Transitioning Toward a

CIRCULAR ECONOMY

for Automotive Plastics and Polymer Composites

American Chemistry Council

Plastics Division

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About this Report

The American Chemistry Council (ACC) Plastics Division led the development of this report, guided by the ACC Auto Team under the leadership of Gina Oliver, Senior Director, ACC Plastics Division. Vital contributions were made by the Auto Team members and experts from the polymers and automotive communities. Nexight Group provided stakeholder engagement and report development support to ACC and prepared this document.

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The transition toward a **circular economy** for industrial goods will require the automotive industry and its suppliers to rethink the ways that vehicles and their materials are designed, constructed, used, and handled at end of life. **We're starting the conversation *now*.**

MOBILITY

Aspirationally, a circular economy is one in which, **by design**, **no molecule is wasted** while continuing to meet performance requirements and bring value throughout the supply chain.

The traditional linear economy follows a make, use, dispose path that wastes precious natural resources. A circular economy is designed to keep resources in use for as long as practicable by extracting maximum value from them while in use and recovering and reusing materials at the end of each service life. In essence, it's a new, more comprehensive way of thinking about supply chain structure, material and product design, and end-of-life recovery that has significant **environmental benefits**, supports **longer product lifetimes**, and presents a potential **$4.5 trillion opportunity by 2030** for businesses[1]—$400–600 billion of which could go to automotive companies and their suppliers.[2]

Working to achieve circularity often supports sustainability goals, which focus first and foremost on reducing environmental impacts and improving the efficiency of products throughout their lifecycle. However, trade-offs between greater circularity and other facets of sustainability may sometimes be considered, such as if increased energy consumption is required to recover and reuse end-of-life materials. While the terms are not interchangeable, both circularity and sustainability efforts seek to make the most out of natural resources while protecting the environment and can support one another as mobility continues to evolve.

As circularity grows in importance, **the plastics and polymer composites industry is committed to working together and with part suppliers and automakers to help the automotive industry transition toward a circular economy**.

PRINCIPLES OF A CIRCULAR ECONOMY

Design materials, products, and systems to be circular (e.g., design for disassembly and recovery)

Reduce demand for finite raw materials

Eliminate in-process scrap production

Reuse recovered materials in new products

Refurbish and remanufacture products to extend useful service lifecycles

Recover and recycle materials at the end of their usable life

2. THE NEED FOR CIRCULAR AUTOMOTIVE PLASTICS AND POLYMER COMPOSITES

Advanced plastics and polymer composites are critical to **enabling future mobility**.

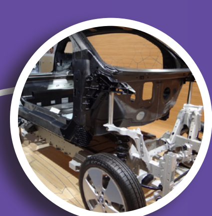
Transformative technological, cultural, and economic megatrends are converging to reshape the role of the vehicle and the ways people move from one place to another. Plastics and polymer composites hold tremendous value for helping the automotive sector realize the future requirements for personal mobility.

PLASTICS AND POLYMER COMPOSITES ENABLE FUTURE MOBILITY

Enable the **safe integration of sensors, electronics, and batteries** to vehicles

Signal transparency for active safety systems and sensors including radar, and Light Detection and Ranging (LIDAR)

Provide **high strength-to-weight ratio** to offset added weight increases and improve vehicle efficiencies



Carbon fiber frame with honeycomb impact panels

Plastic battery assembly

Enable **design and seamless integration of high-value electronic content**

Additively printed control button

TRENDS FOR THE FUTURE OF PERSONAL MOBILITY

Autonomy	Electrification
Connectivity	Shared Mobility
Circularity	Sustainability

Support a **reimagination of vehicle interiors**

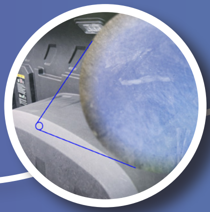
Seating concept

Help **modernize transportation infrastructure**

Plastic network vehicle charging stations

Plastic infrastructure components that can enable connectivity

Promote a **sustainable design and supply chain**



2019 GMC Sierra Denali lightweight carbon fiber composite truck bed includes pocket reinforcements made from recycled carbon fiber thermoplastic materials

For automakers to take full advantage of all the benefits plastics and polymer composites offer, our materials need to be **highly circular**.

Automakers are making **public commitments to circularity**

Many major automakers have set goals and begun implementing initiatives to improve the circularity of their operations—some specifically related to their use of plastics. Regardless of their current level of commitment, many **automakers are driving toward more circular approaches**, **signaling the need for plastics and polymer composites to do the same**.

Several automakers have also established "vehicle recovery networks"—partnerships to set up closed-loop recycling operations for the recovery of automotive parts once they reach end of life. Automakers like Ford,[3] BMW,[4] and Renault[5] have set up free take-back networks that accept end-of-life vehicles from owners in countries around the world. While many of these networks are currently being driven by the demand for recycled advanced high-strength steel (AHSS), they can also prove valuable for recycling polymer-based materials.

In addition, **original equipment manufacturers (OEMs) are participating in larger circular economy initiatives**. For example, the World Business Council for Sustainable Development's circular economy initiative, Factor 10, is a CEO-led organization that brings companies together to reinvent how businesses find, use, and dispose of the resources and materials that make up global trade. The BMW Group, Ford, Honda, Volkswagen, Renault, and tire manufacturers Goodyear, Bridgestone, Continental, Kumho Tire, Hankook, Michelin, Pirelli, Yokohama Tires, and Toyo Tires are among the leading private companies that support the effort.[6]

AUTOMAKER COMMITMENTS TO CIRCULARITY

BMW has pledged to **"replace artificial materials with recycled and sustainable raw materials" throughout their entire "value chain"** and has instilled a "Design for Recycling" principle to flow end-of-life vehicle components back into the materials cycle.[7]

In its Sustainability Report 2020, Ford states its aspiration to "only use renewable and recycled plastic materials with lower life cycle impacts that provide equivalent or better quality, appearance, and performance as existing materials." It also establishes an interim **target of 20 percent renewable and recycled plastics by 2025** as the company makes "progress toward a circular economy."[8]

Volvo set a goal of using **25 percent recycled plastics in cars starting in 2025**.[9]

In addition to setting sustainability goals, General Motors has committed to increasing the percentage of sustainable materials in their vehicles—in partnership with their suppliers, **at least 50 percent of the materials in their vehicles will be sustainable by 2030**.[10]

Toyota is currently committed to four initiatives related to circularity: 1) use **eco-friendly materials**, 2) **use auto parts longer**, 3) develop **recycling technologies**, and 4) **manufacture vehicles from end-of-life vehicles**.[11]

Nissan has set a target that, out of all raw materials used in the production of cars, they will aim for **30 percent to be material alternatives that do not depend on newly-extracted resources by 2022**. They will aim to do this by strengthening their use of recycled material, developing biomaterials, collaborating with suppliers, increasing internal recycling and lightweighting vehicles.[12]

Legislation abroad explicitly restricts the use of materials that are not recyclable in vehicles...

Europe is leading the way in implementing legislation that restricts the use of materials that are not recyclable in vehicles. Automakers and suppliers alike are taking these cues seriously and are using them to make decisions that impact their future operations.

End-of-Life Vehicles Directive

European Directive 2000/53/EC—issued on September 18, 2000—aims to address the waste created by end-of-life vehicles by categorizing them in regulatory terms as hazardous waste that must be decontaminated and recycled.[13] As of January 1, 2015, manufacturers are obligated to reuse 95 percent of end-of-life vehicles overall: 85 percent recycled and 10 percent for generating energy in their passenger cars (M1) and light commercial vehicles (N1). It is also the first European Union waste directive to introduce extended producer responsibility, which requires car manufacturers to design and promote processes for managing the waste created by their products.[14] In Germany, this legislation has translated into a requirement for automotive manufacturers to receive scrap cars for free.[15]

Motor Vehicle Reusability, Recyclability, and Recoverability Directive

Issued October 26, 2005, European Directive 2005/64/EC strictly prescribes the responsibilities of vehicle manufacturers to fulfill requirements of Directive 2000/53/EC in order for their passenger cars and light commercial vehicles to be put on the market.[16] These responsibilities include collecting and making available the data needed to perform the calculations required by the Directive; recommending a strategy to ensure dismantling, reuse of component parts, recycling and recovery of materials; and managing the breakdown of the materials, among others. The Directive also outlines the components that cannot be reused in the construction of new vehicles, such as airbags, seat belt assemblies, and steering lock assemblies.[17]

Circular Economy Action Plan (EU)

The European Union has also identified a Circular Economy Action Plan that identifies 54 strategies of "closing the loop" of product lifecycles supported by 10 billion euros in funding. It includes a strategy that will involve the remanufacturing of end-of-life vehicles and the utilization of plastics that reduce the weight of vehicles:

> *The Commission will adopt a strategy on plastics in the circular economy, addressing issues such as recyclability, biodegradability, the presence of hazardous substances of concern in certain plastics, and marine litter.*[18]

The Circular Economy Action Plan is also supplemented by the European Commission Circular Economy Package, which includes funds that support the development of a circular economy.[19]

...while **domestic legislation** at the state level is beginning to place responsibility for recyclability on the manufacturer

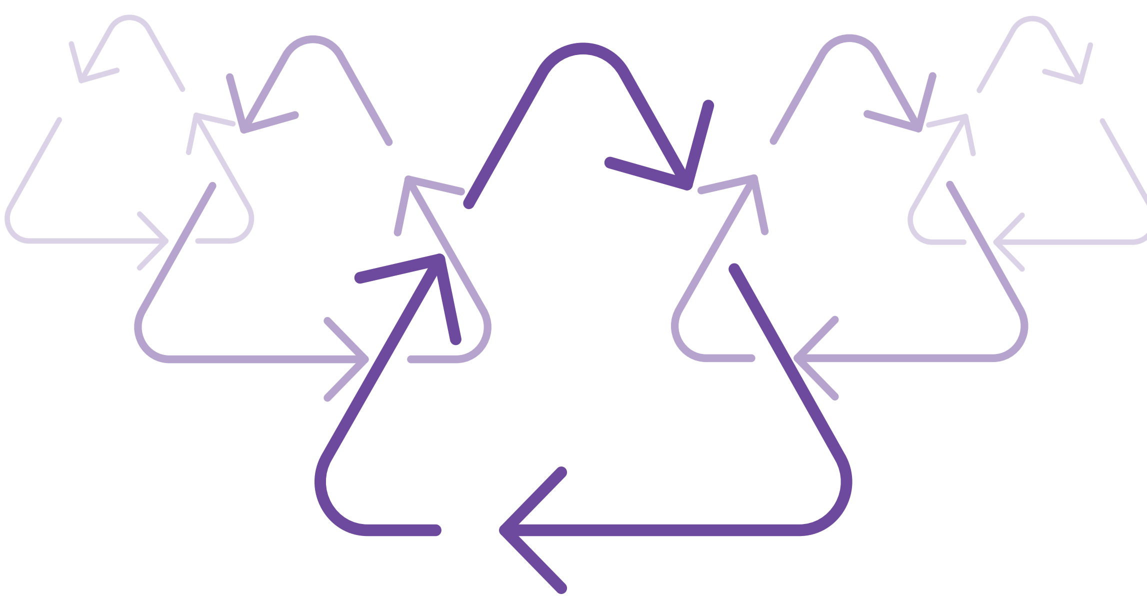
While legislation specifically restricting the use of non-recyclable materials in vehicles has not yet been instituted in the United States, legislation has been introduced in both California and Maine that would shift at least some of the responsibility of recyclability on producers.

Circular Economy and Plastic Pollution Reduction Act 2019-2020

This bill, proposed by the California Department of Resources Recycling and Recovery, would have required producers, retailers, and wholesalers to ensure that all single-use packaging and single-use products that are manufactured on or after January 1, 2030 are recyclable or compostable.[20] According to the bill, "recyclable" means regularly: collected, separated, and cleansed by service providers; sorted into defined streams; processed and reclaimed or recycled with commercial recycling processes; converted to feedstock for making new products; recycled in efficient quantity and quality to maintain market value.[21] Although the bill stalled in the Legislature,[22] it may be reconsidered in 2021.

Maine: Resolve, To Support Municipal Recycling Programs

This resolve asks the Maine Department of Environmental Protection to draft extended producer responsibility legislation that would require packaging producers to help fund the cost of recycling common household packaging.[23] It passed and was signed by Maine's governor in May 2019.

