Recycling Past and Present and the New Innovation Challenge for Materials at End-of-Life

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Executive Summary: Recycling is critical for the drive towards a circular economy and sustainable materials. More than ever, consumers, industries, governments, and academics are looking at end-of-life materials processing with the simultaneous goals of reducing emissions and energy consumption from primary materials production, encouraging sustainable practices, and securing the supply chains of key materials. However, attention on recycling practices and markets has been inconsistent over the years and critical market trends were largely unnoticed up until three years ago. Consequently, when China instituted its import ban on over 20 classes of recycled materials that failed to meet its strict low contamination limit in 2018, widespread and immediate global repercussions were felt throughout the recycling industry, particularly in the United States (U.S.). To understand the magnitude of this most recent market disruption to the U.S. recycling industry, it is instructive to trace recycling's origins and evolution to identify where the recycling model has succeeded and where there exist opportunities for improvement. In this vein, this assessment gives a brief overview of the historical development of recycling in the U.S., the state of the industry today, and a discussion of specific materials classes where recycling has achieved varying degrees of success. By providing this context, this assessment aims to generate a discussion based on a systems-wide approach and provide examples of intervention strategies that help move communities toward more sustainable materials management.

I. Introduction: history of recycling in the United States

Recycling culture in the U.S. has not always been so ingrained in the collective consciousness. The concept of recycling went through many iterations over the past century, slowly gathering momentum as awareness grew about America's waste problem and the negative side effects of mass consumerism. The earliest models of recycling were informal and adopted out of necessity; campaigns during World War II encouraged citizens to recover everything, from metal cans to rubber boots to kitchen fat (Goodyear n.d.). Later models were introduced as cost-cutting measures or as opportunities to increase revenues for municipalities by selling recycled materials to foreign markets. Taking a holistic view of the history of recycling in the U.S. reveals two key trends. First, the increase in waste generated per capita associated with economic growth and the increase of plastics in the nation's waste and recycling streams is intimately connected with trends in the oil and gas industry. Second, the history of recycling markets has its roots in local communities acting alone. This meant that key recycling trends were missed, sowing the seeds for the industry-wide market collapse in 2018. Understanding how and why recycling developed, as well as what happens to recycled materials when they are processed in materials recycling facilities, can point to opportunities that result in more circular economies, i.e. economies that employ a systems-based approach to support processes and activities that maximize the utility or value of a resource for as long as possible and where recycling will play a central role.

i. The influx of cheap oil

If World War II taught governments anything, it was that oil was a critical, strategic resource that could tip the balance in geopolitical power. This lesson pushed Western countries to seek large oil concessions in the Middle East and to encourage rapid oil development that secured abundant, cheap oil supply chains (Yergin 2009). The influx of cheap oil for use as an energy resource and critical feedstock initiated a period of great economic growth and a massive cultural shift in the U.S.. Consumers, recovering from the years of war rationing and oil shortages, rejoiced in the apparent new abundance. Oil consumption in the U.S. tripled between 1948 and 1972, from 5.8 to 16.4 billion barrels per day, and with excess oil supply a new petrochemical industry burgeoned (Yergin 2009). Plastics became ubiquitous in modern American households. With this new prosperity fueled by cheap and overflowing energy, convenience was the name of the game and as a result, consumption—and subsequent waste generation—skyrocketed. Between 1960 and 1990, annual pounds of waste generated per capita grew on average 20% per decade, with noticeable increases in plastics (***Figure 1***).

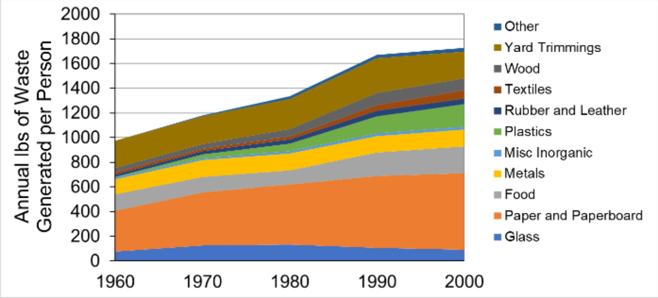

Figure 1: Annual pounds of municipal solid waste generated per person in the U.S. from 1960-2000. Waste generation data obtained from the EPA and population data obtained from the World Bank (US EPA 2017b; "Population, Total - United States | Data" n.d.).

