and other synthetics; this is expected to grow to 68% by 2030 [2]. The impacts of rapidly rising consumption rates are compounded by a system that produces significant amounts of waste and is not designed to efficiently recover materials from key junctures of the life cycle of textiles. An estimated >25% of textile fiber is wasted during garment production. [3] Another 75% (EU) to 85% (US) of all clothing products sold to consumers go directly to landfill or incineration at the end of their first use cycle.[4]

Polyester ("PET") is perhaps the most important synthetic fiber used in outdoor apparel. While the fashion sector uses less PET than the outdoor sector, it also consumes a significant quantity of PET for blended fabrics (e.g., cotton/polyester). GreenBlue attempted to quantify the amount of pre-consumer PET waste generated by fabric weaving and garment suppliers for a small group of brands. We received limited data from suppliers for three out of the eight brands that participated in the study. GreenBlue also attempted to obtain aggregated data from the Sustainable Apparel Coalition (SAC) that had just recently completed an update from suppliers reporting data for the Higg Index Facilities Module. However, the SAC reported that it is not currently tracking pre-consumer fabric waste by fiber type from suppliers but expects to have more detailed information in future updates to the Higg Index Facility Module.

Pre-Consumer Flows

Some of the primary sources of pre-consumer apparel textile waste are:

- Defective or otherwise unsold garments
- Cut and sew fabric scraps
- Fabric weaving waste
- Fabric dyeing waste/rejects
- Yarn dyeing or solution-dyed/integral color waste/rejects
- End-of-roll textile waste
- Textile swatch waste

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[1] Remy, Nathalie, Eveline Speelman, and Steven Swartz. "Style That's Sustainable: A New Fast-Fashion Formula." McKinsey & Company Sustainability & Resource Productivity, Oct. 2016, http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/style-thats-sustainable-a-new-fast-fashion-formula.

[2] Pulse of the Fashion Industry. Global Fashion Agenda and The Boston Consulting Group, 2017, https://www.copenhagenfashionsummit.com/wp-content/uploads/2017/05/Pulse-of-the-Fashion-Industry_2017.pdf. pp. 132-133.

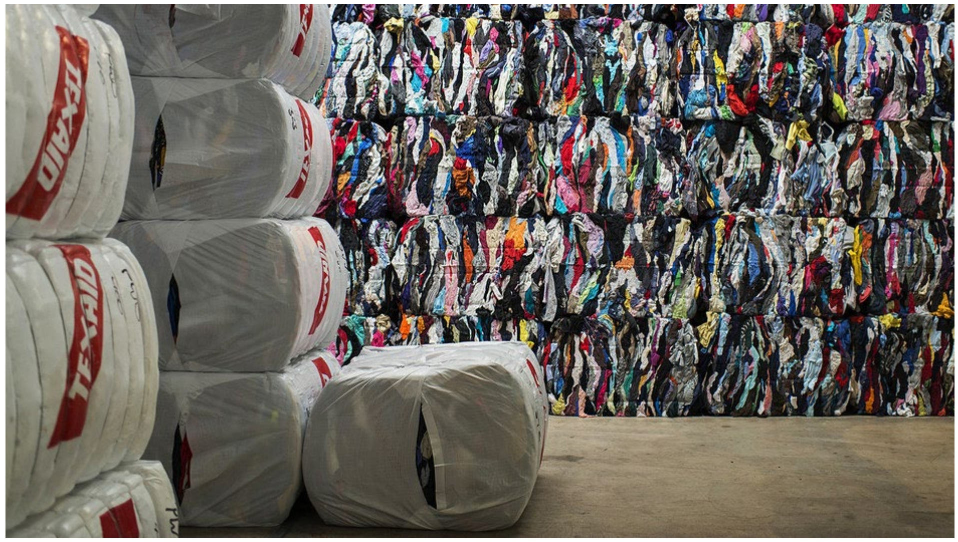
[3] Runnel, Ann et al. "The Undiscovered Business Potential of Production Leftovers within Global Fashion Supply Chains: Creating A Digitally Enhanced Circular Economy." Reverse Resources, October 2017.

[4] Kinden, Traci and Gwen Cunningham. Circular Textiles Infrastructure. Circle Economy, 2017. p. 7.

- Clothing sample waste
- Sampling yardage waste

From a sample of twenty two suppliers, survey results indicate that:

- The most common fibers reported as blends with PET at varying percentages are nylon, elastane, and cotton; less frequently reported fibers in blends included wool, viscose/rayon, silk, linen, and metallized fiber. Unfortunately, suppliers did not provide the percentage mix of PET vs other fibers for all of the waste reported. The sample group of suppliers reported generating a total of approximately 4.8 million pounds of PET scrap annually that would meet the minimum 80% PET content required by most of the chemical recyclers covered in this report.
- The price range of PET textile scrap sold was between \$0/lb and \$1.20/lb with a mean price of approximately \$0.05/lb. In some cases, suppliers reported that they pay waste disposal companies to collect their PET textile scrap.
- A substantial majority of suppliers that generate fabric scrap report they have the ability to segregate >80% PET-rich materials from blends that contained less PET if there were sufficient economic incentive to do so.
- Other pertinent factors that may impact the recycling of pre-consumer yarn and fabric scrap include local regulations that limit the ability of companies to export these materials or that require explicit permission, as well as costs to transport textile scrap from apparel production facilities often located in Asia to recycling facilities in North America or Europe.



TEXAID

Like other sectors covered in this report, pre-consumer sources of PET yarn and fabric scrap are qualitatively ideal feedstocks for both mechanical and chemical recycling. Chemical recycling has a clear advantage over mechanical in its flexibility to process the diversity of inputs associated with the manufacture of a garment into virgin quality recycled PET resin to start the loop over again.