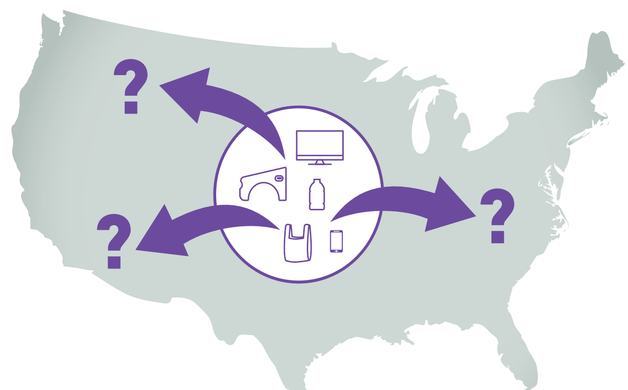


Decreasing capacity for handling materials at end of life is driving the need for additional options

In 2018, China instituted its National Sword Policy, which placed restrictions on imports of certain recyclables, including mixed paper and most plastics.[24] As the number one exporter of plastic scrap in the world,[25] U.S. companies and municipalities are facing a changing recycling landscape that for now has some choosing to just throw their recyclables away—76 percent of U.S. plastic waste was landfilled in 2017.[26] But **as landfills continue to fill up and previously recyclable materials are added to the mix, the financial and environmental costs of landfilling waste will continue to grow**.

Landfill tipping fees have been historically higher in Europe—many countries are currently well above the €100 per ton mark.[27] In the United States, tipping fees are currently far less (an average $52.09 per ton in 2019[28]) but rising—Consumer Price Index data showed that over most of the past decade, trash costs in the United States rose higher than inflation, spiking 4 percent in 2018 compared to the 2.4 percent inflation seen for all items that year and continuing to rise in 2019.[29]

The combination of limited places to send plastic recyclables—a process that is already complex for automotive plastics and polymer composites[30]—and increasing landfilling costs has many companies and municipalities working to **identify new and different ways to manage end-of-life materials**. These include innovative technologies and business models, such as advanced recycling technologies to support circular supply chains (replacing virgin inputs with renewable or recovered materials) and resource recovery (recycling waste into secondary raw materials),[31] as well as introducing extended producer responsibility policies that place the financial responsibility of waste management on manufacturers,[32] among others. The general public will also have to be assured that plastic-led circularity efforts are achieving their intended results, creating even greater demand for new approaches that truly enable more circular plastics and polymer composites.



Challenges facing traditional automotive recycling are creating the opportunity to reimagine it

Automotive recyclers—including dismantlers and shredders—have been successfully diverting material out of landfills and into other uses for decades. But as the parts and materials compositions of vehicles continue to change along with shifting trends in personal mobility, the automotive recycling industry will need to adapt in order to remain economically viable.

Current automotive recycling processes involve dismantlers (e.g., salvage yards) removing and properly disposing of fluids as well as removing and sometimes rebuilding usable parts for sale. Dismantlers then send the hulk (i.e., "what's left") to one of just under 300 shredding facilities across the country,[33] which shred the hulk into fist-sized chunks of material and then use magnets to sort materials to be sold for scrap. This **traditional shredding and sorting process does not allow for a range of valuable materials to be harvested for reprocessing and contaminates others**. As more advanced materials are incorporated into vehicles, this issue could become even more problematic for recyclers.

The U.S. automotive recycling infrastructure is currently spread out throughout the country with markets and partnerships between dismantlers and shredders forming primarily within regional geographies. While this model of operation has worked in the past, this **siloed approach makes the comprehensive incorporation of new processes and technologies that can accommodate advanced materials and parts challenging**. In addition, **online part sales are causing dismantlers to experience more competition and higher customer expectations**—the business relationships that ruled the past are now being replaced by product availability, price, time of delivery, and product delivered as expected or better.[34] This trend is driving down profit margins for recyclers and forcing the industry to start unifying under standard processes and procedures.[35] Other economic influences—such as OEM repair standards, challenged markets for scrap material, and too many unlicensed operators—are also forcing the automotive recycling industry to rethink how they operate.[36]

As the automotive recycling industry reaches its inflection point, the opportunity to innovate with circularity in mind is ripe. **Effective partnerships between automotive recyclers, OEMs, Tier suppliers, materials producers, and technology developers** could help form mutually beneficial supply networks, streamline market development, and significantly contribute to addressing separation and sorting in material, part, and vehicle design. Automotive recyclers would also benefit from **information sharing about the state of the art in vehicle and part design**—some progressive auto recyclers are already working to identify, inventory, and sell more parts by expanding beyond traditional top parts, such as electronic sensors and light-emitting diode (LED) lights.[37] The transition toward a circular economy cannot happen without a commitment from the automotive industry and its suppliers to developing the infrastructure and separating capabilities for vehicle recycling.

Growing demand for mobility as a service requires more durable products with longer lifetimes

Mobility as a service—digitally-enabled car sharing and ride hailing—is expected to become a key driver of growth and profitability in tomorrow's auto markets.[38] Across China, Europe, and the United States, the shared-mobility market was nearly $54 billion in 2016 ($23 billion in the United States alone) and is expected to grow by 28 percent annually from 2015 to 2030.[39]

Currently, a host of mobility as a service options exist. In addition to common ride hailing apps like Uber and Lyft and peer-to-peer car sharing like Turo and Getaround, OEMs—including BMW, Cadillac, Volvo, Jaguar Land Rover, Mercedes-Benz, Porsche, Audi, Genesis, and Nissan—are ramping up their car subscription services, as are third-party service providers like Canvas, Flexdrive, Less, Borrow, Hertz, Fair, and Carma.[40] As a result of this development, through 2030, **roughly a third of the expected increase in vehicle sales from urbanization and macroeconomic growth likely will not happen because of shared mobility**.[41]

As consumers become more comfortable with the concept of mobility as a service, **the growth of ridesharing and car-sharing services will introduce changes to automotive systems**—particularly vehicle interiors. Consumers will continue to expect advancements such as durable interior materials that can stand up to the wear and tear of use as a shared vehicle; scratch-resistant materials to protect expensive displays and touchscreens; and hygienic materials with self-cleaning, anti-odor and anti-microbial properties for improved passenger experience and comfort.

Mobility as a service is also expected to reduce average vehicle lifespans due to increased usage rates. **Vehicles will require resilient and highly durable materials designed to withstand increased usage rates and improve vehicle lifecycle performance**. Design for disassembly, repair, and replacement will also be critical to extend useful product lifetimes and enable the efficient recycling and re-insertion of materials back into new vehicles.

Increasing vehicle electronic content will shift the automotive industry to a **consumer electronics mindset**

CASE STUDY: DELL'S APPROACH TO CIRCULARITY[42,43,44]

With e-waste as the world's fastest-growing waste stream and a global recycling rate of only 15 percent, Dell saw an opportunity to make its products and processes more circular.

Growing closed and open loop networks to source recycled materials	Dell set a 2020 goal of using 100 million pounds of recycled-content plastic and other sustainable materials in their products, which they achieved in the first half of 2019. **Open loop:** Since FY14, Dell has used 56.9 million pounds of post-consumer, recycled-content plastics from sources such as beverage bottles and CD cases in hundreds of product models. They have also used 2 million pounds of reclaimed carbon fiber from the aerospace industry to make their laptop bases and backs as well as plastics from windshields to make waterproof coating for backpacks and bags. **Closed loop:** This process recycles plastics from used electronics—collected through the Dell Reconnect Partnership with Goodwill®, their Asset Resale and Recycling Services (ARR), and other global collection sources—into new plastic parts for their products. Since pioneering this process in FY15, Dell has used more than 35 million pounds of closed-loop plastics in over 125 models of their products.
Expanding product life	Dell's lifecycle approach aims to keep viable products and parts in circulation for longer, with global efforts to reuse, refurbish, and resell products and parts to extend their lifetimes as much as possible. They design their products with long life and ease of upgrade and repair in mind, using minimal glues and adhesives, modular designs, and consistent screw sizes.
Collecting end-of-life products	Through its Global Takeback Program, Dell has recovered 2 billion pounds of used electronics. Dell Reconnect offers consumers free drop-off at participating Goodwill® locations and their ARR provides secure, on-site pickup for commercial customers. Dell also provides guidance on what customers should do with their used products at dell.com/recycle.

As consumer demand pushes vehicles to become **"smart phones on wheels"** that offer more services and features, the automotive industry will shift to thinking more like consumer electronics producers. This means **integrating take back programs, designing for disassembly, and incorporating parts that can be revised, upgraded, and recovered, among other models**.[45] To increase their resilience against external shocks like resource scarcity and reduce their environmental impact, companies such as Dell and Apple are moving toward more circular models of operating.[46] As automakers follow suit, the plastics and polymer composites industry needs to be able to meet their demands.

CASE STUDY: APPLE'S APPROACH TO CIRCULARITY[47]

In an effort to end its reliance on mining, Apple has made substantial investments in improving the circularity of its operations.

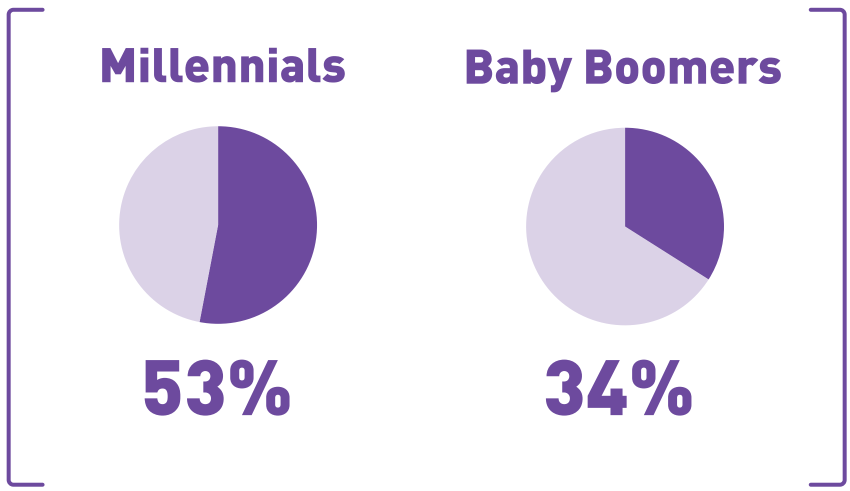
Sourcing recycled and renewable materials	Apple systematically developed "Material Impact Profiles" to assess the environmental, social, and supply impacts for each of the 45 elements and raw materials included in their products and prioritize what to tackle first. They are exploring different ways to make each material more recyclable or renewable, deepening their relationships with downstream recyclers and partnering with suppliers further upstream to use fewer materials and find alternative, recycled sources. For example, they have identified recycled alternatives for 24 different grades of plastic, allowing them to use an average of 38 percent recycled plastic across 82 components for products released in 2019.
Expanding product life	Apple aims to design its products for durability, running its products through its Reliability Testing Lab to prove that the materials it uses can meet rigorous performance requirements. The company also invests in its software update mechanism, claiming to bring updates to more devices than anyone else to enable their customers to use their devices longer. It also has a network of service providers equipped with diagnostics and calibrations to target repairs precisely to avoid unnecessary service and replacement of parts.
Collecting end-of-life products	Apple Trade In provides consumers the opportunity to trade in their devices for a credit if it can be reused or will recycle it for free if not. Apple either refurbishes traded-in phones—in FY18, they directed more than 7.8 million devices to new users—or recycles them, recovering the materials for use in their own products. Apple has also invested in AI disassembly technology to recover materials. It latest robot Daisy can disassemble 200 iPhones per hour and remove the product materials of 15 versions of the iPhone.

Growing **consumer sentiment against single-use plastics** could extend to engineered plastics

Negative consumer sentiment toward single-use plastics has had a dramatic impact on the way the world treats these materials. As many as 127 governments have taken action to reduce the use of plastic bags through policy efforts and measures and about 27 nations have active legislation to either ban or significantly restrict single-use plastics (i.e., straws and dishware).[48] Many businesses have followed suit, with companies like Aramark, The Coca-Cola Company, and McDonald's taking action toward the removal of single-use plastics from their supply streams.[49] And, according to an Accenture survey, 22 percent of consumers have stopped buying food and beverage packaging altogether.[50] In Europe, some projections indicate that this negative consumer attention is expected to dampen long-term demand for petrochemicals going into plastic production—including ethylene and propane—as well as plastics like polyolefin and polyester.[51]

A Nielsen survey indicates that 73 percent of Millennials (those born from 1977 to 1995) are willing to pay more for sustainable goods and are more willing than Baby Boomers (53 percent versus 34 percent) to forgo a brand in order to buy products that are environmentally friendly.[52] It's this future, sustainability-focused market that automakers are setting their sights on. With even the environmentally friendly wind industry facing negative public attention for the tens of thousands of aging composite turbine blades heading to landfills,[53] **the automotive plastics industry can proactively address this change in consumer sentiment by working with OEMs to address shifting customer preferences**.