Amid this growth, the 1960s were marked by significant gains won by prominent environmentalist movements in the U.S. which, among many things, culminated in the celebration of the first ever Earth Day on April 22, 1970 (History.com Editors n.d.). Nearly three months later, the Environmental Protection Agency (EPA) was established by executive order to regulate and enforce pollution limits nationwide. It was in 1970, too, that the iconic recycling symbol, designed by Gary Anderson at the University of Southern California, won a design competition sponsored by the Container Corporation of America (Goodyear n.d.). However, it would be another ten years before the first modern recycling programs were established.

ii. The early recycling programs

The first curbside recycling initiative was promoted by Don Sanderson, then a city council member for Woodbury, New Jersey. It was an effort inspired not by an environmental agenda but as a way to cut landfill costs for the town (Davis 2019). After contacting local companies, Sanderson realized that some of the trash residents were throwing away could be marketed to companies who would then reuse the materials for other purposes. Sanderson began advocating for a law that would require all residents to separate their glass, metal, and paper waste in separate buckets at the curb. The town's initial response was overwhelmingly negative. Newspapers wrote scathing reports about Don Sanderson and residents–angry and worried that their taxes would go up–dumped trash on his lawn. When Don Sanderson made it known that his proposal would save the town money on landfill costs, public opinion quickly turned, and Sanderson's law passed. Within three months, Woodbury, New Jersey achieved an 85% compliance rate in their recycling program (Goodyear n.d.). Thus, the new curbside recycling model was established.

Similar curbside recycling programs spread slowly to other small communities throughout the US, mostly as an effort to save money on landfill costs. However, one event in 1987 forced America's hidden waste problem to the forefront of public discourse and hastened the rollout of municipal recycling programs nationwide. *Morbro 4000*, a barge carrying 3,100 tons of New York City's trash set sail for what would turn out to be a long, eight-week cruise down the east coast of the U.S.

and through the Caribbean in search of a place to offload its garbage (McFadden 1987). After being rejected by North Carolina, Alabama, Mississippi, Louisiana, Texas, Florida, Mexico, Belize, and the Bahamas, the *Morbro 4000* finally gained clearance to return to Brooklyn—where its journey began—only to sit in limbo while legal and political battles played out before the garbage was finally incinerated. This singular event drew national attention to the U.S.' waste problem and its lack of landfill space; recycling seemed like an obvious cure.

The rollout of recycling programs began with curbside sorted collection systems. Households meticulously separated their recyclables by material type and left them at their curbside for collection. But in the late 1980s and early 1990s, a confluence of several factors once again encouraged a shift in the recycling model in the U.S.. Throughout the 1980s, the U.S. imported large quantities of consumer products from China; cargo ships arrived daily to the U.S. and would return to China, empty. At the same time, demand in China for recyclables used as feedstocks in manufacturing consumer goods was growing (Rico and Martin 2018; Solman 2018; Morawski 2009). Municipalities, with their large supply of recyclables, saw a convenient business opportunity. Cities and recycling processors could sell their recyclables to Chinese producers and ship them via the empty cargo ships returning to China at very low shipping costs. These changes meant that the need to ramp up recycling efforts was growing, especially because recycling was not only economical but, in many cases, generated revenue for the cities and processors that had robust recycling programs (Dillon 2018; Kuffner 2017; Taylor and Money 2019; Rosengren et al. 2019). The large, hungry recycling markets opening in Asia, compounded with renewed commitments to divert waste from landfills, incentivized the industry to seek alternative ways to expand recycling.

