

**U.S. House of Representatives Committee on Science, Space, and Technology
Subcommittee on Research and Technology Hearing: “Plastic Waste Reduction and Recycling
Research: Moving from Staggering Statistics to Sustainable Solutions”**

Testimony of

Gregory A. Keoleian
Director, Center for Sustainable Systems
Peter M. Wege Professor, School for Environment and Sustainability
Professor, Civil and Environmental Engineering
University of Michigan

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Introduction

My name is Greg Keoleian and I am the Peter M. Wege Professor of Sustainable Systems at the University of Michigan, where I also serve as the Director of the [Center for Sustainable Systems](#), which I cofounded in 1991 through a competitive US EPA grant. I hold appointments as Professor in the School for Environment and Sustainability, and Professor in the Department of Civil and Environmental Engineering. I earned my PhD in Chemical Engineering from the University of Michigan. I wish to thank Chairwoman Stevens and Ranking Member Waltz, as well as the other members of the Subcommittee for inviting me to this hearing.

My research focuses on the development and application of life cycle models and sustainability metrics to guide the design and improvement of products and technology. Our Center has conducted over 100 life cycle studies analyzing diverse systems including conventional and alternative vehicle technology, renewable energy technologies, buildings and infrastructure, consumer products and packaging, and a variety of food systems. Plastics materials are often constituents in the systems I study. Life cycle assessment models characterize the environmental impacts of products across production, use, and end-of-life management and provide a comprehensive basis for evaluating sustainability performance that also highlight environmental hotspots, tradeoffs, and improvement opportunities. Metrics that are evaluated often include primary energy consumption, greenhouse gas emissions, solid waste, and water use impacts. Life cycle cost models are used to evaluate and reduce the total cost of ownership of products including purchase price, maintenance and service costs, and disposal costs.

The Center for Sustainable Systems developed the first comprehensive characterization of plastics use by resin type across the entire U.S. economy, encompassing 2017 production, sales, use markets and end-of-life management [1]. In addition, I have a current research project developing a tool for evaluating environmental sustainability of plastics waste reduction innovations through funding from Morgan Stanley.

I fully support the stated goal of the *Plastic Waste Reduction and Recycling Research Act* which is to “provide for a coordinated Federal program to accelerate plastics waste reduction and support recycling research and development for the economic and national security of the United States, and for other purposes.” In my testimony, I wish to highlight specific challenges and opportunities based on my sustainable systems analysis research and offer a set of recommendations related to the proposed bill. Much of this testimony is based on research published in *Environmental Research Letters* [1].

Scope of the plastics waste problem

Plastics—synthetic organic polymers—are ubiquitous in today’s society. These versatile materials are relatively inexpensive, lightweight, strong, durable, corrosion resistant, and have valuable thermal and electrical insulation properties. When blended, co-extruded, or combined with performance enhancing additives, the diversity of existing plastics exhibit a wide range of properties. Their extraordinary design potential and flexibility, combined with low cost and durability means that the global use of plastics now exceeds most other man-made materials in nearly all industrial sectors, aside from construction where concrete and metals still dominate. This extensive and often highly specialized plastics economy, however, has also resulted in significant challenges at the end-of-life management of plastic products in recovering and retaining the economic and technical value of the materials. The outcome has been significant ‘leakage’ of plastics out of the economy in the form of waste and plastics pollution.

An estimated 4900 million metric tonnes (Mt) of the 8300 Mt total of plastics ever produced globally have been discarded either in landfills or elsewhere in the environment [2]. Most common plastics do not biodegrade, and their accumulation in and contamination of natural environments is an ever-increasing concern [3–6]. Further, the vast majority of plastics are derived from fossil fuels, and global production (including both feedstock and manufacturing energy requirements) currently represents around 8% of global annual oil and gas consumption [7]. Emissions associated with the 407 Mt of conventional plastics produced globally in 2015 correspond to 3.8% of global greenhouse gas emissions in that year [8], and in the United States (US), plastics production accounts for 1% of national greenhouse gas emissions [9]. Projections based on current growth rates suggest that emissions from plastics could reach 15% of the global carbon budget by 2050.