Percentage of people **willing to forgo a brand** in order to buy products that are **environmentally friendly**



Without highly circular plastics and polymer composites, automakers may find themselves with no choice but to turn to other material solutions.

In the same way that mainstream food and beverage companies[54] have committed to redesigning their products and business models,[55] the trends above could force automakers to require recyclability in automotive design. Inaction now from the plastics and polymer composites industry may prevent them from being ready to respond to such abrupt changes, disadvantaging polymer-based materials compared to other options.

Fortunately, the plastics and polymer composites industry recognizes the need to focus on circularity and **is already taking steps to transition toward a circular economy**.

Repurposing **plastic waste and recyclates** into automotive materials and parts

BMW

BMW is **reusing CFRP production scraps** to manufacture the roofs for its i3 and i8 models as well as the rear seat structure in the i3. SGL Automotive Carbon Fibers reports that 10 percent of the CFRP used in the BMW i vehicles is recycled.[56]

Ford

Ford is **designing molded plastic engine components using recycled post-consumer nylon carpet**. Over the past 20 years, partner Wellman/PRET has supplied Ford with around 350 million pounds of nylon from recycled, post-consumer carpet.[57]

Jaguar Land Rover

Jaguar Land Rover has used **recycled feedstock from BASF** to manufacture plastic **front-end carrier prototypes** for its first electric SUV.[58]

Renault

Renault worked with Les Filatures du Parc (a French company specializing in carded yarn) and Adient Fabrics (the world's leading supplier of automotive seats) to develop a unique, patented **textile product made from safety belts, textile scraps and plastic bottle recycling**. The innovative short loop manufacturing process reportedly reduces the carbon footprint by 60 percent compared to the standard process.[59]

The plastics and polymer composites industry is already working to help automakers meet their goals of increasing the use of recycled materials in their vehicles. The use of recycled materials not only reduces the demand for virgin materials but can also help reduce CO_2 emissions over the entire lifecycle of the vehicle to help automakers meet sustainability targets—the processing of recycled aggregates can generate 40–70% fewer CO_2 emissions compared to virgin aggregates.[60]

BASF

BASF produces polymers from both post-industrial and post-consumer waste. Nypel® 6030G HS BK resin uses **post-industrial waste, such as films or carpet fiber**, while Petra® 7010, a thermoplastic polyester, is based on **100% post consumer polyethylene terephthalate (PET)**.[61]

Braskem

Braskem currently offers an I'm green™ **post-consumer recycled polypropylene (PP)** to the U.S. market for use in automotive, housewares, and consumer goods. Feedstock for the I'm green™ recycled PP is **derived from PP twine** typically used for hay bales in the agricultural sector that would otherwise be directed to landfills after use.[62]

Celanese

Celanese's ECOMID® recycled PA66 and PA6 compounds contain between **20% to 95% high-quality, post-industrial recycled polyamide fibers and textiles.** Using material recycled from the automotive, furniture, and construction industries, ECOMID® has been used in engine fans, engine covers, cable channels, strut bearings, airbag housing, shift lever/adapter plate acoustic baffles, and fuse box holders.[63]

LANXESS

Lanxess produces polybutylene terephthalate (PBT)/PET blends—Pocan® ECO—reinforced with glass fiber and **up to 30% post-consumer recyclate** that are suitable for processing by injection molding and have been used in the electrical and electronics industries.[64,65]

SABIC

SABIC produces CYCOLOY™ C8080REC—a **resin system for composite materials made from recycled polycarbonate (PC)** and **acrylonitrile butadiene styrene (ABS)**.[66] It has been used on numerous exterior automotive trim applications.

Using **renewable feedstock** in plastics and polymer composites

BASF

As part of its Elastoflex® E generation of systems, BASF has developed a **foam system based on renewable raw materials**. Elastoflex® E 3496/102 uses castor oil as a renewable raw material and can be used to produce complex components that are both light and thin. Used primarily in instrument panels and door elements, this development was awarded an Society of Petroleum Engineers (SPE) Environmental Category Award in 2017.[67]

BASF's CONTOURA™ combines the company's Acrodur® resins with a variety of natural, recycled, or synthetic fibers to produce a **pre-preg composite** that is ready to be molded for a variety of uses, including the automotive and RV industries. CONTOURA™ uses both thermoset and thermoplastic grades of Acrodur resins to provide increased thermo-mechanical stability, increased rigidity, and up to 20 percent lighter weight than other nonwoven fiber composites. Other benefits include a lower carbon footprint than current materials—when paired with natural fibers, CONTOURA™ offers up to **85 percent renewable or natural content**.[68]

Braskem

Braskem's I'm green™ bio-based products include both a **polyethylene (PE) and ethylene vinyl acetate (EVA) produced from sustainably sourced sugarcane**. I'm green™ bio-based PE retains the same properties, performance, and application versatility of fossil-based PE, making it immediately usable in the plastics production chain.[69] Both the I'm green™ PE and EVA are able to be recycled in the same chain as traditional PE and EVA and are the first renewable materials of their kind to be produced on an industrial scale.[70,71]

Celanese

Celanese collaborated with International Paper to develop an application for Ford's 2018 Lincoln Continental Luxury sedan that used **composites combining cellulose fiber from trees with long-glass fiber in a PP matrix**. The application resulted in significant cost savings achieved by reducing weight up to 25 percent per part. Implementing this solution achieved cycle time reductions of approximately 20-40 percent and significant energy savings resulting in an estimated 14 million kilograms (15,400 tons) of carbon dioxide (CO_2) reductions.[72]

Covestro/Neste

Covestro and Neste have partnered to promote the use of sustainable raw materials in plastics production. Neste will supply Covestro with hydrocarbons made from entirely renewable raw materials, such as waste and residue oils and fats. Covestro will be able to incorporate the **renewable hydrocarbons** directly into their existing production infrastructures to produce **high-performance plastic** for use in applications such as car headlamps, LED lights, and automotive glazing.[73]

In addition to materials made from recycled content, the industry is also working to develop **plastics and polymer composites materials that use renewable materials**. The addition of raw materials such as plant-based oils and naturally occurring fibers are diversifying the industry's feedstock options while helping automakers meet their emissions reduction, sustainability, and circularity goals.

Ford

Ford has worked to incorporate eight different types of renewable feedstocks into their production processes, including soy, castor beans, rice hulls, coconut, cellulose, kenaf, wheat straw, and jute.[74] Some of the applications using these materials include:

Soy-based polyurethane foam in seat cushions, backs, and headrests, which helped Ford reduce its annual CO_2 by more than 20 million pounds and its volatile organic compound emissions by 67 percent.[75]

Wheat straw PP composites in injection molded interior components of the 2010 Ford Flex, which reduce CO_2 emissions by 30,000 pounds per year.[76]

PP compound reinforced with rice hulls were used to replace talc-reinforced PP in electrical support brackets in the 2014 Ford F-150.[77]

Kenaf fiber integrated into PP door bolsters of the 2013 Ford Escape, which has reduced the weight of the door bolsters by 25 percent and improves fuel economy.[78]

LANXESS

In 2013, LANXESS ran a production campaign of a **bio-based PBT using butanediol (BDO) made from sugars**. Bioengineering manufacturing company Genomatica patented the commercially proven process for creating bio-based BDO, which uses direct fermentation to convert the sugars. The resulting BDO met LANXESS specifications and enabled it to be directly fed into LANXESS's continuous PBT production process.[79]

SABIC

As part of its TRUCIRCLE™ solutions, SABIC launched a **Certified Renewable PC plastic** (based on International Sustainability & Carbon Certification [ISCC] certification) that is **made from 60 percent renewable feedstock** (i.e., tall oil derived from pulp waste) that may be used for applications in all market segments, including automotive. SABIC's PC cradle-to-gate life-cycle assessment study reveals potentially significant reductions in carbon footprint (up to 50 percent) and fossil-fuel depletion (up to 35 percent) for production of its LEXAN™ PC resin with renewable feedstock.[80]

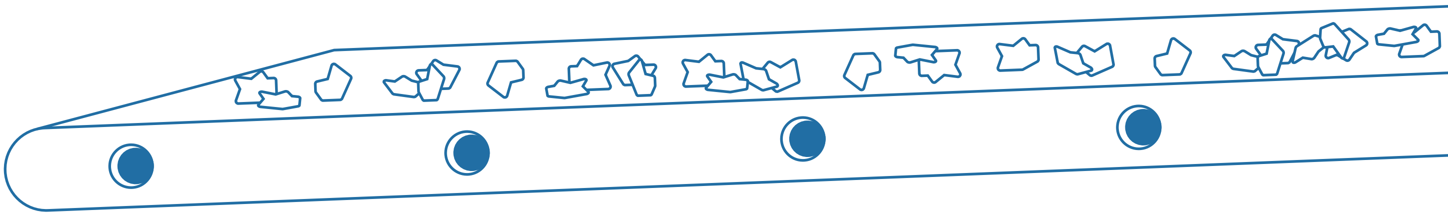
Advancing **materials separation and cleaning** technologies

Advanced plastics separation technology

Ad Rem—a joint venture between machine building group Valtech and recycling group Galloo—is a Belgian-based recycling company that provides **advanced separation technology** for e-scrap, car shredder residues, and incinerated bottom ash.[81] Their patented plastic separation process enables Ad Rem to **extract and fully recycle the polyolefins and polystyrenes (PS) from the plastic waste at a level of quality that the company states meets all required standards as demanded by the automotive industry**, which automatically qualifies it for a wide array of other possible applications.[82] Ad Rem is currently building a plastics recycling facility in Japan that will be operated by Planic—a joint venture between Toyota Tsusho, Veolia Japan, and Kojima Sangyo—with the potential to process 40,000 tons of plastic scrap per year.[83]

Cleaning technology for painted TPO and PC/ABS plastics

Geo-Tech—a recycling company that specializes in coated plastics used in automotive and consumer applications—employs a **cleaning process** that can **recycle painted thermoplastic olefin (TPO) and PC/ABS blend plastics**.[84] The company works with automotive manufacturers to recycle post-industrial plastics, which is a service that not only reduces waste but also saves money. Geo-Tech worked with one automotive manufacturer in Michigan to recycle 100 percent of their painted TPO and PC/ABS plastics—its cleaning process produces recyclate materials that met the original prime material specifications.[85]



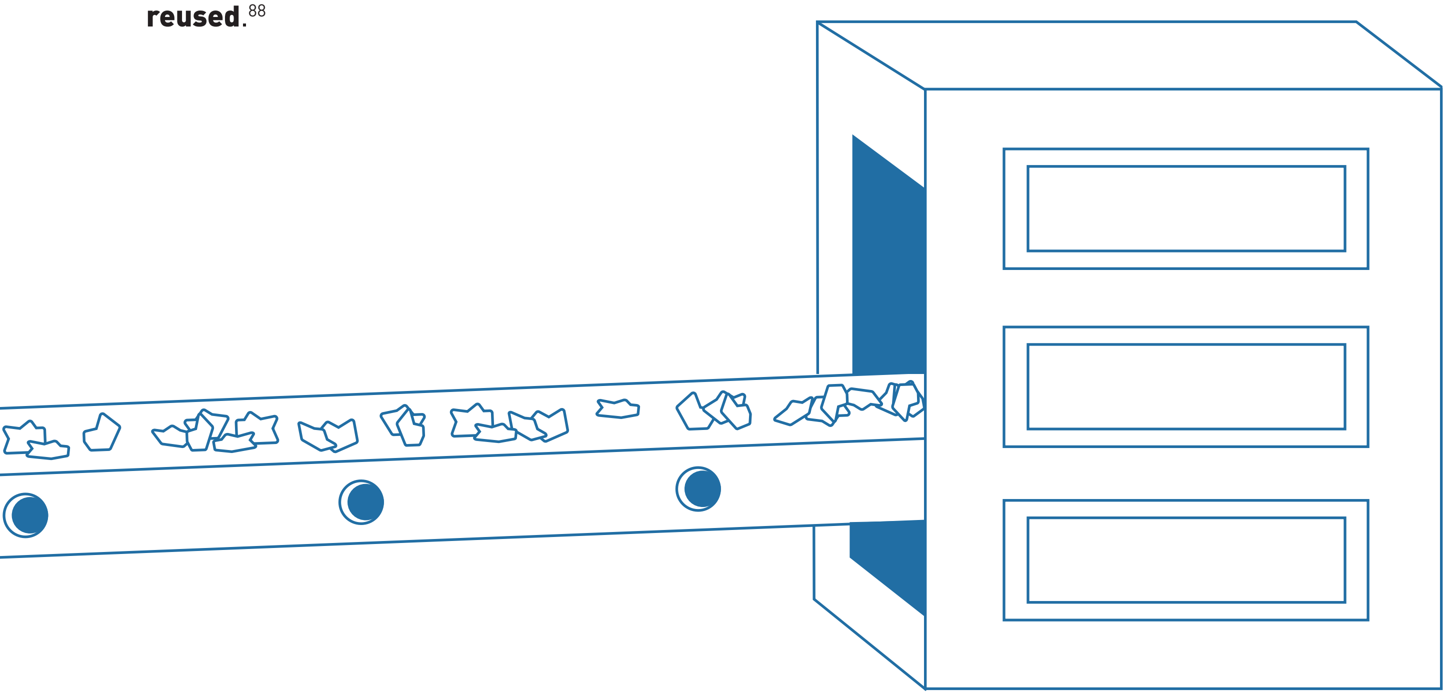
Proper washing and sorting of recycled plastics into single polymer groups is challenging but critical to ensuring the highest quality recycled materials. Chemical companies have the potential to play an important role in improving the operations of plastics-waste collection and sorting by contributing new technology in areas such as better solvents and additives for washing plastics as well as tracing materials that can be added to plastics to facilitate automated infrared sorting.[86]