To increase recycling participation rates, reduce collection costs, and achieve ambitious waste diversion goals, a new model which became known as single-stream recycling was pioneered in 1995 in California (Laskow 2014). The advent of single-stream recycling—where all recyclables are discarded into a single bin—touted many benefits. First, transportation costs were substantially reduced by substituting multi-compartment trucks with single compartment trucks. Because curbside sorted recycling programs required trucks with multiple compartments, the number of trips to and from the processing facility in a typical collection route was dictated not by the full capacity of the truck but rather the capacity of the first compartment that filled. In contrast, single-stream collection programs could take advantage of using single-compartment collection trucks that could be on the road until their full capacity was reached, reducing the number of trips to the processing facility ("Kerbside Recycling: Indicative Costs and Performance" 2008). Second, using a single compartment truck made it possible to automate collection, thereby increasing the collection efficiency and simultaneously decreasing labor requirements, injury risks, and workers compensation. Between the reduced transportation costs and automation, single-stream recycling promised significant reductions in collection costs ("Kerbside Recycling: Indicative Costs and Performance" 2008; Morawski 2009; "An Assessment of Single and Dual Stream Recycling Including Current Program Performance in Large Ontario Municipalities" 2012). Finally, single-stream recycling was expected to increase municipal recycling rates because of its ease and convenience for consumers who no longer had to sort their recycling (Lakhan 2015; "Executive Summary Report for Recycling Analysis" 2018). Single-stream recycling provided a way for municipalities to increase participation rates and simultaneously cut costs. For these reasons, American communities with access to single stream recycling programs increased from 29% in 2005 to 80% in 2014 (Koerth 2019). Between 1960-2017, The U.S. increased recycling by 1600%, from 5.61 to 94.17 million tons (***Figure 2***).

With an undiscerning, robust market for the U.S.'s recyclables in Asia and a new, simple way to scale recycling programs, America's waste problem was largely forgotten, even as new developments were happening that would later become very problematic.

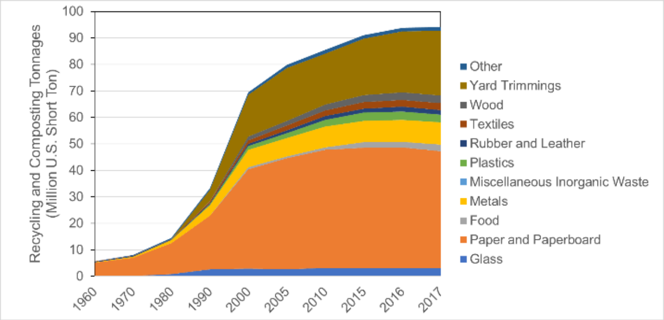

Figure 2: Annual Recycling and composting tonnages (U.S. short tons) in the U.S. from 1960-2017. Recycling data obtained from the EPA (US EPA 2017b).

iii. Over-reliance on Asian markets and the 2018 collapse

By 2016, the U.S. was exporting approximately one-third of its recyclables, half of which (16 million tons) was going to China (Rico and Martin 2018). The U.S.'s reliance on international markets, particularly those in China, had become so imbalanced that in some areas, particularly on the West coast, recycling markets were sending 80-90% of their paper or plastic materials to China (Rosengren 2018a; Jaquiss 2018; Rosengren et al. 2019; Krieger 2019; Shao 2019; Zarka 2019). In one extreme example, Friedman Recycling, a Phoenix-based company operating in New Mexico, Arizona, and Texas sold as much as 99% of its recycling to China (Dyer 2019). Globally, the size of the Chinese market was unprecedented; approximately 45% of all plastics recycled between 1992-2016 had been sent to China and in 2016 alone, China imported 60% of the recyclables worldwide (Jaquiss 2018; Brooks, Wang, and Jambeck 2018).