Exhibit 1 represents our best understanding of the material flow of plastics in the US circa the year 2017, based on available data. This material flow map characterizes plastics production, sales, use markets and end-of-life management by resin type and application. Details of data sources and notes corresponding with specific flows are provided in [1]. Due to data limitations, these flows are largely based on North American production and sales. Scaling these N. American flows based on the gross domestic product of the represented countries for each resin (see note in Table 1, [1]) suggests that the usage of plastics in the US is 93% of the reported total presented in Exhibit 1. Flows highlighted in gray indicate where data were not available to differentiate the plastic flow by resin type.

Observation 1: Plastics waste crisis is more than a packaging waste problem

Packaging is the largest defined use market for plastics. **Two thirds of the plastic put into use in the US in 2017, however, went into markets other than packaging.** These other sectors – consumer products, furniture and furnishing, electrical and electronics, transportation, buildings and construction - introduce unique challenges and opportunities. They include products with short- (disposable serveware, trashbags, diapers), medium- (clothing, tools, electronics, furniture, small appliances), and long- (large appliances, automobiles, buildings) lifetimes. This means that materials retired from medium- and long-lifetime products were designed and manufactured 5-50 years or more in the past, and such material and product innovations will not appear in the disposal stream until many years in the future.

More than three-quarters of the plastics reaching end-of-life went to landfill, and less than 8% was recycled. Note, this figure is lower than the 8.7% figure reported for 2018 by EPA as it also includes plastic recycling in other sectors; I believe the statistic reported in the bill rounds the EPA Municipal

Solid Waste (MSW) characterization figure of 8.7% to 9%. Inefficiencies in sorting and reprocessing likely mean that an even smaller percentage returns as feedstock for new products. Estimates of leakage of plastics to natural environments (based on data for N. America) represented 2% of the “end-of-life” plastics in the US in 2017. Globally, environmental leakage of plastics is dominated by mismanaged waste treatment, primarily in the form of open dumping sites; in N. America, however, these losses are considered negligible [10]. On the other hand, microplastic losses from tire abrasion, road markings erosion, and laundering of synthetic textiles in N. America are notable.

Plastic recycling of Municipal Solid Waste (MSW) has increased slightly in the last decade but has remained less than 9%. Plastic recycling percentages are much lower than other materials recycled from MSW. Recycling as a percent of total MSW generated in 2018 was 68.2% for paper and paperboard, 34% for metals, 25% for glass, 18% for rubber and leather, 15% for textiles, and 17% for wood [11]. These materials have higher recycling rates because of factors such as ease of separation, secondary material quality and/or available markets compared to plastic commodity materials. Unmoderated production of plastic products has resulted in unacceptable accumulation of debris in landfills and in natural environments, representing a gross waste of resources and disruptions to wildlife and ecosystem function.

Observation 2: Multiple technical and economic barriers limit plastics material recovery

Packaging

In theory, most of the thermoplastics used in packaging have very high recyclability, and the short lifespan and high volume of single-use plastic packaging makes it attractive for recapturing its material value. Current low recycling rates can often be traced to market issues including inexpensive virgin feedstocks, combined with material quality aspects that are inherent in the current system, either due to product design (choice of: materials and combinations of materials, colors, additives, formats, labels) or use and handling (contamination with dust, soil, organics, incomplete separation of recycling streams) [12]. For example, the PET recycling rate of 29% reported in [13] reflects the recovery or collection of PET bottles in 2017. 16% of the total bottles collected were exported out of the US, and only 67% of the recovered PET bottles purchased by US reclaimers in 2017 became clean flake available for reuse as recycled PET [14].