Cleaning and sorting technology for heavily contaminated PE film

FVH Folienveredelung Hamburg GmbH & Co. KG uses **heavily contaminated film scraps** as a raw material source at its production facility in Schwerin to make high-quality PE plastic pellet (ecophoenixx®). The company uses its HydroDyn® washing plant technology to wash, separate, and dry the material and a patented extruder system from EREMA that uses melt filtration upstream of extruder degassing to produce the high-quality pellets.[87] As a result, **100 percent of the PE input material can be reused**.[88]

Cleaning technology for recycled PP and PE

Quality Circular Polymers (QCP), a Netherlands-based joint venture between LyondellBasell and SUEZ, is working on an **advanced sorting and cleaning technology** to produce **high-quality, high-value recycled PP and PE**.[89] The joint venture—in which LyondellBasell markets QCP's materials and SUEZ secures the feedstock for the plant—aims to process 600,000 tons of plastic waste in 2020.[90]



Designing plastics and systems for **longevity, recyclability, and disassembly**

Design for longevity

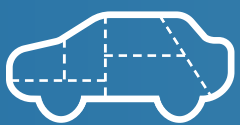
Product life-extension, a key aspect of circularity, is typically achieved through remanufacturing and repairing and can go a long way in reducing landfilling. **Solvay** has developed **UV stabilizers** that extend the lifespan of automotive polyolefin plastic parts. [91]

Design for recyclability

Dow is working to develop **high-performance resins, additives, and compatibilization technologies** to minimize issues like cross-linking, high odor, and off-color that are commonly associated with recycled plastics. Dow's RETAIN is a resin technology that enables ethylene-vinyl alcohol copolymer (EVOH) packaging to be recycled at store drop-off locations.[92] Its VERSIFY resin technology enhances the performance of recycled PE contaminated with polypropylene to allow for the incorporation of recycled content.[93]

Exxon Mobil's Vistamaxx™ performance polymers **compatibilize PE and PP plastics**, allowing them to mix in the melt. This removes the need for the costly and time-consuming separation of recyclates, which can help manufacturers use more recycled material in their high-value applications. Using high-density polyethylene (HDPE) recycle and 5 percent Vistamaxx polymers can help the environment and offer cost saving potential.[94]

Rethinking the design of automotive plastics and polymer composites, the components they make up, and the systems that process them with end of life in mind will be a critical aspect of a truly circular economy as well as a potential market advantage. Some plastics producers are already working with their partners in the automotive value chain to do just that.



Design for remanufacturing and disassembly

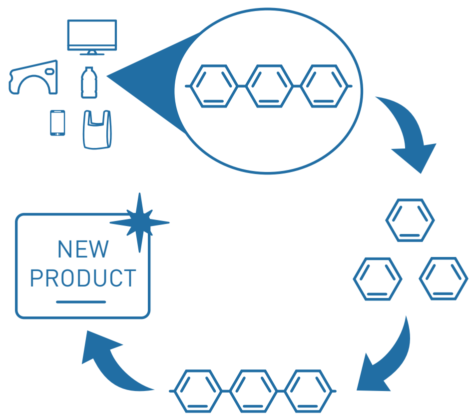
Designing products so that they can be easily, cost-effectively, and rapidly taken apart at end of life requires coordination The **U.S. Department of Energy's Reducing EMbodied-Energy And Decreasing Emissions (REMADE) Institute** has been supporting efforts to improve the coordination of design for disassembly across the value chain.

Design for Remanufacturing project with RIT, Caterpillar, and Remanufacturing Industries Council (RIC) – Through this project, the team created a set of **"design for remanufacturing" rules** that allow design engineers to integrate remanufacturing considerations in component and part designs. The aspiration is to integrate these design rules into various engineering tools and computer-aided design (CAD) platforms and verify the design rules on existing parts provided by the industrial partner to identify potential changes to improve part manufacturability. This integration of remanufacturability into the design paradigm is expected to enable energy savings and emissions reductions.[95]

Concept of Value-Retention Processes – Dr. Nabil Nasr, founding CEO of REMADE, introduced the term **"Value-Retention Processes (VRP)"** in a 2018 report released on behalf of the United Nations Environment Programme's International Resource Panel (IRP). VRP is described as "manufacturing processes that retain value within a circular system (versus linear system)." VRPs include: arranging direct reuse, repair, refurbishment or comprehensive refurbishment, and remanufacturing. The report also details "design principles for VRP products" and their associated design approaches and claims that for vehicle parts, VRPs can reduce raw material use, GHG emissions, and embodied energy for vehicle parts by 80 to 99 percent.[96]

Developing **advanced recycling technologies**

Advanced recycling converts plastic waste into feedstock that can be used to create a variety of chemicals and products, including new plastic.[97] At least 60 organizations are currently working to scale up depolymerization, pyrolysis, and other emerging plastic processing methods—the North American market for the resulting products could top $120 billion annually.[98] A recent ACC study noted that investing in 260 new facilities using advanced recycling could produce $9.9 billion in economic output and generate more than 38,000 jobs in local communities across the country.[99] And since the implementation of China's National Sword policy in January 2018, $4.8B in cumulative recycling investments have been in announced in the U.S. alone.[100]



Depolymerization

Using a chemical reaction, depolymerization breaks down molecule networks, yielding smaller molecules (monomers and oligomers). Below are just a few of the depolymerization advances the industry is currently pursuing.

Plastics manufacturer **Trinseo** has teamed up with other PS manufacturers in Europe to form **Styrenics Circular Solutions**, which aims to transform the styrenics industry by **unlocking PS circularity** and making the material infinitely recyclable.[101] Recently, the joint initiative announced a collaboration with Pyrowave—a pioneer technology developer in the plastic-to-plastic advanced recycling—that includes an in-depth evaluation of the company's proprietary **catalytic microwave depolymerization technology**.[102]

Loop Industries decomposes PET back into monomers (like-new recycled PET pellets) and has established major partnerships to change the recycling supply chain (Gatorade, PepsiCo, Coca-Cola, L'Oreal, Nestle Waters, and Evian).[103]

Petrochemical company **Indorama** signed a deal with Loop industries to **build a PET depolymerization unit in the United States** that can depolymerize **up to 88 million pounds of scrap PET annually**.[104] Indorama's objective is to achieve at least 25 percent recycled content in plastics sold for packaging production and plans to do so by investing $1 billion in recycling over the next five years.[105]

ReVital Polymers, Pyrowave, and INEOS Styrolution launched a consortium to recycle single-use PS packaging through catalytic microwave depolymerization technology.[106]

Feedstock recycling

Feedstock recycling involves the use of thermal processes—typically pyrolysis and gasification—to convert polymers into simpler molecules, such as hydrocarbons, petrochemicals, and fuels, that can be used to make other products or burned to recover thermal energy. Examples of current efforts to advance and scale up this technology include the following:

Global specialty chemical company **Eastman** offers two innovative recycling solutions: a **carbon renewal (gasification)** technology that can transform flexible plastic packaging, plastic films, polyester carpet and mixed plastics for use in durables, packaging and textiles, and a **polyester renewal** (glycolysis and methanolysis) technology that can process waste polyester for the production of new polyester-based polymers.[107]

In partnership with **Plastic Energy**, **SABIC**—as part of its TRUCIRCLE™ solutions—is constructing a **mixed-plastic waste pyrolysis facility** in the Netherlands that is expected to be operational by 2021.[108] The plant will produce petrochemicals and feedstock precursors and is estimated to have the potential to process 20,000 tons of recovered plastics (PE, PP, and some PS) annually.[109]

Agilyx's Oregon-based **pyrolysis plant breaks down up to 10 metric tons of PS daily into monomer precursors** (i.e., raw materials for conversion back into new polymers).[110] Agilyx is currently working with 30 companies on PS depolymerization projects—chemical company Ineos Styrolution plans to use Agilyx's technology to build a plant in Illinois with the potential to convert 100 tons of PS waste per day.[111] More recently, Agilyx announced a partnership with Lucite International (an industrial material subsidiary of Mitsubishi Chemical Corporation) to deliver an advanced recycling solution for polymethyl methacrylate (PMMA), a synthetic resin used in shatter-resistant windows, skylights and aircraft canopies.[112]

Through its ChemCycling™ project, **BASF** is **cooperating with partners** who use thermochemical processes **to transform plastic waste into pyrolysis oil to scale up feedstock recycling**.[113] The focus of BASF's project is on difficult-to-recycle plastic waste (i.e., multi-layer food packaging, automotive composites). In the pilot phase, BASF has sourced batches of pyrolysis oil and manufactured first prototypes with customers (e.g., packaging, refrigerator components, insulation boxes for sensitive applications). BASF has also invested in Quantafuel—a Norwegian start-up company and mixed plastic waste pyrolysis specialist—to help **develop their own advanced recycling business**. Automotive manufacturer Jaguar Land Rover has used BASF's recycled feedstock to develop a plastic front-end carrier prototype for its first electric SUV.[114]

Toyota is partnering with materials producer **Toray** to build a pilot plant to demonstrate an energy-efficient thermal decomposition **recycling method for carbon fiber reinforced polymer (CFRP) composites**. The method will thermally decompose the composite matrix resin and use it as the energy source to recover carbon fiber.[115]

Optimizing manufacturing processes to improve efficiency

Plastics and polymer composites offer OEMs and parts suppliers tremendous flexibility to increase the efficiency of their manufacturing processes. With plastics, manufacturers have a range of available options for reducing waste and improving efficiency through approaches such as parts integration and the use of regrind and reprocessing of defective parts. The high strength-to-weight ratio of many novel plastics also allows automakers to reduce vehicle weight, delivering fuel-efficiency improvements.