Post-Consumer Flows

Capturing the value of post-consumer PET feedstocks is much more complex. The primary source is the used clothing industry, which has grown into a fairly mature and efficient market. Clothing resellers collect and sort used clothing into two primary fractions - wearable and non-wearable. The vast majority of their revenue comes from the sale of the wearable fraction. The non-wearable fraction is manually sorted and separated into natural fibers like cotton, bamboo and other hydrophilic cellulosics, or into synthetic fibers. Cellulosics are sold to recyclers who process them into staple fibers and yarns for manufacturing paper, woven and non-woven textiles and industrial wiping rags ("wipers"). Synthetics are sold to recyclers whose major markets are manufacturers of non-wovens for various uses such as automotive trunk-liners, sound deadening barriers and headliners. Other applications include filtration media, home insulation, furniture padding, geotextiles for soil erosion control applications, and carpet underlayment.

The largest source of post-consumer PET textiles is the used clothing industry, which is comprised of both nonprofit (e.g., Goodwill, Salvation Army) and for-profit (e.g., I:CO/SOEX, Trans-Americas Trading Co., TEXAID) enterprises. GreenBlue received representative data from two used clothing companies suggesting that approximately 15-25% of the clothes collected are "polyester-based". Manual sorting in Asian facilities could render a bale that is 90-98% polyester content garments for an approximate cost of $0.11-$0.16/lb ("hardware" - zippers, buttons, buckles, and snaps - not removed). Approximate costs for the European market were reported as $0.02-$0.34/lb, although it was less clear if a bale had the same purity level as reported for Asia. The greatest challenge for used clothing suppliers is to be able to sort the non-wearable fraction of PET garments more granularly to meet the specifications of higher value end markets where the minimum content of PET fiber per garment would need to be around 80% and above. Realizing this, some companies are investing considerable resources into research and development of more sophisticated methods for automatically sorting non-wearable ("recyclable") garments by fiber type to maximize their potential value.

A growing number of brands like H&M, Patagonia and Eileen Fisher are also collecting used clothing at retail locations, but such programs, while growing, still represent a minority of the post-consumer stream. The potential benefits of brands playing a larger role in the secondary market are:

1. Assurance that wearable clothing stays in the reuse market, maximizing the economic and environmental benefits of the original product;
2. Continuation of a relationship with customers by providing an economic incentive to bring clothing back to their original source;
3. An opportunity for brands to leverage the investments made to market the original garment by reselling it through their own retail or online channels;
4. The potential to increase top line sales by structuring collection incentives as credits towards future purchases;
5. An opportunity to find new customers who value the brand but cannot afford the initial purchase price. Brands could further segment resale pricing based on the condition of the garment into "like new at a good price" or "not perfect at a great price" to move inventories more quickly; and
6. An opportunity to manage the resale process more closely to reduce the risk of brand dilution or negative brand perception.

If these leading brands are successful in selling used clothing through their own retail channels, this new trend could become the new "normal". Their efforts combined with the more traditional players in the used clothing industry could translate into an significant reduction in the environmental impacts associated with the apparel industry.

Complex problems require multifaceted solutions

Despite the gains that have been made in building a more efficient and profitable market for used clothing, increasing rates of production and consumption of apparel goods will continue to create excess textiles. All stakeholders want solutions that will assure that the non-wearable fraction is recycled back into useful products as opposed to permanently losing its potential value through landfill or incineration. An ecosystem of service providers and technologies continues to emerge, filling in critical niches necessary to create a circular supply chain capable of capturing more value from both wearable and non-wearable fractions of reclaimed clothing.

Extending the service life of clothing

Increasing attention is being paid to keeping used clothing in reuse cycles for as long as possible. Small entrepreneurial companies are offering services to help brands manage their used clothing programs and to renew clothing that might ordinarily be destined for recycling. A good example is The Renewal

+ READ ABOUT THE RENEWAL WORKSHOP

THE RENEWAL WORKSHOP- ECO-FRIENDLY APPAREL FROM PREMIUM OUTDOOR CLOTHING BRANDS.

Workshop which estimates that as much as 65% of the goods that brands send to them as “non-wearable” are salvageable as renewed clothing. Another example is [Yerdle Recommerce] which helps brands to leverage the growing market for used clothing to their advantage by taking greater control over what happens to their products to minimize brand risk, increase customer engagement, and to reap additional profits. These services collect and manage data about incoming and outgoing inventories which not only allow greater transparency for brands to trace the flow of their products in the secondary market but will also provide valuable data to the recycling community.

+ READ ABOUT PATAGONIA

Patagonia’s Worn Wear program is a good example of a brand-driven multi-faceted strategy that combines designing for durability to maximize reuse potential of each garment, sharing the resale value with customers that return garments through a trade-in value, promoting repair of used garments to extend garment life further, supporting markets by using recycled fibers, and conducting research to find advanced processes for recycling used clothing at the highest functional value possible.

Designing clothes differently

Outdoor apparel brands have also been experimenting with different design and material selection strategies that enhance the recyclability of their products such as:

- Reducing the different types of materials used without sacrificing the functional performance of garments

PATAGONIA CLOUD RIDGE JACKET

- If using fabrics of different fiber types, designing garments to have one dominant fabric (at least 80%)
- Using fiber types that have better recyclability profiles (e.g., polyester or nylon 6 vs polyurethane or PVC)
- Designing garments to use a single resin type for all fiber and hardware functions - “mono-material” constructions
- Increasing recycled content in garments to ensure that markets exist to recycle their products, ideally back into raw materials for apparel production

A few examples of brands employing design for recyclability strategies include the following:

Patagonia is aggressively working towards its vision of all of the products it makes being made out of 100% recycled material and being 100% recyclable. A prime example is its [Cloud Ridge Jacket], a waterproof/breathable three component shell made from 100% polyester designed to be recycled using [TEIJIN’s]

GREENBLUE

Eco-Circle® chemical recycling process. Realizing that in a true circular economy, supply and demand are two sides of the same coin, Patagonia has also been committed to creating market demand for recycled materials. Its re///collection™ clothing line uses 100% recycled polyester, 100% recycled down and 100% recycled wool. The company is also pushing the market to supply them with high recycled content in zippers and buttons to ensure that all of their products are 100% pure raw materials for the next cycle.