Meanwhile, several key trends in U.S. waste and recycling streams were going unnoticed. First, annual global and U.S. plastics production per capita had been growing rapidly since the 1950s and 1960s (***Figure 3***). As plastics became increasingly prevalent, particularly in single-use packaging, plastics as a percentage of the total municipal solid waste generated in the U.S. swelled from below 1% in the 1960s to around 13% in 2017 (***Figure 1***) while investment in efficient recycling and sorting processes for the myriad of plastic products lagged far behind (US EPA 2017b). The increase in plastics use and lack of investment in recycled materials processing in the U.S. mirrored what was happening globally, particularly among Western countries. As a result, less than 10% of the plastics produced globally were being recycled while around 80% was accumulating in landfills or in the environment (Geyer, Jambeck, and Law 2017; Brooks, Wang, and Jambeck 2018; Meidl 2018).

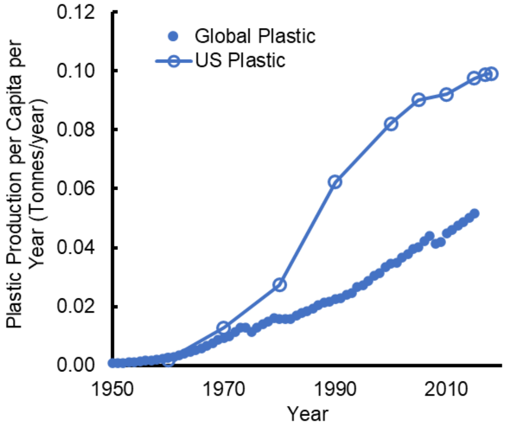

Figure 3: Growth per capita in yearly global and U.S. plastic production in metric tonnes per year (Geyer, Jambeck, and Law 2017; "World Population Prospects - Population Division - United Nations" n.d.; "Population, Total - United States | Data" n.d.; US EPA 2017a).

Second, Americans were becoming less careful with the items they were putting into their recycling bins. The phenomenon became known as "wish-cycling". When deciding between throwing an item into the trash bin or the recycling bin, more often than not consumers were choosing to "recycle" the item. However, this behavior had a detrimental effect on the quality of the recyclables being generated in the U.S. ("Downstream of Single-Stream" 2002; "An Assessment of Single and Dual Stream Recycling Including Current Program Performance in Large Ontario Municipalities" 2012; Koerth 2019; Lakhan 2015; Morawski 2009; 2010). Contamination levels in processed recyclables had grown to, on average, approximately 25% (by weight); in some cities the contamination levels were reported to reach as high as 40% (Rosengren et al. 2019; Hafner 2019; Danahey 2018; Thomas 2019; Kuffner 2017; "Downstream of Single-Stream" 2002). In comparison, one study found that a variety of dual-stream sorting programs (e.g. papers and fibers in one bin, everything else in another) had contamination levels around 10% ("Downstream of Single-Stream" 2002). In Memphis, Tennessee, though there was a 200% increase in volume of recyclables collected after switching to single-stream recycling in 2014, there was a 700% increase in the contamination levels, from 2% to 16% (Greene 2019). Frequent contaminants included dirty diapers or charging cords; at worst, these contaminants only caused delays from frequent shutdowns. However, more serious and dangerous contaminants such as lithium-ion batteries (which could catch fire in the facilities), propane tanks, live ammo, or loaded guns were also finding their way into the recycling stream (Allard 2019).

Third, as a direct consequence of the higher contamination levels, materials recovery facilities (MRFs) were absorbing much of the increased processing costs and simultaneously producing an inferior product ("Single Stream Recycling- Total Cost Analysis" 2004). These trends had serious downstream implications, particularly in tight markets (e.g. the 2008 market crash) where contamination levels could have a drastic impact on the price of recyclables sold on the market. For example, a bale of high-purity milk jugs could command a price as high as $600 per ton but if the bale required additional processing by the buyer, that price could drop to as low as $20 per ton (Kuffner 2017). However, while there existed large international recycling markets willing to pay for recyclables with high average contamination levels, there was no market driver to encourage innovations in the sorting equipment at recycling facilities. Technical upgrades to MRFs that would improve sorting were slow to be implemented and the domestic market for recyclables in the U.S., particularly plastics and paper, was in a decline; they simply could not compete with China's low production costs.