Thin wall instrument panels

SABIC's STAMAX™ resin helps **decrease instrument panel (IP) wall thickness** to less than 2mm thick (compared with the 2.4 mm/0.09 in. microcellular molded benchmark).[116] Using a proprietary process from International Automotive Components (IAC), the manufacturer injects the material into the mold with a foaming agent, then immediately opens the mold a few millimeters to control the final density of the part. During the process, the foaming agent produces CO_2 bubbles that create a foamed core.[117]

The foamed solution with STAMAX™ resin requires less material than a comparable non-foamed solution, **delivering 15 percent weight savings** (compared with a comparable solid plastic component) and resulting in **CO_2 emission reduction**.[118] In addition, the solution with STAMAX resin delivers very low VOC emission levels and enables shorter cycle times.[119] STAMAX™ resin was used to produce IPs for both the **2017 BMW Mini Countryman**[120] and the **2017 Lincoln Continental**.[121]

Blow-molded air ducts

ExxonMobil's Santoprene™ thermoplastic vulcanizates (TPVs) can be blow molded to produce a wide variety of products with the performance of rubber and the processability of plastic, such as rack and pinion boots, air ducts, and suspension bellows. The material exhibits excellent retention of physical properties after repeated histories when blow molded, which allows for up to **20 percent of regrind usage** throughout the production process.[122]

Santoprene TPV was used to produce a multi-functional-exchange, **blow-molded air duct used on the Subaru 2010 Legacy & Outback**. Along with hard PP resins from Channel Prime Alliance, the resulting air duct replaced a combination of rubber hose, metal and resin ducts, the resonator, and clamps with a **single part produced in a single process step** where material change, wall thicknesses, and inner pressure are all controlled very precisely. The application **saved an estimated 30-40 percent in weight and 25-35 percent in both direct and indirect costs**.[123]

Mono-material headlamps

Covestro designed an automotive headlamp made exclusively out of Makrolon® polycarbonate-based materials. The mono-material design uses **more than 10 fewer parts and fewer manufacturing steps**, reduces the need for separation before recycling, and results in a weight savings of **1.8 kg less weight per lamp** compared with the existing metal-based multi-material design. It also features infrared transparency to support sensor integration and solar-blocking qualities to extend life.[124]

Investigating the **viability of automotive plastics recovery models**

Effectively removing plastics and polymer composites from end-of-life vehicles and recycling or reusing them requires not just technology that can do the job, but also coordination between the plastics industry, collision repairers, auto recyclers, Tier suppliers, OEMs and a business model that provides value to all stakeholders. To date, the plastics industry has taken steps to explore and test models for creating new sources of plastics from end-of-life vehicles.

Plastics recovery from bumper fascia

The **Plastics Industry Association** led a three-phase project with 19 companies to explore the viability of collecting and recycling auto plastics from end-of-life vehicles and building a basic recovery model for whole parts before shredding. Beginning with a focus on TPO in bumper fascia, **Phase I demonstrated the technical feasibility of recovering end-of-life vehicle bumpers** from a broad range of vehicles to create very high-quality TPO pellets at a cost less than prime TPO. It also **explored potential markets**, getting feedback from molding company i2Tech and Toyota, and created a directory of recyclers who process TPO bumpers nationwide.[125]

Phases II and III focused on scale-up, exploring whether other recyclers could produce high enough quality stock and whether the final recycled plastic continued to deliver sufficient quality. The Institute of Scrap Recycling Industries (ISRI) initially said that auto shredders did not see an economic benefit to removing bumpers, but the study suggests exploring other options—for example, if repairers, especially those whose OEM core programs only require a piece of the original part rather than the complete fascia, could send fascias to the plastics industry for lower net expense than the cost of a landfill or even make a net profit, it could be economically beneficial for all involved.[126]

Plastics recovery from battery cases

Federal requirements to recover lead from vehicle batteries has helped push the recycling of their plastic components as well—**more than 95 percent of battery cases are recycled**.[127] Battery recycling facilities break down the batteries and separate the components, recovering the plastic PP pieces which are washed, dried, and sent to a plastic recycler. Employing a closed loop model, **recyclers heat and pelletize the plastic into uniform sizes and send them to manufacturers** who use them to create new battery cases.[128]

Participating in the supply "web"

Making new connections with other companies who stand to benefit from materials recovery and recycling is critical to reimagining supply chains in support of a more circular economy. More than 1,500 businesses—including automakers and chemical companies—are currently participating in the Materials Marketplace. Spearheaded by the United States Business Council for Sustainable Development, the Materials Marketplace operates as a cloud-based platform where traditional and nontraditional industrial waste streams are matched with new product and revenue opportunities.[129] Instead of a traditional linear supply chain, this creates a supply "web" that relies on building and interconnecting business relationships, jobs, and economic activity to deliver value.[130]

Funding R&D for circular economy solutions

Recognizing the need to uncover new ways of making plastic and polymer composites more circular, the industry has already taken steps to fund R&D in a variety of areas.

Alliance to End Plastic Waste

All over the world, public and private sectors have come together to address the plastic waste challenge. The Alliance to End Plastic Waste is an independent and global non-profit, public charity with **50 member companies and supporters** partnering with national and local governments, environmental and economic development NGOs, and communities to develop solutions that will help solve the global plastic waste challenge. The Alliance is **targeting to invest $1.5 billion over five years** toward solutions to prevent the leakage of plastic waste and contribute to a circular economy, with focus in four strategic areas: waste management and recycling infrastructure, innovation, education and engagement, and clean up.[131] Through the development of sustainable and economically viable solutions, the Alliance will scale investments and impact working with venture capital, private investors, development banks, and governments for transformational change.

Institute for Advanced Composites Manufacturing Innovation (IACMI)

IACMI is funding several projects on circularity and recyclability of fiber-reinforced plastic composites (FRPCs), including the following:[132]

A **scalable low-heat pyrolysis method** that can recover all liquids, tars, and oils from end-of-life composite materials and convert them into clean synthetic gases while recovering valuable glass and carbon fiber materials; it has the dual benefit of improving the sustainability of composite materials while reducing the amount of scrap and end-of-life composites sent to landfill.

A patent-pending **recycling approach to reclaim carbon fiber composites into downcycle material applications**, including shipping containers, marine, infrastructure, and construction applications.

A **closed-loop chemical recycling method for uncured automotive carbon fiber pre-preg** manufacturing scrap that uses 95 percent less energy at half the cost of virgin carbon fiber.

A **process for fabricating sheet molding compound using recycled carbon fiber** that is estimated to reduce cost by 50 percent and embodied energy by more than 60 percent compared with currently available carbon fiber sheet molding compound.

U.S. GOVERNMENT AGENCIES: SUPPORTING A MORE CIRCULAR ECONOMY FOR PLASTICS AND POLYMER COMPOSITES

In addition to the automotive plastics and polymer composites industry, U.S. Government agencies have launched significant R&D and education and workforce development efforts focused on improving the recovery, recycling, reuse, and remanufacturing of plastics.

In August 2020, DOE's **REMADE Manufacturing Institute** announced approximately **$35 million to support R&D** that will enable U.S. manufacturers to increase the recovery, recycling, reuse, and remanufacturing of plastics and other materials.[133] Funding will be available to support both transformational R&D projects—those with the potential to transform recycling and remanufacturing industries through technological innovation—or traditional R&D projects, which align with the research priorities in the REMADE roadmap and help to achieve REMADE's four primary goals:[134]

- Develop technologies capable of reducing energy and emissions through a reduction in primary material consumption and an increase in secondary feedstock use in energy-intensive industries
- Develop technologies capable of achieving "better than cost and energy parity" for key secondary materials
- Promote widespread application of new enabling technologies across multiple industries
- Educate, train, and develop the incumbent and future workforce to support deployment of REMADE technologies

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As part of a $96 million funding opportunity focused on bioenergy research and development, DOE released an FOA in January 2020 on the **upcycling of waste/legacy polyolefins to fiber reinforced polymer matrix composites** for automotive, industrial, and construction applications.[135]

In March 2020, DOE announced up to **$25 million in funding for plastic recycling R&D**—BOTTLE: Bio-Optimized Technologies to Keep Thermoplastics out of Landfills and the Environment—as well as a National Laboratory-led BOTTLE Consortium focused on designing new plastics and recycling strategies in collaboration with industry and academia. The funding opportunity focuses on topic areas including highly recyclable or biodegradable plastics, novel methods for deconstructing and upcycling existing plastics, and collaborations with the BOTTLE Laboratory Consortium to tackle challenges in plastic waste.[136]

The U.S. Department of Energy (DOE) and ACC signed an **MoU to collaborate on Innovative Plastics Recycling Technologies** in February 2020.[137]

NIST awarded a $3.2M grant to fund the Center for Materials and Manufacturing Sciences, a research center focused on polymers and polymer recycling at Troy University in September 2018.[138] The first steps of establishing the center include developing a state-of-the-art laboratory in polymer recycling to help advance capabilities, as well as offer a support structure for local and national industries. In the long term, the Center aims to address plastics recycling from a holistic perspective, addressing complex issues of collecting, sorting, and cleaning with characterization.

But **there is more to be done**. We need to come together as an industry to **prioritize and work on activities to advance circularity**.

Uncovering the opportunities that a circular approach can offer the automotive plastics and polymer composites industry requires close coordination with all stakeholders in the automotive value chain, including vehicle shredders and recyclers. The industry-identified areas of focus that follow that can serve as a starting point to help guide the collective path forward.

Continue to develop **advanced recycling and recovery technologies**

Advanced recycling has shown tremendous promise in early stage development to yield true circularity for automotive plastics and polymer composites. In addition to providing options for handling diversely formulated end-of-life automotive and engineering resins and turning them into valuable feedstock, a recent ACC report revealed the potential **economic impact of expanding advanced plastic recycling and recovery (APRR) technologies in the United States to be nearly $10 billion**.[139]

Leveraging federal funding at national laboratories to improve APRR technologies—such as high-speed, non-destructive testing and evaluation (NDT/NDE) techniques for end-of-life sorting to rapidly identify grades of plastics and polymer composites for reuse and remanufacturing and methods for cost-effectively recovering and retaining the performance and properties of advanced fibers—will help demonstrate the feasibility of recovering and recycling engineered plastics. For promising sorting and recycling technologies that already exist, demonstrating their reliability and ability to cost-effectively handle a broad spectrum of materials at scale will be a critical step in assuring stakeholders that undue strain will not be placed on the recycling infrastructure.

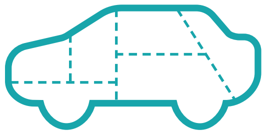
Increasing plastics content in vehicles and, as a result, in automotive shredder residue (ASR) also makes investigating treatment and reuse technologies for ASR a sizable opportunity for the industry. The potential new feedstreams of recycled plastics that the change in ASR content represents has the potential to change economics of ASR recycling, making the development of new technologies in this area a priority.[140]

Invest in a **robust and coordinated recycling infrastructure**

In addition to developing innovative APRR technology, the automotive plastics and composites industry must invest time and resources into **laying the groundwork for a robust recycling infrastructure that will bring waste plastics back into the value chain**. This is not something that can happen in a vacuum—the industry must form a partnership network with state and local economic development groups, the vehicle salvage industry, automotive recyclers, Tier suppliers, and OEMs to identify effective, realistic APRR strategies non-commodity/mixed plastics that are mutually beneficial for all involved. Leveraging this collective expertise to address challenges like the consistency of post-consumer resin material streams, improving collection schemes, and implementing new APRR technologies at scale, will help build a more robust and convenient infrastructure that will motivate circularity stewardship and ensure widespread impact.

A key aspect of building this infrastructure effectively is working with federal, state, and local governments to secure regulatory support for advanced recycling technologies and help drive R&D incentives and industry co-investments.[141] To date, bills have been introduced such as HR 7228 - Plastics Waste Reduction & Recycling Act, which would send funds to NIST, NSF, DOE, EPA, and NOAA to increase research and coordination on plastic waste reduction and recycling,[142] and HR 5115 - RECOVER Act, which calls for federal funds to improve various aspects of recycling collection and processing infrastructure and would establish a recycling infrastructure program within EPA.[143] In 2019, Iowa, Tennessee, and Texas became the fourth, fifth, and sixth states to pass bills supporting advanced recycling facilities that convert plastic waste into raw material via advanced recycling, which includes pyrolysis and depolymerization.[144,145] In addition to ongoing advocacy work, the industry could consider developing guidelines and recommendations for lawmakers on how to support and facilitate the building of the infrastructure needed for versatile, effective, and efficient recycling of mismanaged plastic waste.

Uncovering new business models that can help pay for infrastructure development and position these facilities as economic drivers for communities is another important area of focus. In Iowa, converting 25 percent of the state's post-consumer plastics into feedstocks and transportation fuels could support five advanced recycling and recovery facilities and generate $309 million in economic output annually.[146] In Tennessee, converting 25 percent of the state's post-consumer plastics into manufacturing feedstock and transportation fuels could support eight advanced recycling and recovery facilities and generate $264 million in economic output per year.[147]



Design high-quality **automotive plastics for easier disassembly, refurbishment/reuse, and recycling**

Plastics and polymer composites have an inherent flexibility in their design—it's what makes them an ideal material for so many of the personal mobility advances of the future. The industry is uniquely positioned to **leverage the qualities that plastics offer to build eventual disassembly, refurbishment/reuse, and recyclability into the DNA of its materials** while maintaining the lightweight strength that defines today's automotive plastics and polymer composites.