The North Face has published its commitment to use 100% recycled content for all of its polyester fabric by 2016 to increase the demand for recycled PET. The Denali Jacket is one example of this commitment.
A sign that key suppliers are helping their customers to design for circularity is YKK, one of the world's largest fastener manufacturers is marketing NATULON, a line of zippers made from various sources of recycled polyester and designed to be 100% recyclable.

Innovations in Sorting

Two of the greatest obstacles for increasing the value of the recyclable fraction of used clothing are the cost of labor for manual sorting and the purity of materials that can be sold to recyclers. In an effort to address these two constraints, some companies and nonprofit organizations are conducting research to develop more sophisticated methods for automatically sorting non-wearable ("recyclable") garments by fiber type to maximize their potential value to recyclers and to earn a better return on investment.

Fibersort Project

Circle Economy and five other project partners launched a €3.53m project and received a €1.95m grant from Interreg North-West Europe to commercialize Fibersort, a technology that uses recent advances in near infrared spectroscopy (NIRS) to automatically sort large volumes of mixed post-consumer textiles by fiber type. Once sorted, these materials become reliable, consistent input materials for high value textile-to-textile recyclers. Fibersort will be especially useful for mechanical and chemical recycling processes that require high percentages of a target fiber (e.g., PET, nylon 6, cotton) and as low a level of contamination as possible so they can produce salable end products to return to the textile supply chain as opposed to selling them outside of the industry.

TEXAID

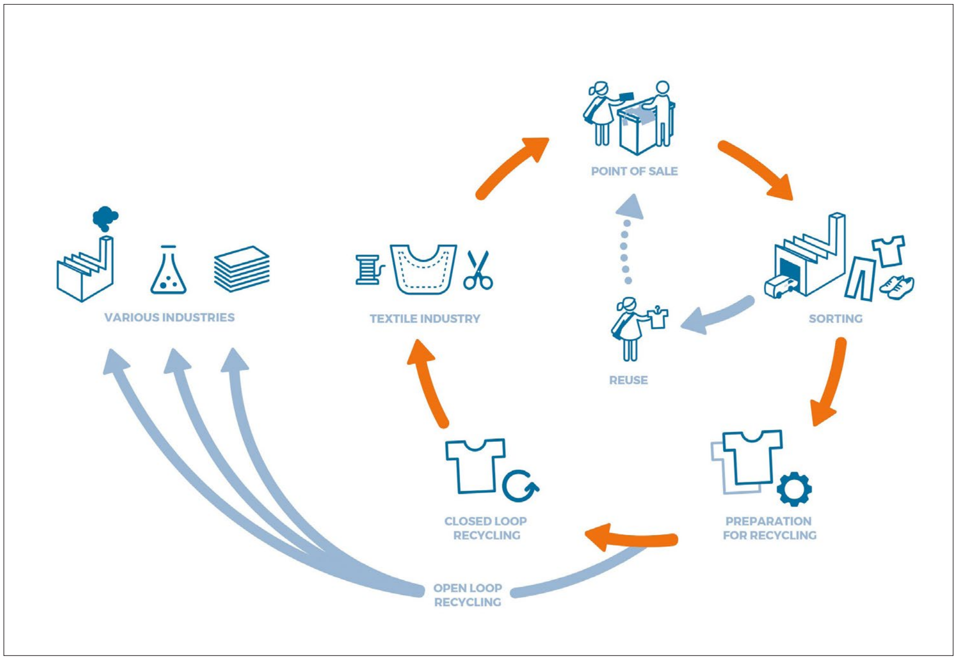
Located in Switzerland's Uri canton with satellite operations in Germany, Austria, Bulgaria, Hungary and Morocco, TEXAID is a charity-private partnership with a mission to "ensure that used textiles are kept in the value-added chain for as long as possible." The company is part of a research consortium called the Swedish Innovation Platform for Textile sorting (SIPTex/FITs), coordinated by the IVL Swedish Environmental Research Institute. Similar to Fibersort, SIPTex/FITS is based on visual and near-infrared spectroscopy (NIRS) technology. The research objective is to design a process for automated sorting that can handle large volumes at a high rate of throughput, resulting in two levels of quality: 1) high purity of fiber type for recirculation back, ideally, into fibers and yarns suitable for apparel and 2) well characterized lower value materials that can be downcycled into other uses. "We want to preserve textile fibers for as long as is feasible, and as high up in the cycle as possible. Only when they can no longer be used to create new textiles, only then should they be repurposed as stuffing for car doors etc.," says Maria Elander.[5] The scope of research also includes developing a business model for a large scale automated textile sorting facility where the research team will evaluate operational and maintenance costs, end markets, supportive government policies, volume of available feedstocks, and the market value of end products. It will also examine centralized and decentralized textile collection systems and methods of consumer education to increase collection volumes.[6]

Innovations in Textile Recycling

Refer to "Selected PET Chemical Recycling Technologies"

+ READ ABOUT SELECTEDPET CHEMICAL RECYCLING TECHNOLOGIES

[5] Recycling and reuse – by hook or by crook." IVL Swedish Environmental Research Institute, 31 March 2017. http://www.ivl.se/english/startpage/top-menu/pressroom/in-focus/recycling-and-reuse---by-hook-or-by-crook.html.
[6] TEXAID, 2017 project summary



SOURCE: I:CO website

of this report

I:CO/SOEX

I: Collect AG ("I: CO") is part of the SOEX group, which is the world's largest textile sorting and recycling group, with processing and distribution outlets all over the world. I:CO serves over 60 retail partners (including H&M, North Face, and Levi's) in 65 countries, designing and managing its customers' retail collection programs, transport logistics, and sorting and resale of wearable clothing in the secondary market or as materials to various recycling markets.