After years of tightening restrictions on the purity of plastics imports, China implemented its ‘National Sword’ program in January 2018, banning imports of nearly all plastic waste into the country and greatly disrupting material flows in the global recycling industry [15]. Exports from the US and other developed countries shifted to Southeast Asian countries including Malaysia, Vietnam, Indonesia and Thailand, which have also begun to implement regulatory policies on plastic waste imports [16]. These importing countries often lack sufficient infrastructure to properly manage plastic waste [17], increasing the likelihood of leakage. These dramatic changes in the global recycling markets are not reflected in the material flow data presented here and shown in Exhibit A. In addition, COVID 19 has increased the generation of plastic waste.

E-waste

Electronic waste (e-waste) is becoming an increasing concern, with a global annual growth rate of 3%–4% [18]. Plastics content in this e-waste is estimated at 20% [19] to 33% [20]. The heterogeneous combination of polymer types in e-waste makes recycling difficult. In addition, mechanical recycling of e-waste is often complicated by the presence of brominated flame retardants which have been banned as an additive for new products. Detection and extraction of these compounds is possible but adds to cost [21]. It is estimated that up to 2.5 Mt of polycarbonates can potentially be recovered from e-waste

globally each year if efficient and cost-effective recovery methods become available [22]. Examples of commercially viable mechanical recycling of e-waste plastics exist but cannot handle the current volume and diversity of plastics [18]. Research into selective recovery through solvent extraction of mixed polymer e-waste is promising [23, 24] and pyrolysis is also being explored [23, 25], though none of these technologies appear to be commercially viable at present.

Buildings

Modern building methods are utilizing an increasing amount of plastics, primarily in the form of PVC and HDPE used for piping, house wraps and siding, trim and window framing, and plastic-wood composites, as well as PUR used primarily as insulation. Recovery of these materials at end-of-life is extremely challenging given that building demolition typically produces mixed waste with low fractions of plastics, as well as the nature of the plastics themselves: PVC recycling is difficult and PUR thermosets cannot be mechanically recycled.

Transportation

The transportation sector utilized over 4% of plastics in 2017, primarily in the production of new automobiles [26]. Growth in this sector has been due primarily to lightweighting efforts and new applications of engineering resins with specialized properties. Over 95% of EOL vehicles in the US are recycled for their metals content, but economics currently limits dismantling and recycling of plastic parts in N. America; the majority of plastics currently end up in Automotive Shredder Residue (ASR) as small pieces mixed with other materials. Separation and recovery of plastics in ASR is challenging: 39 different types of basic plastics and polymers are commonly used to make cars today, and state-of-the-art separation technologies are very capital intensive. Thermoplastic polymers in ASR are often technically capable of being recycled, but the cost to separate, clean and collect often exceeds that of virgin plastic, especially with low oil and natural gas prices [27].

Systems analysis tools are necessary to overcome these challenges

Regardless of instrument, development of new waste and recycling policies must take a systems level, life-cycle approach to avoid burden shifting or promotion of less environmentally sustainable alternatives. Solutions to these rising problems will come in myriad forms, but there is widespread agreement that greatly improved coordination between product design and end-of-life is necessary. While technological innovations can be developed to improve recycling infrastructure, it is critical that more holistic solutions are developed to address the plastics waste crisis that emphasize other life cycle design strategies and green principles. These include dematerialization, material substitutions, product reuse, extension of product service life, product repairability and remanufacturing. Examples of this strategies can be found in [28, 29].

Research should also investigate adoption and transferability of technology and policy innovations that have already been demonstrated. Many solutions exist today in States and municipalities that can potentially be replicated and adopted elsewhere. What are the barriers to greater adoption of bottle bills; only 10 states have container deposit laws? Recycling rates are significantly higher in these states. Geography is also important as needs are different between developed and developing countries that lack basic waste management infrastructure, and also between urban and rural areas where population density can impact the economics of waste management systems.