Developing automotive plastics in a way that is connected to the development and deployment of corresponding after-use systems and infrastructure requires close coordination with stakeholders throughout the value chain. Advancing end-of-life sorting and identification, such as incorporating consistent identifiers/markers (e.g., tracing materials that can be added to plastics to facilitate automated infrared sorting) is needed to help track parts and materials throughout the value chain and facilitate logical sorting and distribution. Industry members should also seek opportunities to work with OEMs and Tier suppliers on making part dismantling/removal of plastic parts prior to shredding the car body not just a part of material design, but also an integral part of the vehicle design phase. To help guide materials development, the industry could consider leading the development of multi-stakeholder domestic policy proposals to set standards and requirements for the recyclability, repairability, and ecological design of automotive plastics and polymer composites.

Conduct **rigorous lifecycle assessments** of circular plastics and polymer composites

Conducting a thorough assessment of the entire lifecycle of circular plastics and polymer composites—including robust reuse and recovery approaches—would provide information to assess the environmental impact advantages of these plastics compared with other materials choices. To do so, the industry could establish an industry group or committee to identify and set lifecycle assessment (LCA) standards for high-use automotive plastics and composites to ensure consistency across the industry and frame the advantages of circular materials in a data-driven way that would be useful to the automotive industry.

A more rigorous LCA that proves significant advantages of circular plastics and polymer composites development could go a long way in **boosting the development of new automotive applications with high recovered materials content**. It will also help **justify the new business models** that will be necessary to meet circularity objectives. Engaging directly with OEMs to ensure their understanding of LCAs and mass balance principles will be critical to maximizing the value of the LCA.

Explore **new business models** that enable profitable circularity

In addition to technology advances and infrastructure development to support circular automotive design, recycling, and material reuse, plastics companies should begin exploring new business models that will let them thrive in a circular automotive economy. **Establishing new partnerships, investing in novel technology providers, and securing sufficient access to waste-plastics feedstock supplies** may be parts of new business approaches needed to succeed.[148] Feedstock arrangements could be long-term supply agreements with municipalities or waste-management companies, or backward integration, where a plastics company acquires or establishes automotive shredders or other waste-collection operations.[149] Working now to assess novel business models may provide long-term opportunities to the industry for value creation as it pursues a more circular future.

CASE STUDIES: LIFECYCLE ASSESSMENT

Microsoft

MICROSOFT'S LCA[150]

Microsoft uses **LCAs** to evaluate and reduce the systemic environmental impacts of their hardware products. Product environmental LCA is a science-based method that calculates the environmental impacts of all activities involved in extracting raw materials and producing, using, transporting, and disposing of a product throughout its lifecycle.

The LCA calculation is performed using **GaBi digital technology**—a software tool that runs on the Windows platform. The company's calculations are based on an LCA in accordance with ISO 14040 and ISO 14044 standards, complemented by ETSI TS 103 199 and ITU-T L.1410. These calculations include **extraction of raw materials**, **upstream materials preparation**, **electronic component manufacturing**, **subassembly manufacturing and assembly**, **final assembly**, **distribution to customer**, **product use**, and **end-of-life treatment**. Microsoft's LCA results represent their best understanding of a product's lifecycle environmental impacts at the time of LCA publication and are revised as needed to accommodate changes in methodology.

MAGNA

ULTRALIGHT AUTOMOTIVE DOOR LCA[151]

In cooperation with DOE and partners FCA US and Grupo Antolin North America, Inc., Magna International Inc. developed a new state-of-the-art **ultralight door design** in 2017 that achieved a **40% overall mass reduction** compared to the baseline door. A **comparative LCA study** of the door parts was conducted to produce quantitative information about their potential life cycle environmental performance compared with conventional parts.

The LCA study was conducted in accordance with the International Organization for Standardization (ISO) standards 14040 series. It followed the specific rules and requirements provided in the Canadian Standards Association (CSA) Group guidelines for conducting LCA of auto parts incorporating weight changes due to material composition, manufacturing technology, or part geometry. The results showed **lower potential environmental impacts due to lightweighting** compared to the baseline: global warming potential was lower by 6.0 g CO_2 eq/km with powertrain adaptation and 2.8 g CO_2 eq/km without, and total primary energy demand was lower by 86 kJ/km with powertrain adaptation and 40 kJ/km without.

5. CALL TO ACTION

The **automotive plastics and polymer composites industry stands ready to help rethink** the ways that vehicles and their materials are designed, constructed, used, and handled at end of life.

The transition toward a circular economy for automotive plastics and polymer composites will require the automotive plastics and polymer composites industry to work together as well as with OEMs, shredders, recyclers, research organizations, and governments to conduct strategic, whole-value-chain thinking and coordination. While this change cannot happen overnight, members of the automotive plastics and polymer composites industry can begin to lay the groundwork today.

HOW TO WORK ON CIRCULARITY TODAY

1. **Encourage innovation within your organization** to position plastics and polymer composites as a key enabler for circularity in the automotive industry

2. **Support and participate in industry-wide efforts to advance circular design** of polymer materials and automotive components/systems

3. Support and, where possible, **lead efforts to improve supply chain circularity** with your automotive partners and suppliers

4. **Continue to educate the automotive supply chain** about the circularity potential of polymer-based materials

5. **Contribute to building the workforce** with skills and capabilities needed to shift toward a circular economy

6. **Advocate for R&D support** from state and federal governments to help fund technology development and demonstration

7. **Participate in standards processes** to ensure circularity standards take into account the needs and requirements of plastics and polymer composites

8. Work with the automotive value chain to **develop essential and robust automotive recycling infrastructure**

9. Partner with automotive value chain to **drive designs and processes for vehicle disassembly**

10. **Identify and apply lessons learned from other industries** working to improve circularity (e.g., packaging, wind, aerospace)

FOR MORE INFORMATION about the circular economy for automotive plastics and polymer composites, contact Gina Oliver at Gina-Marie_Oliver@americanchemistry.com.

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APPENDIX B. ACRONYMS

ABS	acrylonitrile butadiene styrene
AHSS	advanced high-strength steel
APRR	advanced plastic recycling and recovery
ASR	automotive shredder residue
ARR	Asset Resale and Recycling Services
BDO	butanediol
CAD	computer-aided design
CFRP	carbon fiber reinforced polymer
CO_2	carbon dioxide
EVOH	ethylene-vinyl alcohol copolymer
FRPC	fiber-reinforced plastic composite
HDPE	high-density polyethylene
IP	instrument panel
ISCC	International Sustainability & Carbon Certification
ISRI	Institute of Scrap Recycling Industries
LCA	lifecycle assessment
LED	light-emitting diode
LIDAR	Light Detection and Ranging
NDT/ NDE	non-destructive testing and evaluation
OEM	original equipment manufacturer
PBT	polybutylene terephthalate
PC	polycarbonate
PE	polyethylene
PET	polyethylene terephthalate
PP	polypropylene
PS	polystyrene
SPE	Society of Petroleum Engineers
TPO	thermoplastic olefin
TPVs	thermoplastic vulcanizates
VRP	Value-Retention Processes

APPENDIX C. NOTES

1. Accenture, "Chemical (Re)action: Growth in a circular economy," August 30, 2019, https://www.accenture.com/us-en/insights/chemicals/chemical-reaction-circular-economy.
2. Accenture, "Automotive's latest model: Redefining competitiveness through the circular economy," 2016, https://www.accenture.com/t20160913T221220__w__/bd-en/_acnmedia/PDF-27/Accenture-AutomotiveLatestModel_Infographic.pdf.
3. Ford Motor Company, *Sustainability Report 2018/19*, 2018, https://media.ford.com/content/dam/fordmedia/North%20America/US/2019/06/05/sr18-summary.pdf.
4. BMW Group, *Sustainable Value Report*, 2018, https://www.bmwgroup.com/content/dam/grpw/websites/bmwgroup_com/responsibility/downloads/en/2019/2019-BMW-Group-SVR-2018-Englisch.pdf.
5. Groupe Renault, *Registration Document Including Annual Financial Report 2018*, 2018, https://group.renault.com/wp-content/uploads/2019/04/registration-document-2018.pdf.
6. Thuermer, Karen, "Automakers Enter the Circular Economy Area Development," *AreaDevelopment*, 2018, https://www.areadevelopment.com/sustainable-development/q3-2018-auto-aero-site-guide/automakers-enter-the-circular-economy.shtml.
7. BMW Group, *Sustainable Value Report*, 2018, https://www.bmwgroup.com/content/dam/grpw/websites/bmwgroup_com/responsibility/downloads/en/2019/2019-BMW-Group-SVR-2018-Englisch.pdf.
8. Ford Motor Company, *Sustainability Report 2020*, 2020, https://corporate.ford.com/microsites/sustainability-report-2020/assets/files/sr20.pdf.
9. Doyle, Alister, "Volvo sets goal of 25% recycled plastics in cars," *Automotive News Europe*, June 18, 2018, https://europe.autonews.com/article/20180618/ANE/180619754/volvo-sets-goal-of-25-recycled-plastics-in-cars.
10. General Motors, "Sustainability: Our Path to a Better Planet," https://www.gm.com/our-stories/sustainability/global-renewable-goals.html (accessed September 2020).
11. Toyota, "Challenge 5 Challenge of Establishing a Recycling-based Society and Systems," https://global.toyota/en/sustainability/esg/challenge2050/challenge5/ (accessed September 2020).
12. Nissan Motor Company, "Toward Zero New Material Resource Use," https://www.nissan-global.com/EN/ENVIRONMENT/GREENPROGRAM/DEPENDENCY/ (accessed September 2020).
13. European Parliament, Council of the European Union, *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles - Commission Statements*, September 18, 2000, https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32000L0053.
14. Gallone, Toni and Agathe Zeni-Guido, "Closed-loop polypropylene, an opportunity for the automotive sector," *The Journal of Field Actions*, Special Issue 19, 2019, https://journals.openedition.org/factsreports/5225.
15. World Business Council for Sustainable Development, "Circular policy action brief: 2019 update," 2019, https://docs.wbcsd.org/2019/12/WBCSD_Policy_Action_Brief_2019.pdf.
16. European Parliament, Council of the European Union, *Directive 2005/64/EC of the European Parliament and of the Council of 26 October 2005 on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability and amending Council Directive 70/156/EEC*, October 26, 2005, https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32005L0064.
17. Mitic, Saša and Ivan Blagojevic, *End-of-Life Vehicle Disposal and its Influence to the Environment*, December 2018, https://www.researchgate.net/publication/329914503_END-OF-LIFE_VEHICLE_DISPOSAL_AND_IT'S_INFLUENCE_TO_THE_ENVIRONMENT.
18. European Commission, *Closing the loop - An EU action plan for the Circular Economy*, February 12, 2015, https://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_1&format=PDF.

19. European Commission, *Research & Innovation Projects relevant to the Circular Economy Strategy: Horizon 2020 calls 2016-2018*, November 2, 2019, https://ec.europa.eu/research/environment/pdf/h2020_projects_circular_economy_2016-2018.pdf.

20. World Business Council for Sustainable Development, "Circular policy action brief: 2019 update," 2019, https://docs.wbcsd.org/2019/12/WBCSD_Policy_Action_Brief_2019.pdf.

21. California Senate, *Solid waste: packaging and products*, SB-54, Amended in Assembly August 25, 2020, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200SB54.

22. American Chemistry Council, "California Packaging Recycling Legislation Stalls," September 14, 2019, https://www.americanchemistry.com/Media/PressReleasesTranscripts/ACC-news-releases/California-Packaging-Recycling-Legislation-Stalls.html.

23. 129th Maine Legislature, *Resolve, To Support Municipal Recycling Programs*, May 2019 https://legislature.maine.gov/legis/bills/bills_129th/billtexts/HP104101.asp.

24. Semuels, Alana, "Is This the End of Recycling," *The Atlantic*, March 5, 2019, https://www.theatlantic.com/technology/archive/2019/03/china-has-stopped-accepting-our-trash/584131/.

25. The Observatory of Economic Complexity, "Scrap Plastic," 2018, https://oec.world/en/profile/hs92/73915/ (accessed September 2020).

26. U.S. Environmental Protection Agency, Advancing Sustainable Materials Management: 2017 Fact Sheet, November 2019, https://www.epa.gov/sites/production/files/2019-11/documents/2017_facts_and_figures_fact_sheet_final.pdf.

27. European Environment Agency, "Typical charge (gate fee and landfill tax) for legal landfilling of non-hazardous municipal waste in EU Member States and regions," March 19, 2013, https://www.eea.europa.eu/data-and-maps/figures/typical-charge-gate-fee-and.

28. "EREF releases analysis on national landfill tipping fees," *Recycling Today*, October 29, 2019, https://www.recyclingtoday.com/article/eref-releases-analysis-national-msw-landfill-tipping-fees/.