In collaboration with the SOEX Group, I:CO collaborates with international research institutes and private sector technology companies to find innovative technologies which can help create greater circularity of textiles. It is participating in two research consortia projects: RESYNTEX and Trash2Cash. RESYNTEX is a research consortium that aims to produce secondary raw materials from unwearable textile waste. Its goal is to design a complete value chain, from textile waste collection through to the production of new feedstock for chemicals and textiles. The scope of research includes both mechanical and chemical recycling processes for cotton, nylon, polyester and wool fibers. RESYNTEX is exploring the use of biochemical processing to transform natural and synthetic fibers into chemical intermediates such as glucose for bioethanol, purified terephthalic acid (TPA) and ethylene glycol (EG) for the production of PET resins, protein hydrolysate for resins and adhesives and polyamide oligomers for various chemicals.[7]

Trash2Cash, also an EU funded research initiative, includes 18 partners from 10 countries. Its objective is to create regenerated fibers and other high quality industrial materials from pre- and post-consumer textile waste. The consortium is focused on methods for chemically "upcycling" textile and paper waste into new, virgin quality fabrics.

Creating more effective markets

Circle Economy

READ ABOUT CIRCLE ECONOMY

Circle Economy ("CE") is a nonprofit organization based in Amsterdam, Netherlands that was founded to help build an effective infrastructure for the collection and reutilization of excess textiles. CE uses "excess" versus "waste" to emphasize that it is not the inherent value of these materials that is lacking but rather the lack of an effective, interconnected system to realize their value. The organization's objective is to not only reclaim lost resources but to also create a more circular textile industry that will increase the quality and, therefore, market value of all textile materials intended for recycling. CE's Circle Textiles Programme has three primary initiatives it believes are fundamental to stimulating system-level change to make the textile industry more circular and more socially and economically profitable. Circle Market is a digital online trading platform that connects the supply and demand of excess

[7] RESYNTEX: A New Circular Economy Concept. 1 December 2016. http://www.resyntex.eu/images/downloads/RESYNTEX_Introduction_Presentation_2016.pdf.

textiles. Such a platform serves several functions that are necessary for building an efficient and more sophisticated infrastructure for recycling textiles. First, it provides motivated buyers and sellers with the means to easily find one another. Second, it can be a source to define standard material specifications, provide an accurate characterization of listed textiles, and allow recyclers and other demand side users to distinguish higher vs. lower quality goods. Matching quality specifications with market-based price ranges will be key to creating a more efficient market that balances quality and cost and helps minimize risk for recyclers. Third, the platform is being designed to help mechanical and chemical recyclers make critical decisions about where to build plants or to focus material acquisition efforts by enabling them to identify national and regional feedstock zones to build their own supply chains.

Amplifying Demand

A key component of creating more effective markets is driving more demand for high quality recycled textile materials. It is important that brands employ strategies to amplify the demand signal to stimulate all of the different nodes of the supply chain to be responsive. More brands are participating in pre-competitive collaborations to tackle some of the complex challenges facing the apparel industry. Through more extensive cooperation and sharing of human, financial and creative resources, brands can leverage their combined purchasing power to increase market demand for both recycled and recyclable materials.

Notable collaborations include the Outdoor Industry Association (OIA), the Sustainable Apparel Coalition (SAC) and the Zero Discharge of Hazardous Chemicals Programme (ZDHC). An interesting example of companies collaborating to stimulate market demand for recycled polyester is the Textile Exchange rPET (recycled polyester) Working Group. Textile Exchange is a nonprofit with a mission to inspire and equip people to accelerate sustainable practices in the textile value chain. The rPET Working Group, which consists of brands, retailers, fiber suppliers and supporting organizations, convened just over one year ago to facilitate greater cooperation of brands and their suppliers in their shared goal of increasing the demand and supply of recycled polyester. It has identified three main goals: to replace virgin polyester with rPET, to increase availability of rPET, and to create price parity with virgin polyester. Since its inception, the group has defined concepts, terms and FAQs to communicate more effectively with stakeholder audiences. It has also outlined existing sources of rPET by region, fiber type, and processing methods. Brands and retailers have also specified and documented their performance requirements. In an effort to send a clear signal to its market, the rPET Working Group has drafted a letter of intent signed by brands, suppliers and other stakeholders publicly committing their companies to increase the use of rPET in the products they purchase and sell.

Although the diversity of materials used in the apparel sector as well as the issues of collection and sorting of pre- and post-consumer apparel scrap present challenges to closed-loop recycling of apparel textiles, recent initiatives by brands, nonprofits, and others in this sector show promise in moving this sector toward a circular economy.

Contract Textiles

The contract textile industry may not have the same visibility that the apparel industry enjoys despite this sector's efforts to understand how to design and manufacture more sustainable textiles. As early as 2004, the Association of Contract Textiles (ACT) formed a coalition of companies that eventually published a consensus-based, multi-attribute standard for designing more sustainable fabrics - the NSF/ANSI 336-2011 Sustainability Assessment for Commercial Furnishings Fabrics. The contract textile sector was also the first to use yarns with high recycled content from PET bottle flake, and was an early advocate for screening textile chemicals for their impacts to human and environmental health.

Pre-Consumer Flows

GreenBlue solicited data from contract textile mills who are members of ACT. While only 18% of the mills provided data, they represent some of the largest producers of this sector. Nine facilities reported generating a total of 2.9 million pounds of PET textile waste in 2016. These same facilities reported an average sales price for these materials between $0.04 and $0.16 per pound. Most of the facilities indicated that they would be able to keep PET fabric waste separated for collection if chemical recyclers pay more than recyclers who are downcycling materials into lesser value uses where separation by synthetic fiber type is not usually necessary. GreenBlue did not survey mills that exclusively manufacture residential textiles, but there is some overlap between mills that manufacture both contract and residential fabrics.