Recommendation 1: Research is needed to fill in data gaps in plastics material flows and expand key life cycle inventory databases

The data challenges encountered in characterizing plastics material flows are a call for improved data collection, coordination and transparency. Improved understanding of plastic material production and usage in various product sectors can promote further coordination between product design and manufacturing and material recovery and reprocessing efforts. It can also assist in directing well intended R&D and capital resources toward bottleneck stages in greatest need of development and innovation.

The accuracy of life cycle models is dependent on the quality-of-life cycle inventory databases, and publicly available data are limited. It is important to update and expand the types of plastic materials and composites in the US LCI database National Renewable Energy Laboratory and the Argonne National Laboratory GREET LCI database.

Recommendation 2: Life cycle analysis and circular economy models are needed to guide plastics waste innovations and develop robust cost effective solutions

Life cycle assessments of plastics used in products can elucidate tradeoffs and guide improvements. For example, I collaborated with Dow Chemical to investigate the life cycle performance of building insulation products. This study examined from a life cycle perspective the changes in GHG emissions resulting from the use of two rigid thermal insulation products manufactured and installed from 1971 to 2025 [30]. Surprisingly, GHG emissions related to 1971 insulation production and fugitive releases of blowing agents were found to be greater than GHG savings from reduced heating loads. Solutions need to consider all stages of the life cycle. Although this insulation currently becomes construction and demolition waste, the greenhouse gas emissions payback for today's insulation is less than one year because upstream manufacturing and fugitive emissions were dramatically reduced.

National labs have begun to study circular economy methods and metrics including NREL, ANL, and NIST. This research should be expanded through collaborations with colleges and universities with expertise in the academic field of industrial ecology. Industrial ecology is the academic scientific field of the circular economy, which is a popularization of industrial ecology concepts and tools.

Life cycle perspectives are needed to improve product design and policy interventions that can result in more cost-effective environmental outcomes. Fuel economy standards focus only on vehicle use impacts and do not consider the energy, greenhouse gas emissions and waste associated with materials production, vehicle manufacturing and end-of-life management stages. Vehicle electrification and greater renewable electricity sources will influence material selection decisions and shift the profile of environmental footprints for parts and components in the future.

Life cycle models are necessary to evaluate circular economy strategies. A life cycle design study of milk and juice packaging with Dow Chemical indicated significant differences between refillable plastic (HDPE, PC) and glass bottles, gable top containers, HDPE jugs, and plastic pouches (used in Canada) [31]. Single use pouches result in less life cycle waste and energy use than other containers. Refillable plastic bottles outperformed glass because of weight differences that influenced transportation energy use. A life cycle study of reusable systems for drinking water delivery indicated clear advantages from a cost and environmental perspective over single use water bottles [32].

Recommendation 3: Emphasize interdisciplinary R&D to develop plastic waste solutions

For technological plastic waste reduction solutions to be implemented they must overcome market barriers highlighted in this testimony. At the core, the current plastics waste crisis is an economic problem. Leakage of plastic out of the economy and related impacts on the environment represents an externality.

Sustainable solutions that are effective when there is alignment between technology, markets, policy and behavioral drivers. Interdisciplinary research is needed to navigate the complexity of the plastic waste crisis. Research programs that bring together diverse experts such as engineers, industrial ecologists, economists, policy analysts, and behavioral scientists can achieve convergence more quickly and develop more robust solutions. Examples of successful interdisciplinary research programs at NSF include Materials Use: Science, Engineering, and Society (MUSES), Resilient and Sustainable Infrastructure (RESIN), Sustainable Energy Pathways (SEP), Sustainability Research Networks (SRN), and other Environmental Sustainability programs. Implementation of plastic waste innovations can be accelerated by sponsoring more research that brings together academics and industry, government, and community partners to co-create solutions.

Recommendation 4: R&D should also target product system design solutions beyond recycling

The proposed bill emphasizes the development of recycling infrastructure to solve the plastics waste crisis. I strongly encourage the broadening of the research scope to develop solutions that can avoid or limit the generation of waste. These strategies include dematerialization, material substitutions, service life extension of products, reuse, and remanufacturing. Strategies can often be more cost effective and environmentally sustainable than increasing recycling levels for products.