29. Huetter, John, "Plastics industry might want auto body shops' bumper fascias," *Repairer Driven News*, July 10, 2019, https://www.repairerdrivennews.com/2019/07/10/plastics-industry-might-want-auto-body-shops-bumper-fascias/.

30. Gallone, Toni and Agathe Zeni-Guido, "Closed-loop polypropylene, an opportunity for the automotive sector," *The Journal of Field Actions*, Special Issue 19, 48-53, 2019, https://journals.openedition.org/factsreports/5225.

31. Organisation for Economic Co-operation and Development, *Business Models for the Circular Economy: Opportunities and Challenges from a Policy Perspective*, October 2018, https://www.oecd.org/environment/waste/policy-highlights-business-models-for-the-circular-economy.pdf.

32. McCormick, Erin, "America's 'recycled' plastic waste is clogging landfills, survey finds," *The Guardian*, February 18, 2020, https://www.recyclingtoday.com/article/eref-releases-analysis-national-msw-landfill-tipping-fees/.

33. Recycling Today Staff, "A changing landscape: The 2018 list and map of U.S. auto shredding locations shows that more auto shredders are operating in 2018 than in 2016." *Recycling Today*, October 4, 2018, https://giecdn.blob.core.windows.net/fileuploads/document/2018/10/26/2018_auto_shredder-map.pdf.

34. Smith, Caryn, "The shifting paradigm of automotive recycling,"*Recycling Today*, September 6, 2019, https://www.recyclingtoday.com/article/the-shifting-paradigm-of-automotive--recycling-september-2019/.

35. Ibid.

36. Ibid.

37. Ibid.

38. Accenture, "Mobility as a Service," https://www.accenture.com/us-en/insight-mobility-automotive-ecosystem (accessed September 2020).

39. Grosse-Ophoff, Anne, Saskia Hausler, Kersten Heineke, and Timo Möller, McKinsey & Company, April 18 2017, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-shared-mobility-will-change-the-automotive-industry.

40. Hyatt, Kyle and Sean Szymkowski, "Roadshow's guide to vehicle subscription services, a buying or leasing alternative," *Roadshow by CNET*, March 4, 2020, https://www.cnet.com/roadshow/news/2020-new-car-subscription-service-guide-buying-leasing-audi-genesis-porsche-volvo-mercedes/.

41. Grosse-Ophoff, Anne, Saskia Hausler, Kersten Heineke, and Timo Möller, "How shared mobility will change the automotive industry," McKinsey & Company, April 18 2017, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-shared-mobility-will-change-the-automotive-industry.

42. Wolk-Lewanowicz, Agata, Kate Rolle, Louise Koch, and Stephen Roberts, *The Business Case for a Sustainable Supply Chain: Dell*, May 12, 2017, https://i.dell.com/sites/doccontent/corporate/corp-comm/en/Documents/circular-case-study.pdf.

43. Dell Technologies, *FY19 Corporate Social Responsibility Report*, 2019, https://corporate.delltechnologies.com/en-us/social-impact/reporting/fy19-csr-report.htm#overlay=/content/dam/delltechnologies/assets/corporate/pdf/progress-made-real-reports/dell-fy19-csr-report.pdf.

44. Dell Technologies, "Circularity at work," https://corporate.delltechnologies.com/en-us/social-impact/advancing-sustainability/sustainable-products-and-services/circular-design/circularity-at-work.htm (accessed June 2020).

45. Circle Economy, On the Road to the Circular Economy, August 2016, https://www.circle-economy.com/resources/on-the-road-to-the-circular-car#:~:text=The%20emergence%20of%20digital%20technology,more%20power%20than%20ever%20before.&text=Lower%20entry%20barriers%20for%20technology,speed%20up%20in%20the%20future.

46. PwC, *The road to circularity*, 2019, https://www.pwc.de/de/nachhaltigkeit/pwc-circular-economy-study-2019.pdf.

47. Apple, *Environmental Responsibility Report*, 2019, https://www.apple.com/environment/pdf/Apple_Environmental_Responsibility_Report_2019.pdf.

48. UN Environment Programme, *Legal limits on single-use plastics and microplastics*, December 6, 2018, https://www.unenvironment.org/resources/report/legal-limits-single-use-plastics-and-microplastics.

49. Matz, Sara Napolitano, "Companies Working to Reduce Single-Use Plastics," January 3, 2019, https://www.uschamberfoundation.org/blog/post/companies-working-reduce-single-use-plastics.

50. Accenture, "More than Half of Consumers Would Pay More for Sustainable Products Designed to Be Reused or Recycled, Accenture Survey Finds," June 4, 2019, https://newsroom.accenture.com/news/more-than-half-of-consumers-would-pay-more-for-sustainable-products-designed-to-be-reused-or-recycled-accenture-survey-finds.htm.

51. Simon, Frederic, "How Europe's war on plastics is affecting petrochemicals," Euractiv, August 27, 2019, https://www.euractiv.com/section/energy/news/how-europes-war-on-plastics-is-affecting-petrochemicals/.

52. Nielsen, "Was 2018 the Year of the Influential Sustainable Consumer?" Insights, December 17, 2018, https://www.nielsen.com/us/en/insights/.

53. Martin, Chris, "Wind Turbine Blades Can't Be Recycled, So They're Piling Up in Landfills," Bloomberg Green, February 5, 2020, https://www.bloomberg.com/news/features/2020-02-05/wind-turbine-blades-can-t-be-recycled-so-they-re-piling-up-in-landfills.

54. Caron, Christina, "Starbucks to Stop Using Disposable Plastic Straws by 2020," The New York Times, July 9, 2018, https://www.nytimes.com/2018/07/09/business/starbucks-plastic-straws.html.

55. Royte, Elizabeth, "Eat your food, and the packaging too," National Geographic, August 2019, https://www.nationalgeographic.com/environment/future-of-food/food-packaging-plastics-recycle-solutions/#close.

56. Plastics Market Watch, *Automotive Recycling Devalued is now Revalued*, 2016, https://www.plasticsindustry.org/sites/default/files/2016-03256-SPI-PMW-Auto-Recycle-web.pdf.
57. Ford Motor Company, *Sustainability Report 2018/19*, 2018, https://media.ford.com/content/dam/fordmedia/North%20America/US/2019/06/05/sr18-summary.pdf.
58. BASF, "K 2019 – New products from plastic waste: BASF customers showcase prototypes made from chemically recycled material," July 9, 2019, https://www.basf.com/global/en/media/news-releases/2019/07/p-19-254.html.
59. Renault, "Groupe Renault Co-Develops a Unique Fabric Made from 100% Recycled Materials for New Renault Zoe," November 14, 2019, https://en.media.groupe.renault.com/news/groupe-renault-co-develops-a-unique-fabric-made-from-100-recycled-materials-for-new-renault-zoe-6232-989c5.html.
60. Ellen Macarthur Foundation, *Completing the Picture: How the Circular Economy Tackles Climate Change*, v.3, September 26, 2019, https://www.ellenmacarthurfoundation.org/assets/downloads/Completing_The_Picture_How_The_Circular_Economy-_Tackles_Climate_Change_V3_26_September.pdf.
61. BASF, "Recycled/Renewable Products PMP & PMR," presentation in Wyandotte, MI, January 29, 2020.
62. Braskem, "Braskem America Launches I'm green Recycled Polypropylene," October 16, 2019, https://www.braskem.com.br/usa/news-detail/braskem-america-launches-im-green-recycled-polypropylene.
63. Celanese, "Ecomid® Polyamide Compounds," https://www.celanese.com/engineered-materials/products/Ecomid (accessed September 2020).
64. SpecialChem, "Pocan® ECO T 3215," Omnexus Material Selection Platform, https://omnexus.specialchem.com/product/t-lanxess-pocan-eco-t-3215-000000 (accessed September 2020).
65 SpecialChem, "Pocan® ECO T 3220," Omnexus Material Selection Platform, https://omnexus.specialchem.com/product/t-lanxess-pocan-eco-t-3220-000000 (accessed September 2020).
66. SABIC, "Cycoloy* Resin C8080REC," 2008, http://www.va-so.com/download/cycoloy-pc-abs/cycoloy-pc-abs-other/C8080REC.pdf.
67. BASF, "Innovative foam for thin and light instrument panels," August 1, 2018, https://www.basf.com/global/en/media/news-releases/2018/08/p-18-269.html.
68. BASF, "BASF launches impregnated fiber mat technology for nonwoven fiber composites at CAMX 2017," September 6, 2017, https://www.basf.com/us/en/media/news-releases/2017/09/P-US-17-091.html.
69. Braskem, "I'm green™ Polyethylene," http://plasticoverde.braskem.com.br/site.aspx/Im-greenTM-Polyethylene (accessed August 2020).
70 Ibid.
71. Braskem, "I'm green™ EVA," http://plasticoverde.braskem.com.br/site.aspx/EVA-Verde-I-m-green-eng (accessed August 2020).
72. Celanese, "Celanese and International Paper Collaborate with Ford to Win Environmental Award for Sustainable Materials in Automotive," November 9, 2018, https://www.celanese.com/en/engineered-materials/News-and-Media/2018/November/ce-and-ip-collaborate-with-ford-to-win-environmental-award-for-sustainable-materials-in-automotive.
73. Covestro, "Renewable raw materials for plastics production," May 27, 2020, https://www.covestro.com/press/renewable-raw-materials-for-plastics-production/.
74. Mielewski, Deborah. " Greening the Blue Oval: Building the Bio-based Automobile," Ford Motor Company, https://www.michiganchemistry.com/assets/2017-Meeting/2017Presentations/Ford%20-%20Debbie%20Mielewski%20presentation%20-%20Greening%20the%20Blue%20Oval%20-%20Building%20the%20Bio-based%20Automobile.pdf (presentation, accessed August 2020).
75. Ford Motor Company, "Debbie Mielewski: Ford Motor Company Research Scientist: Shaping the Future of Ford with Persistence and a Love of Trash," https://media.ford.com/content/fordmedia/fna/us/en/people/debbie-mielewski.html (accessed August 2020).

76. Mielewski, Deborah. " Greening the Blue Oval: Building the Bio-based Automobile," Ford Motor Company, https://www.michiganchemistry.com/assets/2017-Meeting/2017Presentations/Ford%20-%20Debbie%20Mielewski%20presentation%20-%20Greening%20the%20Blue%20Oval%20-%20Building%20the%20Bio-based%20Automobile.pdf (presentation, accessed August 2020).
77. Ibid.
78. Ford Motor Company, " Ford Uses Kenaf Plant Inside Doors in the All-New Escape, Saving Weight and Energy," Cision PR Newswire, January 26, 2012, https://www.prnewswire.com/news-releases/ford-uses-kenaf-plant-inside-doors-in-the-all-new-escape-saving-weight-and-energy-138138273.html.
79. LANXESS, "First production of bio-based polybutylene terephthalate (PBT) in a world-scale plant using 1,4-butanediol (BDO) made from renewable feedstock," June 25, 2013, http://lanxess.us/en/us-media/us-news/2013-00085e/.
80. SABIC, "SABIC Outlines Intentions for TRUCIRCLE™ to Close Loop on Plastic Recycling," https://www.sabic.com/en/news/21891-sabic-outlines-intentions-for-trucircle-to-close-loop-on-plastic-recycling January 23, 2020.
81. "Belgian Separation Technology Dominates the Global Plastic Recycling Transition," *Global Recycling*, https://global-recycling.info/archives/3276, (accessed September 2020).
82. Ibid.
83. Ibid.
84. Plastics Market Watch, *Automotive Recycling Devalued is now Revalued*, 2016, https://www.plasticsindustry.org/sites/default/files/2016-03256-SPI-PMW-Auto-Recycle-web.pdf.
85. Ibid.
86. Hundertmark, Thomas, Chris McNally, Theo Jan Simons, and Helga Vanthournout, "No time to waste: What plastics recycling could offer," McKinsey & Company, September 2018, http://www.mckinsey.com/industries/chemicals/our-insights/no-time-to-waste-what-plastics-recycling-could-offer?cid=eml-web.
87. Hofmann, Michael, "FVH as a Pioneer in Plastics Recycling," Erema Plastics Recycling Systems, https://www.erema.com/en/success_stories/IDobj=1305 (accessed September 2020).
88. Ibid.
89. Messenger, Ben, "IN DEPTH: SUEZ JV Closing the Loop on Plastics" *Waste Management World*, August 10, 2018, https://waste-management-world.com/a/in-depth-suez-jv-closing-the-loop-on-plastics.
90. Ibid.
91. Solvay, "Making reusable plastics a reality," April 8, 2020, https://www.solvay.com/en/article/road-warrior-protected-plastic-means-more-sustainable-plastic.
92. Testimony of Tim J. Boven, Recycling Commercial Director for the Americas, Packaging & Specialty Plastics, Dow, Before the Subcommittee on Research & Technology, Committee on Science, Space and Technology U.S. House of Representatives, "Closing the Loop: Emerging Technologies in Plastic Recycling," April 30, 2019, https://www.congress.gov/116/meeting/house/109359/witnesses/HHRG-116-SY15-Wstate-BovenT-20190430.pdf.
93. Ibid.
94. ExxonMobil, "Rethink Recycle with Vistamaxx™ performance polymers," https://www.exxonmobilchemical.com/en/products/polymer-modifiers/vistamaxx-performance-polymers/rethink-recycle (accessed September 2020).
95. REMADE Institute, Impact Report 2019: Advancing the Nation in Sustainable Manufacturing, 2019, https://static1.squarespace.com/static/59678de486e6c0c5f27e2a3c/t/5da6095fc1cf5076eb157351/1571162464291/REMADE+Impact+Report+2019+Web+version.pdf.
96. Remanufacturing Industries Council, "New Remanufacturing Report Affirms the Importance of Reman for the Economy and Environment," October 24, 2018, http://www.remancouncil.org/news/new-remanufacturing-report-affirms-the-importance-of-reman-for-the-economy-and-environment.