There are three basic categories of textile waste:

- Fiber waste: generated in the process of transforming resin to filament or staple fibers, including spinning
- Yarn waste: generated during yarn formation processes, but prior to fabric weaving
- Fabric waste: generated during fabric weaving processes, including dyeing and finishing

Fiber and yarn wastes include rejects or off-quality goods that are almost always reincorporated back into the production of first quality products. An exception is when fibers or yarns are colored using pigments ("solution-dyed") or with dyes ("package-dyed"). Colored fibers and yarns deemed as "off-quality goods" are usually sold to recyclers.

Most pre-consumer textile waste is generated from fabric weaving, fabric application (e.g., chair or office panel), and disposal at end-of-use. Fabric mills reported PET waste from the following sources: "false" selvedge, yarn cone waste, left-over yarns from the weaving process and damaged or rejected bolts of fabric. Two mills reported yarn cone waste as being a significant source of PET, as each cone contains as much as 0.5-1.0 pounds of unused yarn left on

"FALSE" SELVEDGES .

LEFTOVER YARN ON CONE AFTER BEING TRANSFERRED TO WARPING BEAM.

the cone. The cores are made of either cardboard or rigid PET and have been a challenge for mills to find recyclers willing to process them. The rigid PET cores are an excellent feedstock material for chemical recycling.

NONWOVEN INSULATION.

Survey responses and supplemental research indicate that the most common end markets for pre-consumer PET textile wastes are for nonwoven applications such as automotive trunk-liners, sound deadening barriers and headliners. Other applications include filtration media, emergency relief blankets, furniture cushions, tackable office system panels, home insulation, geotextiles for soil erosion control applications, carpet underlayment, stuffing for toys, fill for comforters and roll goods sold as fabric.

GreenBlue did not include a survey question for the percentage of fabric waste that is uncolored (“greige”) vs. colored via wet or solution-dyeing or surface printing. Greige scrap is a high quality input for mechanical recyclers. However, opportunities for mechanically recycling colored PET textile waste back into first quality yarns are very limited due to the diversity of dissimilar materials used in PET fabric constructions. Fabric blends using other fiber types such as cotton, rayon, or acrylic may range from 5%-80% of the finished fabric. Non-PET polymers, primarily acrylic, are used as back coatings at up to 1% of the weight of fabric. Other challenges include very diverse chemistries used to color yarns or fabrics as well as surface finishes for water and stain repellency (also approximately 1% by weight). In the last 15-20 years, manufacturers selling fabrics for healthcare environments have been using synthetic antimicrobial agents such as triclosan, metals or metallic salts of silver, copper, zinc or cobalt, as well as nanoparticle applications of these metals[1]. The diversity and complexity of PET fabric constructions will continue to be major challenges for traditional melt-and-extrude recycling and will require more advanced mechanical recycling techniques to overcome them.

CAR ROOF LINING AND CAR TRUNK LINING.

An alternative approach for mechanically recycling pre-consumer textile waste is to create closed loop systems where key manufacturers in the supply chain partner to sort and collect high purity PET scrap to be used as raw materials to produce new fabrics. A good example of closed loop recycling is Designtex’s collaboration with Unifi, Victor and Steelcase to produce fabrics using fill yarns made from 100% mechanically recycled PET pre-consumer

+ READ ABOUT DESIGNTEX

[1] Moreis, Diana Santos, Rui Miranda Guedes, and Maria Ascensão Lopes. “Antimicrobial Approaches for Textiles: From Research to Market.” Materials, vol. 9, no. 6, 2016, p. 498. http://www.mdpi.com/1996-1944/9/6/498.

scrap.

Chemical recycling could significantly expand the amount of pre-consumer yarn and fabric scrap this sector could recycle because of its ability to successfully process the diverse array of materials used without compromising the quality of the end product, typically new PET resin. This will not only expand the volume of by-products they can sell to derive additional revenue, but it will also increase the supply of recycled yarns they can use to meet recycled content requirements of their customers or certification programs. For example, Facts, the certification program managed by ACT, is based on NSF 336, which outlines a diverse and robust set of criteria that includes a hierarchy of end uses where waste used to make new textile products receives more achievement credits than lower value end uses such as waste-to-fuel or raw materials sold outside the textile supply chain. Chemical recycling will not only allow mills to attain higher levels of certification for their products but it will also create and grow the market for fiber-to-fiber recycled fabrics.

Post-Consumer Flows

The contract textiles sector is a business-to-business industry that supplies contract and commercial interiors manufacturers. As such, it is their customers who determine the end-of-life fate of these textile products.

+ READ ABOUT CONTRACT OFFICE FURNITURE

STEELCASE

Residential Carpet

Pre-Consumer Flows

GreenBlue conducted interviews with four of the largest PET residential carpet producers in the U.S. (combined share of PET residential market approximately 95%) to understand what opportunities might exist for chemically recycling post-industrial waste streams. Manufacturers reported that they were recycling on average up to 90% of the PET waste materials generated from production.

Typical sources of pre-consumer PET waste include:

- Yarn/fiber waste, including sweeps (any yarn too dirty/contaminated to be sold as thread waste or reprocessed), hard waste from extrusion (e.g., "lumps", "chunks", "purges", "drools", and "cakes"), yarn on tubes, loose yarn, and lint from tufting/shearing
- Transition or "off-spec" fiber waste
- "Soft" carpet waste (yarn tufted into primary backing, prior to the application of latex backing), including tufting waste, waste from change-over of colors and finishing chemicals, dye check waste, weight check waste, sew on waste, burned greige goods, etc.
- "Hard" carpet waste (finished carpet waste), including edge trimmings, seam waste, selvedge, QC waste, weight checks, finished carpet > 18", etc.

Two large carpet manufacturers provided documented information for the disposition of pre-consumer materials. Both companies reported that approximately 60% of their waste was sold to external recyclers with the remaining 40% recycled for internal use, and 0% going to landfill or to incineration. However, from interviews it seems that edge trimmings (the leading edge used to pull carpet through the manufacturing process) are produced in significant quantities and are landfilled due to lack of markets to recycle them. This pre-consumer waste stream could be an opportunity for the right recycling technology. The price range for pre-consumer PET sold to external recyclers was \$0.05-\$0.15 per pound. The sales price to external recyclers is similar if not lower than the sales price of mixed bales of PET containers, which should make post-industrial PET carpet fiber waste an attractive, cost competitive feedstock for chemical recyclers.