In January 2018, a large metaphorical sword came down and severed major global recycling ties. Following a precedent initially set by their "Green Fence" policy in 2013, China announced through its 2017 National Sword policy that it would no longer accept 24 classes of solid waste and that it would institute a strict, new contamination limit of 0.5% or lower, citing environmental concerns ("Announcement of Releasing the Catalogues of Imported Wastes Management" 2017). The single largest market for recyclables had closed overnight and left developed nations scrambling to find buyers for low quality product in an oversaturated market (Margolis 2018). Prices for corrugated containers, sorted residential paper, mixed plastic, and mixed paper plummeted (Rico and Martin 2018). Immediately following China's announcement, MRFs that had come to rely heavily on selling their product to Chinese markets were forced to stockpile their processed recycling while they searched for new buyers, waited hopefully for the Chinese market to reopen, paid to offload their recycled materials, or diverted their recycling to landfills. As it became apparent that the policy was not going to change, municipalities across the U.S. renegotiated contracts with recycling processors, in some cases paying more to maintain their programs or canceling them altogether (Rosengren et al. 2019).

Some cities replaced their single-stream recycling programs with dual-stream recycling programs or sponsored large campaigns to reeducate consumers on what materials were recyclable in an effort to clean up their recycling stream and increase its value (Pyzyk 2018; Staub 2018; Roper 2018). Several programs also changed the materials they were willing to collect for recycling. Most importantly, it became apparent that the world was drowning in a tide of recyclables, especially plastics, that for too long had been ignored and disproportionately absorbed by a single country. It also served as a reminder that recycling was not a social service; it was a business subject to market forces where the economics of recycling became harder to justify in depressed markets.

II. Recycling after collection

i. Glass

Not all materials are equally recyclable, nor are they collected in a way that facilitates recycling. One of the materials with the highest recycling potential, glass, is an excellent example of what happens when the recycling loop breaks down. Glass is a unique material because it can be infinitely recycled with no degradation in quality or purity (Jacoby 2019; "Glass Recycling Facts - Glass Packaging Institute" n.d.). Incorporating recycled glass—known in the industry as "cullet" —to make new glass has numerous benefits for glass manufacturers. Using cullet in glass making reduces the need for raw materials, decreases the energy required in the glassmaking process, reduces the operating costs of the furnace, and lowers the emissions of the overall process. High-quality (low impurity) cullet also enhances the quality of glass products either because there are less gas bubbles trapped in the melt or because cullet helps limit the degree of crystal deposition from unmelted starting materials.

With all these benefits, there is a strong demand for high-quality recycled glass materials. However, the transition to single-stream recycling adversely impacted the quality of recycled glass supplies. In single-stream recycling, glass is more likely to break into small pieces during handling, reducing its recoverability or contaminating it with other non-glass materials and different colored glass. As a result, only 40% of glass from single-stream recycling can be recycled, compared with 90% in a multi-stream collection system. Furthermore, glass is often cited as a contaminant for other recycled materials like plastic and paper; because of this, glass has been one of the most frequent materials to be cut from recycling programs. In the U.S., 10 million metric tons of glass is disposed annually, a third of which is recycled. For comparison, 90% of the glass that is disposed of in Europe is recycled (Jacoby 2019).