While Circular Economy is, in part, a paradigm for reducing waste, it is important to note that having circular attributes does not necessarily equate to enhanced sustainability performance [33]. Numerous metrics to evaluate Circular Economy are being developed to evaluate various aspects of the concept. Guidance as to which metrics are most appropriate is limited and some demonstrations point to the fact that these Circular Economy metrics do not always correlate with systems-based sustainability performance results from tools like life cycle assessment [34, 35].

Recommendation 5: Develop a road map to guide R&D coordination across agencies

R&D coordination is critical to systematically address the plastic waste crisis. It would be valuable to develop a road map to set research priorities and avoid research duplication. This would aid in addressing the complex nature of the problem given the wide array of resin and composite types and the wide range of product applications with varying lifetimes from short lived (e.g., single use packaging) to medium (e.g., clothing) to long lived products (e.g., large appliances, vehicles and buildings). Managing retired product streams today also pose different challenges than will be the case for long lived products such as homes that may not be retired for 50 years.

Recommendation 6: Plastic waste reduction solutions should also reduce greenhouse gas emissions

Humanity is facing a climate emergency. Drastic reductions in greenhouse gas emissions are required in the coming decade to avoid irreversible damage to the planet's life support systems and to limit related costs to society. The Intergovernmental Panel on Climate Change indicates that global net anthropogenic CO₂ emissions need to decline by about 45% from 2010 levels by 2030 and reach net zero around 2050 to limit warming to 1.5 C and avoid the most adverse effects of climate change.

We need to prioritize technological plastic waste reduction innovations that also create solutions to accelerate greenhouse gas emissions to zero. For example, energy recovery strategies are problematic because they generate carbon dioxide emissions when plastics waste is combusted.

Conclusion

The plastics waste crisis is worsening, and federally funded R&D is needed to develop robust and sustainable solutions. Solutions to the plastics waste crisis will require a major transformation of systems through technology, community engagement, behavior change, and policy interventions. Technological innovations alone will not be sufficient. The following recommendations are provided to strengthen the current bill.

- To address the complexity of product systems – resins and composites, applications and markets, end-of-life management strategies – effective coordination of research programming across agencies is essential.
- R&D funding investment should be guided in part by a sustainability solutions roadmap. Gaps in the plastic material flows of the US economy need to be filled to provide a more complete characterization of the plastic waste challenges and opportunities.
- Life cycle and circular economy models should be used to evaluate technological innovations to avoid unintended consequences and ensure robust environmental outcomes.
- The plastics waste crisis is bigger than a packaging problem and R&D should focus on innovations and solutions for other market sectors in addition to packaging. including consumer durable goods, electronics, transportation, and buildings.
- To avoid a further proliferation of the plastics waste problem the price differential between virgin plastic and recycled plastic needs to be addressed through both technology and policy interventions; environmental externalities associated with plastic products should be examined as well.
- R&D should extend beyond recycling infrastructure and standards and focus on other product life cycle management strategies.
- R&D by academic and government labs should require participation by industry and community stakeholders to accelerate development and implementation of sustainable solutions.
- Decarbonization should be prioritized as a criterion for evaluating alternative plastic waste solutions.

I appreciate this opportunity to share my perspectives and welcome your questions. Thank you for your attention.

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Exhibit 1

Note: this figure was originally published by *Environmental Research Letters*, reference [1]

Figure caption. Production, imports, exports, use, disposal, and leakage of plastics in the US in 2017. Width of flows scaled to mass (for reference: production of HDPE = 8.576 million metric tonnes). Colors correspond to polymer types (see legend). Numbers in parentheses refer to notes in Table [1](#) of the *Environmental Research Letters* article reference [1]. Note that the difference in mass between production (left side) and end-of-life (right side) in this 2017 snapshot represents a net addition to in-use stock.