Post-Consumer Flows

In 2016, the carpet industry produced and sold approximately 4 billion pounds of commercial and residential carpet in the U.S.[1] Carpet manufacturers consume a significant amount of the amorphous polyester resin produced globally and also provide a significant market for recycled PET bottle flake. According to the Carpet America Recovery Effort (CARE), the organization responsible for managing the carpet industry's collection and recycling activities, sales of PET carpets will continue to increase and are expected to reach nearly 50% of all carpet sales in the near future.

According to CARE's 2016 annual report, of all the post-consumer carpet recycled in the U.S., only 11% was reported to go back into making new carpets – 8% into backing materials and 3% into face fiber. The majority of the post-consumer carpet recycled is used for the manufacture of engineered resins. Nylon 6, nylon 6,6 and polypropylene fibers have material properties suitable for engineering grade resins, but PET is too brittle for injection molding and is not as suitable without fillers and additives.

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[1] Interview, Bob Peoples, CARE, 2017

Unfortunately, as sales for PET carpet are rising, the amount being collected and recycled is declining. Factors contributing to this decline include a lack of end markets wanting to use resin from post-consumer carpet fiber[2] and the low cost of virgin PET resin, resulting in a low market value for recycled PET fibers. Another factor that makes PET residential carpet recycling more challenging is that the material is highly dispersed as compared to commercial grades where recyclers can harvest much larger volumes from office buildings and other commercial and institutional settings. Unless retailers of PET residential carpeting are willing to collect and sell used carpet to recyclers, it will continue to be economically challenging for independent recyclers to efficiently collect used PET carpet.

Without higher value end markets, recyclers are challenged to make the economics of recycling PET carpet work. According to Frank Endrenyi, an industry consultant with expertise in carpet manufacturing and recycling, there are a host of reasons that complicate PET carpet recycling:

- The average "face weight" of PET fiber is not the same in all PET carpet grades. A base grade carpet used for low-end apartment complexes may have a fiber face weight of 22 oz per square yard of carpet whereas a high-end carpet may contain 50-60 oz per square yard. For a recycler, the collection and processing costs are the same for both grades but the return on their investment is significantly different.
- Every residential carpet regardless of fiber face weight contains the same weight of latex and backing materials. The average face weight of PET carpets is around 30 oz per square yard which equals about 47% of the average total weight of the carpet. The remaining constituents - latex and calcium carbonate (approximately 41% of an average carpet) and polypropylene primary backing (approximately 12% of an average carpet) are difficult to separate from the face fiber and are considered low value materials, requiring most recyclers to pay to landfill them or to send them to various facilities that harvest their energy value (waste-to-energy, pyrolysis, and cement kilns). So, the costs of collecting and processing two pounds of whole carpet to obtain approximately one pound of PET face fiber are too high for most recyclers to make a profit.
- The quality of recovered PET face fiber is often too degraded from successive heat histories (e.g., fiber made from 100% recycled bottle flake), wear from foot traffic and UV degradation. The process of re-melting and extruding subjects the polymer to even more heat and also introduces moisture, further compromising the quality of the end product. The resulting resin needs to be solid-stated to increase its intrinsic viscosity if it is to meet the specifications of higher value end markets such as new carpet fiber or PET packaging. Solid-stating equipment is expensive and requires companies who specialize in this process, adding another $0.15/lb to the cost of recycling. Given the poor economics, recyclers opt to sell materials to market applications with less stringent performance requirements.

For the most part, recyclers willing to process PET carpet are producing lower value end products that cost less to manufacture. Some of the more common end products are non-woven materials such as carpet underlayment, auto trunk liners, insulation, sound deadening barriers or geotextiles used for erosion, sediment and stormwater management control. Ron Greitzer, President of Los Angeles Fiber, a leading manufacturer of loose-fill fiber sold to recyclers, and Reliance Carpet Cushion, a producer of non-woven carpet underlayment,- says that he could not recycle PET carpet economically if it were

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READ ABOUT CALIFORNIA CARPET STEWARDSHIP FEATURE

[2] CARE 2016 Annual Report. Carpet America Recovery Effort, 2017. https://carpetrecovery.org/wp-content/uploads/2014/04/CARE-2016-Annual-Report-FINAL-003.pdf. p. 21.

COLLECTION OF CARPET BY REGION - 2016

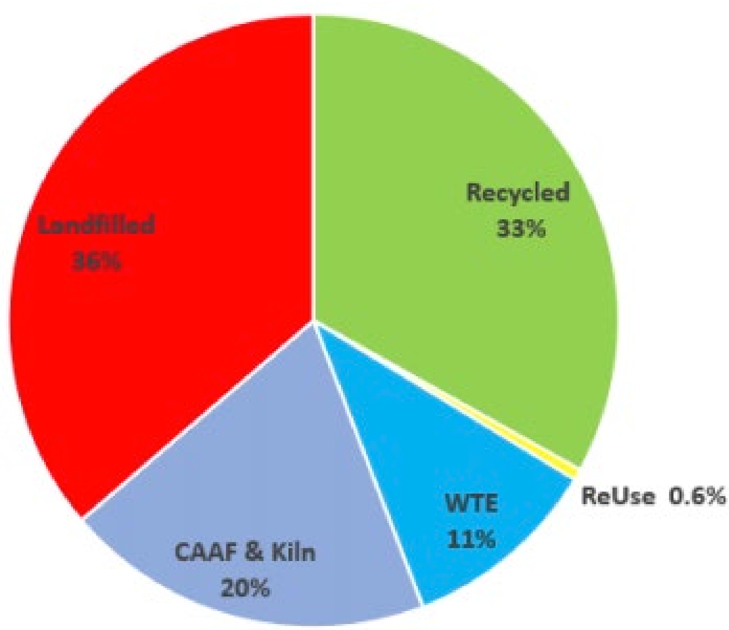
SOURCE: 2017 CARPET AMERICA RECOVERY EFFORT – CARE 2016 ANNUAL REPORT

not for the subsidy provided by CARE as part of California's carpet stewardship program.