But all too often, the final fate for glass in the U.S. is in landfills or in a downcycled state (such as fiberglass, road materials, or landfill covers) where it can no longer be recycled, effectively removing it from the supply stream (Orr 2018; Evancie and Weiss-Tisman 2019; Gayle 2018; Fenston 2019). Glass has immense potential in a closed-circle economy but suffers from ineffective collection and sorting processes. Local efforts, including stimulating demand for recycled glass and encouraging better sorting habits, will enhance the recycling rates, increase the utility of recycled glass, lower energy demand in glass manufacturing, and reduce the carbon emissions from the raw materials processing (Evancie and Weiss-Tisman 2019; Gayle 2018; "Complete Life Cycle Assessment of North American Container Glass" 2010; Jacoby 2019).

ii. Paper and paperboard

Before the National Sword policy went into effect in 2018, the most recycled material in the U.S. was paper and paperboard. In 2017, 66% of the paper and paperboard discarded in the U.S. was recycled, constituting nearly 66% of the total municipal solid waste recycling stream ("Advancing Sustainable Materials Management: 2017 Fact Sheet" 2019; US EPA 2017b). The overall success of paper recycling relied, in large part, on markets overseas willing to accept relatively low-quality mixed paper. Like glass, single-stream recycling had a detrimental impact on the quality of recycled paper materials and conferred higher processing costs to paper mills ("Single Stream Recycling- Total Cost Analysis" 2004; Morawski 2009; 2010). However, strong demand in China made the global recovered paper industry more accepting of high contamination levels; in 2016, China imported 67% of 21.8 million short tons of recovered paper from the U.S. But in 2018, the National Sword policy effectively banned mixed paper (e.g. discarded mail, old telephone books, paperboard, magazines, catalogs) and instituted stricter contamination levels.

Prices for corrugated containers, sorted residential paper, and mixed paper plummeted, and the industry was left with low-quality material with nowhere to go. In 2018, a study from MIT and American Forest & Paper Association found that the containerboard, paperboard, and tissue sectors were only able to absorb 30% of the recycled mixed paper volume that originally was exported to China (Olivetti, Niles, and Chang 2018). Expanding the analysis to include all grades of recovered paper, the model predicted that an oversupply in the domestic markets and highlighted an opportunity for the paper industry to increase domestic recycling capacity or find new markets.

While higher contamination levels have hampered the industry's ability to recycle mixed paper, a similar trend has emerged in cardboard recycling. The rise in online shopping over the past decade has caused a steady increase in the volume of corrugated cardboard in residential recycling bins, a trend known as the "Amazon Effect" (Calma 2019).

Republic Services, the second largest waste disposal company in the U.S., noted an increase of about 5% in the total volume of cardboard that it picked up and resold on recycling markets between 2012-2019. As a volume percentage of the recycling in some areas like New York City, cardboard has been estimated to be approximately half the volume in curbside recycling streams. The shift to more cardboard recycling from private residences, rather than commercial businesses, is leading to more contaminated cardboard; residences are more likely to mix their cardboard with old food containers or unwashed cans which soil the cardboard and degrade its recyclability. Furthermore, the influx of recovered cardboard on the market in the wake of the National Sword policy has reduced prices by 50% or more. With these industry changes in mind, domestic recovered paper markets will need to adapt. There are several options for the industry, including increasing the capacity to process mixed paper, improving the municipal collection system (perhaps moving away from single-stream recycling), increasing consumer education, investing in MRF sorting technology, finding new export markets, and corporate education with the goal of changing corporate policies to encourage reuse, recovery, and design for recyclability (Olivetti, Niles, and Chang 2018).

iii. Plastics

The quintessential and most visible example of where the recycling loop has broken down is plastics. Beginning in the 1950s, global plastics production skyrocketed as plastics revolutionized several industries, particularly the packaging industry. Nowadays, plastics are a key material in multiple sectors with few suitable substitutes, while their waste management has largely been neglected. As recently as 2015, only about 9% of the 6300 Mt of plastic waste generated worldwide had been recycled, 12% had been incinerated, and the remaining 79% (60% of all plastics produced) had been left to accumulate in landfills or in the natural environment (Geyer, Jambeck, and Law 2017). In the U.S. alone, the plastic recycling rate has hovered around 9% since 2012 and approximately 75% has been discarded in landfills. In 2018, the National Sword policy highlighted the magnitude of the plastics waste management problem, particularly for OECD countries who—outside of Hong Kong—export the majority of plastics; one estimate suggests 111 million metric tons of plastics that would have been sold to China will be displaced with nowhere to go by 2030, the bulk of which (~90%) come from plastic packaging materials (Brooks, Wang, and Jambeck 2018).