97. BASF, " Chemical recycling of plastic waste," https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach/chemcycling.html (accessed September 2020).

98. Leif, Dan, " Study details 'transformational' tech in plastics recycling," *Plastics Recycling Update*, April 10, 2019, https://resource-recycling.com/plastics/2019/04/10/study-details-transformational-tech-in-plastics-recycling/.

99. American Chemistry Council, E*conomic Impact of Advanced Plastics Recycling and Recovery Facilities in the U.S.*, February 2019, https://plastics.americanchemistry.com/Economic-Impact-of-Advanced-Plastics-Recycling-and-Recovery-Facilities-in-the-United-States.pdf.

100. American Chemistry Council Plastics Division, " New Investments in Advanced Plastics Recycling in the U.S.," 2020, https://plastics.americanchemistry.com/advanced-recycling-resources/investments-in-advanced-recycling-us.pdf.

101. Trinseo, "Trinseo & Styrenics Circular Solutions," https://www.trinseo.com/Sustainability/Styrenics-Circular-Solutions (accessed September 2020).

102. Styrenics Circular Solutions and Pyrowave, "Styrenics Circular Solutions members to initiate evaluation of Pyrowave plastic-toplastic chemical recycling technology," January 29, 2020, http://styrenics-circular-solutions.com/wp-content/uploads/2020/01/20200129_SCSmembers_Evaluate_Pyrowave_rTechnology_PressRelease.pdf.

103. Closed Loop Partners, "Advancing Circular Systems for Plastics," https://www.closedlooppartners.com/research/advancing-circular-systems-for-plastics/ (accessed September 2020).

104. Paben, Jared, "Virgin plastic giant acquires US PET reclaimer," *Plastics Recycling Update*, December 4, 2019, https://resource-recycling.com/plastics/2019/12/04/virgin-plastic-giant-acquires-us-pet-reclaimer/.

105. Ibid.

106. European Commission, A Circular Economy for Plastics, January 2019, https://www.hbm4eu.eu/wp-content/uploads/2019/03/2019_RI_Report_A-circular-economy-for-plastics.pdf.

107. Eastman, "Our circular solutions," https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Overview.aspx (accessed September 2020).

108. SABIC, "SABIC Outlines Intentions for TRUCIRCLE to Close Loop on Plastic Recycling," January 21, 2020, https://www.sabic.com/en/news/21891-sabic-outlines-intentions-for-trucircle-to-close-loop-on-plastic-recycling.

109 Tullo, Alexander, "Plastic has a problem; is chemical recycling the solution?" October 6, 2019, https://cen.acs.org/environment/recycling/Plastic-problem-chemical-recycling-solution/97/i39.

110 Ibid.

111. Ibid.

112. Agilyx, "Lucite International and Mitsubishi Chemical Corporation increase the pace on a Circular Economy for PMMA with Agilyx Corporation," Cision PR Newswire, May 5, 2020. https://www.prnewswire.com/news-releases/lucite-international-and-mitsubishi-chemical-corporation-increase-the-pace-on-a-circular-economy-for-pmma-with-agilyx-corporation-301052402.html.

113. BASF, " Chemical recycling of plastic waste," https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach/chemcycling.html (accessed September 2020).

114. BASF, "K 2019 – New products from plastic waste: BASF customers showcase prototypes made from chemically recycled material," July 9, 2019, https://www.basf.com/global/en/media/news-releases/2019/07/p-19-254.html.

115. Toray Industries, Inc., " Toray and Toyota Tsusho to Jointly Promote Carbon Fiber Recycling," February 18, 2016, https://www.toyota-tsusho.com/english/press/detail/160218_002954.html.

116. American Chemistry Council, "Thin-Wall IP Substrate," Automotive Plastics, February 16, 2017, https://plasticscar.blogspot.com/2017/02/thin-wall-ip-substrate.html.

117. SABIC, "Foaming for Lighter Structures: 2017 BMW Mini Countryman Instrument Panel Carrier," 2018 https://www.sabic.com/assets/en/Images/FOAMING-FOR-LIGHTER-STRUCTURES-2017-BMW-MINI-COUNTRYMAN_tcm1010-8137.PDF.

118. Ibid.

119. Ibid.

120. Ibid.

121. American Chemistry Council, "Thin-Wall IP Substrate," Automotive Plastics, February 16, 2017, https://plasticscar.blogspot.com/2017/02/thin-wall-ip-substrate.html.

122. ExxonMobil, *Processing guidelines for blow molding*, https://www.exxonmobilchemical.com/en/library/library-detail/17348/santoprene_blow_molding_guide_en (accessed September 2020).

123. American Chemistry Council, "Multi-Functional Exchange Blow Molding Airduct," Automotive Plastics, April 13, 2012, https://plasticscar.blogspot.com/2012/04/multi-functional-exchange-blow-molding.html.

124. Covestro, "Design and functionality, illuminated: Innovative headlamp design with polycarbonate" (November 2019).

125. Huetter, John, "Plastics industry might want auto body shops' bumper fascias," *Repairer Driven News*, July 10, 2019, https://www.repairerdrivennews.com/2019/07/10/plastics-industry-might-want-auto-body-shops-bumper-fascias/.

126. Ibid.

127. American Chemistry Council, "FAQs," Automotive Plastics, https://www.automotiveplastics.com/resources/faqs/ (accessed September 2020).

128. Essential Energy Everyday, "Lead Battery Recycling Helps Beat Plastic Pollution," June 4, 2018, https://essentialenergyeveryday.com/lead-battery-recycling-helps-beat-plastic-pollution/.

129. World Business Council for Sustainable Development, "Circular policy action brief: 2019 update," 2019, https://docs.wbcsd.org/2019/12/WBCSD_Policy_Action_Brief_2019.pdf.

130. United States Business Council for Sustainable Development, "Facilitating Company-to-Company Industrial Reuse Opportunities that Support the Culture Shift to a Circular, Closed-Loop Economy," https://usbcsd.org/materials (accessed September 2020).

131. Alliance to End Plastic Waste, Homepage, https://endplasticwaste.org/ (accessed September 2020).

132. Vaidya, Uday, "Enabling a circular economy approach to advanced composites innovation, manufacturing and use, Part 2," *Composites World*, February 18, 2020, https://www.compositesworld.com/articles/enabling-a-circular-economy-approach-to-advanced-composites-innovation-manufacturing-and-use-part-2.

133. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, "Energy Department Manufacturing Institute Announces a Request for Proposals to Address Recycling, Reuse and Remanufacturing Challenges," August 17, 2020, https://www.energy.gov/eere/articles/energy-department-manufacturing-institute-announces-request-proposals-address

134. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, "Energy Department Manufacturing Institute Announces Call for Proposals to Address Challenges in Plastics Recycling," November 8, 2019, https://www.energy.gov/eere/articles/energy-department-manufacturing-institute-announces-call-proposals-address-challenges.

135. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, "Department of Energy Announces nearly $100 Million for Bioenergy Research and Development," January 23, 2020, https://www.energy.gov/eere/articles/department-energy-announces-nearly-100-million-bioenergy-research-and-development.

136. U.S. Department of Energy, "Department of Energy Announces $25 Million for Plastics Recycling R&D, Launches Upcycling Consortium," March 16, 2020, https://www.energy.gov/articles/department-energy-announces-25-million-plastics-recycling-rd-launches-upcycling-consortium.

137. U.S. Department of Energy, "U.S. Energy Department and American Chemistry Council Sign Memorandum of Understanding to Collaborate on Innovative Plastics Recycling Technologies," February 3, 2020, https://www.energy.gov/articles/us-energy-department-and-american-chemistry-council-sign-memorandum-understanding.

138. Testimony of Tim J. Boven, Recycling Commercial Director for the Americas, Packaging & Specialty Plastics, Dow, Before the Subcommittee on Research & Technology, Committee on Science, Space and Technology U.S. House of Representatives, "Closing the Loop: Emerging Technologies in Plastic Recycling," April 30, 2019, https://www.congress.gov/116/meeting/house/109359/witnesses/HHRG-116-SY15-Wstate-BovenT-20190430.pdf.

139. American Chemistry Council, E*conomic Impact of Advanced Plastics Recycling and Recovery Facilities in the U.S.*, February 2019, https://plastics.americanchemistry.com/Economic-Impact-of-Advanced-Plastics-Recycling-and-Recovery-Facilities-in-the-United-States.pdf.

140. Plastics Market Watch, *Automotive Recycling Devalued is now Revalued*, 2016, https://www.plasticsindustry.org/sites/default/files/2016-03256-SPI-PMW-Auto-Recycle-web.pdf.

141. Cookson, Craig, "Advanced Plastics Recycling Scores Big at Latest Recycling Conference," American Chemistry Council, February 26, 2020, https://blog.americanchemistry.com/2020/02/advanced-plastics-recycling-scores-big-at-latest-recycling-conference/.

142. U.S. Congress, House, *Plastic Waste Reduction and Recycling Act*, HR 7228, 116th Cong., introduced in House June 15, 2020, https://www.congress.gov/bill/116th-congress/house-bill/7228?s=1&r=2.

143. U.S. Congress, House, R*ealizing the Economic Opportunities and Value of Expanding Recycling Act (RECOVER Act)*, HR 5115, 116th Cong., introduced in House November 15, 2019, https://www.congress.gov/bill/116th-congress/house-bill/5115?r=6&s=1.

144. American Chemistry Council, "Iowa and Tennessee Become Fourth and Fifth States to Pass Legislation to Help Recover More Plastics," April 9, 2019, https://www.americanchemistry.com/Media/PressReleasesTranscripts/ACC-news-releases/Iowa-and-Tennessee-Become-Fourth-and-Fifth-States-to-Pass-Legislation-to-Help-Recover-More-Plastics.html.

145. American Chemistry Council, "Texas Becomes 6th State to Pass Legislation to Help Recover More Plastics," WasteAdvantage magazine, May 8, 2019, https://wasteadvantagemag.com/texas-becomes-6th-state-to-pass-legislation-to-help-recover-more-plastics/.

146. "Iowa, Tennessee Pass Bills Supporting Advanced Plastics Recycling," Waste 360, April 11, 2019, https://www.waste360.com/legislation-regulation/iowa-tennessee-pass-bills-supporting-advanced-plastics-recycling.

147. Ibid.

148. Hundertmark, Thomas, Mirjam Mayer, Chris McNally, Theo Jan Simons, and Christof Witte, "How plastics waste recycling could transform the chemical industry," McKinsey & Company, December 12, 2018, https://www.mckinsey.com/industries/chemicals/our-insights/how-plastics-waste-recycling-could-transform-the-chemical-industry.

149. Ibid.

150. Microsoft, *Devices Sustainability at Microsoft: Fiscal Year 2019*, 2019, https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE4d74y.

151. Bushi, Lindita, Tim Skszek and Timothy Reaburn, "New ultralight automotive door life cycle assessment," *The International Journal of Life Cycle Assessment*, 24, 310-323, 2019, https://link.springer.com/article/10.1007/s11367-018-1515-z.

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