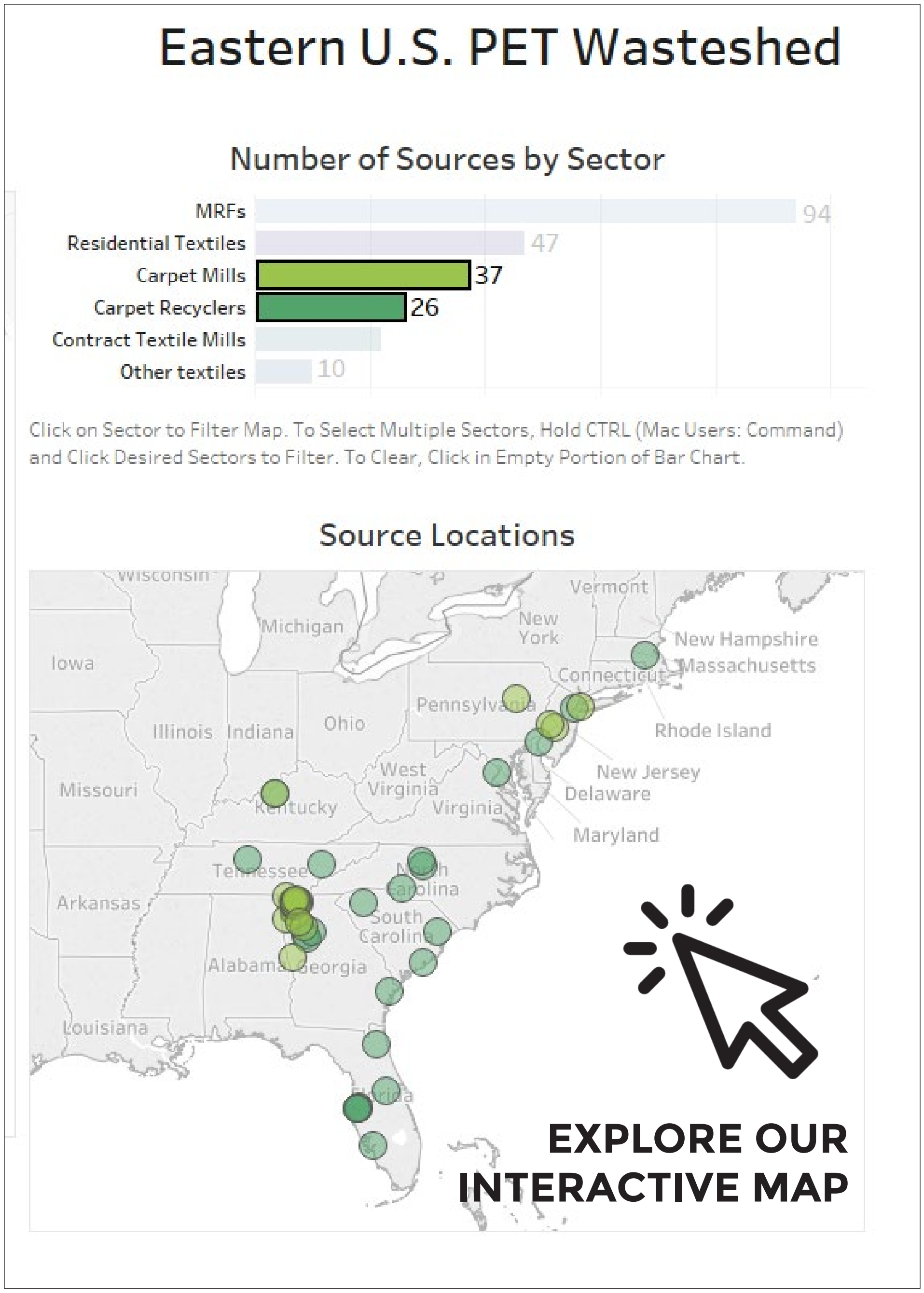
The upside potential for recycling carpets is enormous as only an estimated 33% of carpets collected in the United States are recycled (a recycling rate of 5% of total discards), with an additional 0.6% designated as "reuse" (reused as broadloom or tiles through organizations like Habitat for Humanity, etc).

According to CARE's 2016 report, California is the state with the highest post-consumer carpet collection volume due to its extended producer responsibility mandate that provides subsidies to carpet collectors and recyclers (see "AB 2398 - California Carpet Stewardship Program"). However, 35% of the total carpet collected in the U.S.

Outlets for Post-Consumer Carpet Collected in the U.S. - 2016



SOURCE: 2017 CARPET AMERICA RECOVERY EFFORT —CARE 2016 ANNUAL REPORT is collected in the southeastern region. One of the technology companies covered in this study, Loop Industries Inc., is planning to open one of its recycling plants in the southeastern U.S., where it will have access to a confluence of pre and post-consumer PET materials from multiple industry sectors. This should be a considerable benefit for all stakeholders in the PET textile value chain operating within that region. See "[Eastern U.S. PET Wasteshed]", for an interactive map of geographical locations of these selected PET feedstock providers.



Opportunities and Challenges
Chemical recycling could provide a viable solution for recovering the highest value of PET carpet fibers because unlike mechanical recycling, which has to compensate for any physical degradation of the polymer, it can return the material to virgin quality resin more efficiently and economically than post-treatment ("solid stating") of mechanically recycled resins.