However, expanding the recycling loop to meaningful levels remains elusive for several reasons. Not all plastics can be easily sorted from a mixed recycling stream in today's sorting systems (Davis and Joyce 2019). For example, small plastics (~3 inches or less in size), plastic wraps and plastic grocery bags, and flexible packaging create a host of problems for the sorting equipment at a typical MRF facility. Small plastics, because of their size, can get caught in conveyor belts, stuck in equipment gears, or fall through the sorting equipment. Plastic wraps and plastic grocery bags create a much bigger problem for MRFs; these plastics wrap around the sorting equipment and cause delays in the process each time the sorting equipment is shut down to extricate the plastic from the machinery.

Flexible packaging is even less recyclable for two reasons. First, plastic packaging is flattened in the sorting process and is oftentimes incorrectly sorted with the paper stream; as a result, the paper stream is contaminated and potentially rendered worthless. But the second reason why flexible packaging is not recyclable arises, ironically, from trying to solve another environmental problem: food waste (Tullo 2016). Modern flexible food packaging is durable, lightweight, cheap to transport, and can extend the shelf life of the food inside. However, to achieve these properties, multiple layers of plastic are required, each with a different purpose. This plastic packaging can increase the lifetime of produce from days to upwards of two weeks; using vacuum-sealed packaging can extend the lifetime of meats from a few days to almost a month. For all its benefits, however, the specialized design of flexible packaging significantly impacts their recyclability. The multiple layers cannot be separated at an MRF facility and, if they are processed into small pellets, they are more often downgraded to lower uses like plastic lumber rather than new packaging. One report estimates that only 2% of plastic packaging is recycled and repurposed for its initial high-value use (Tullo 2016; "The New Plastics Economy- Rethinking the Future of Plastics" 2016). The economic losses from the breakdown in the plastic packaging recycling loop are estimated to be as much as $120 billion dollars per year.

In addition to the difficulties of sorting them from a mixed stream, the recyclability of plastics can be impacted by their manufacturing conditions. For example, clamshell packaging is made from the same plastic as beverage bottles but, due to changes in their structural properties during the molding process, they are more difficult to recycle. Similarly, polystyrene products are primarily composed of air and, if recycled, must first be compacted to remove the air. After compaction, though, not enough material can be recovered to justify the extra processing. The only plastics which maintain their value if they are recycled are the #1 (Polyethylene Terephthalate, PET) and the #2 (High Density Polyethylene, HDPE) plastics which, if contamination levels are low, have strong markets ("Smart Plastics Guide," n.d.).

Unfortunately, when it comes to recycling plastics, consumers are presented with inaccurate or misleading messaging. A recent investigative report by NPR and PBS *Frontline* uncovered the truth that the oil and petrochemical industries have known for almost 50 years: recycling plastics at scale is not economically feasible (Sullivan and Gonzalez 2020; Sullivan 2020). In the late 1980s and early 1990s, the plastics industry knew it was at a crossroads as consumer opinion was beginning to turn against plastics. As a result, millions of dollars from the plastics industry were poured into advertising campaigns in the early 1990s praising plastics. Ironically, the most lasting consequence from these campaigns made plastics less recyclable. Powerful lobby groups pushed for mandates in 40 states to mark *all* plastic material with the recycling symbol. Because consumers were given the impression that all plastics were equally recyclable, they began mixing all plastics in their recycling bins, exacerbating an already dire situation. As a result, most plastics are improperly managed, often not diverted to recycling facilities and instead sent directly to accumulate in landfills (Davis and Joyce 2019; Jambeck et al. 2015).