However, chemical recycling cannot overcome the most challenging aspect of recycling post-consumer PET carpet, which requires processing two pounds of materials, on average, to obtain one pound of PET face fiber. GreenBlue conducted depolymerization trials with one of the technology companies, Loop Industries, on face fiber, whole carpet and "edge trimmings". Only the face fiber samples were deemed to be pure enough to be valuable feedstock. The ratio of PET to other materials was too low from whole carpet and edge trimmings to make them economically viable feedstocks capable of meeting Loop Industries' minimum PET content requirement of 80%. Chemical recycling seems to be a better option for "upcycling" the face fiber once separated, but is not a viable solution for whole carpet recycling unless the PET fraction is 80% or greater.

A solution to the challenges of recycling post-consumer carpeting is to design them differently. A typical design for recycling strategy is to strive to produce a "mono-material" product, where all or a significant majority of the product is constructed using a single resin type. An excellent example of a company that has successfully employed this strategy is Mohawk Inc. They have created a "unified floor covering" product

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called Air.o™ for residential carpeting applications. It is constructed from 100% PET materials and Mohawk is is creating a take-back collection network to return whole carpet to one or more of their manufacturing facilities where they will be mechanically recycled back into new face fibers and/or backing materials.

Mono-material products are "pure" nutrients for a cradle-to-cradle system. In California, recyclers would be eager to leverage CARE subsidies in addition to the increased profitability that such products would bring to their businesses. An option as yet unexplored by CalRecycle, the government office that manages California's recycling programs, is whether it is economically feasible for CARE's subsidy program to waive the assessment fees consumers pay per square yard for mono-material carpet/floor coverings. It could provide an incentive for manufacturers to create products that are significantly more profitable to recycle. It would also make these products more attractive to high-volume purchasers such as the home building industry, where assessment fees may influence their decision about which flooring products to purchase.

AIR.O

Contract Office Furniture

The contract office furniture industry is a significant consumer of PET resins for textiles as well as rigid and engineering-grade applications. This sector is the primary customer for the products produced by the contract textile sector. Ninety five percent or more of office panels and fifty percent or more of the office seating manufactured are covered with PET fabrics. Additionally, many of the substrates used to create "tackable" surfaces or sound deadening materials are made from non-woven PET.

The contract office furniture industry has a long history of innovation in sustainable product design and manufacturing. Two companies in particular – Steelcase and Herman Miller Inc. – have demonstrated their leadership by incorporating a diversity of sustainability best practices into their day-to-day business operations, such as working with suppliers to screen materials for chemicals of concern to optimize indoor air quality and minimize negative life cycle impacts in their supply chains. They routinely search for innovative materials that reduce life cycle impacts, such as those with preferred chemistries or high-recycled content to help stimulate market demand for recycled materials. And despite the lack of an effective infrastructure for collecting and recycling all types of furniture, these companies have designed most of their products so recyclers can disassemble them and repurpose the materials as economically as possible. The industry through its association, the Business and Institutional Furniture Manufacturers Association (BIFMA) has created its multi-attribute e3 Furniture Sustainability standard along with its companion certification program - level®.

STEELCASE BUVI RUMBLE SEAT

Pre-Consumer Flows

GreenBlue collected representative data for fabric waste generated by seven panel and seating manufacturing facilities, including design facilities. In 2016 these facilities generated approximately 1.2 million pounds of textile scrap comprised of at least 80% PET. Fabric scraps were either recycled for internal uses or sold to external recyclers for a price range of \$0-\$0.02/lb, and sometimes are given away for no charge to recyclers. All of the companies report they can separate synthetic fibers by type and minimum PET content

STEELCASE OFFICE CHAIR

if economic incentives justify sortation and storage costs.

Survey responses and supplemental research indicate that the most common end markets for pre-consumer PET textile waste are for nonwoven applications such as trunk liners, sound barriers and headliners for automobiles. Other applications include filtration media, thermal insulation for building construction, furniture cushions, tackable office panel systems, geotextiles for soil erosion control, carpet underlayment, stuffing for toys, fiber fill for comforters and roll goods sold as fabric.

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There are a few examples of companies who are exploring ways to mechanically recycle pre-consumer fabric waste back into new woven fabrics. As part of its efforts to make its operations more circular, Steelcase partnered with its fabric design and marketing brand Designtex to explore how best to close the loop on fabric scrap generated by one of its panel system manufacturing facilities. Partnering with key suppliers Unifi (fiber/yarn manufacturing) and Victor (fabric weaving), the initiative not only resulted in the creation of numerous fabric lines using mechanically recycled yarns, but it also developed a system to recycle pre-consumer fabric waste directly back into first quality fill yarns as a prime example of "fiber-to-fiber" recycling. (see Contract Textiles sector profile for more discussion of the challenges of mechanical recycling of PET textiles).

Post-Consumer Flows

The diversity of applications for contract textiles makes it very challenging to recover and recycle PET fabrics. The end-of-life trajectory for these textiles is determined by the fate of the products they adorn. The economics of recycling contract textiles is more promising than residential fabrics because consumers include large commercial or institutional users where there is potential for aggregating significant quantities of PET materials. Contract office refurbishing businesses are probably the single largest source for collecting and recycling textiles from large commercial users, mostly from upholstered furniture, office seating and panel system applications. GreenBlue was unable to collect data from the refurbisher community as the industry is rather fragmented and has little formal industry representation. But there is little doubt that the secondary market for office furniture is a material sink that can yield significant quantities of PET fabric feedstock if there is an infrastructure in place to harvest it.

Other potential sources of post-consumer PET fabric waste are the contract office furniture manufacturers themselves. For example, as part of Steelcase's vision for designing products for a circular economy, it offers its customers several options for

STEELCASE FABRIC
BELOW: HERMAN MILLER WORK SPACE

responsibly "decommissioning" their retired furniture, ensuring that they will be reused by new customers or they will be disassembled into material components for sale into various recycling end markets. It would be a fruitful alliance if Steelcase could open its product stewardship services network to office furniture refurbishers to provide an outlet for the PET fabric waste they generate. In general, these polyester fabrics, even when blended with other fibers, have very high PET fiber content, making them an excellent feedstock for chemical recycling or for fabric-to-yarn mechanical recycling if available in a given region.