Even though China's National Sword policy brought the global and U.S. plastics problem to the forefront, demand for plastics has continued to increase, unabated. This trend was further exacerbated by the pandemic with the need to mitigate virus spread with plastics used in everything from disposable masks to gloves and by rock-bottom oil prices (Chang 2020). To meet future global demand, analysts project plastics production will triple by 2050; oil and gas industries are already heavily investing to ramp up plastic production facilities in an effort to pivot into new sectors as oil demand in the transportation sector declines (Sullivan and Gonzalez 2020; Sullivan 2020). Where this plastic will go—into landfills, the natural environment, or diverted to other countries—remains to be seen.

One proposed solution that is already employed in several regions throughout the U.S. to minimize waste volume and the need for efficient sorting processes is burning plastic waste to extract energy, a process known as "waste to energy" (WTE). The heat released from waste combustion converts water to steam which then drives a turbine to produce electricity. In the U.S. alone, there are 75 WTE facilities operating in 25 states generating, on average, 550 kWh per ton of waste (US EPA 2016). In 2017, an estimated 34 million tons of waste was combusted with energy recovery. However, the number of WTE sites in the U.S. remains limited, primarily because there is ample land available for traditional landfills (and therefore no need to burn waste to accommodate more waste in a limited area), there are large and significant upfront costs for a new WTE facility, the economic payoffs take several years to realize, and there is public opposition due the perception of WTEs being highly polluting.

Despite this perception, there is some evidence to suggest that, over the lifetime of a facility equipped with the most recent air pollution control equipment, WTE sites are less harmful to the environment and have lower CO_2 emissions than coal and have comparable environmental impacts and emissions to natural gas and oil. This evidence would therefore suggest that WTE facilities would not have outsized negative impacts compared with technologies already in place today. However, WTE may still be a less-than-ideal solution because combusting this material represents a huge economic loss equivalent to over $8 billion for plastic waste alone (Garcia and Robertson 2017). Furthermore, one report estimates the potential to save the equivalent of 3.5 billion barrels of oil (an economic value of roughly $176 billion) by advancing more effective and efficient recycling processes for the global plastic solid waste (Rahimi and García 2017). Plastics recycling promises huge energy and economic savings and will be a critical component in the future as oil and gas companies increasingly base their long-term strategies on increased plastics production (Sullivan 2020).

iv. Metals

While glass, paper, and plastics recycling have been complicated in recent decades, particularly after the switch to single-stream recycling, metals recycling does not suffer the same pitfalls. Unlike plastics and paper, metals hold their value and can be up-cycled into high-value materials; like glass, recycling metal scrap offers substantial energy savings and emissions reductions. The metal supply is a combination of two types of material. "Primary" materials are raw materials produced from ores and "secondary" materials which include manufacturing scrap ("new" scrap) and postconsumer scrap ("old" scrap); new scrap and old scrap are combined to calculate recycling rates. While the new scrap recovery rate is considered to be very high because there is a large economic incentive to recover this material during processing, there is a large degree of variability in how efficiently old scrap (i.e. old cars, used beverage cans, machinery) is recovered at its end of life. As recently as 2017, the U.S. recycled 56.6 million metric tons of selected metals[1], equivalent to 47% of the apparent supply and with an estimated value of $33 billion (Singerling and Sangine 2017). Iron and steel constituted the majority (89%) of the recycled metal and 88% of the apparent supply.

However, not all metals are recycled at the same rates. The difference in recycling rates may be attributed to the availability of primary (new) metal sources, supply and prices of scrap metal, ease of recovery of scrap metal, and usability of scrap metal in existing facility processes (Sibley 2011). For these reasons, there is a wide range of recycling rates (defined here as the total metric tons of metal recycled divided by the apparent supply) spanning from a low of 16% (zinc) to 69% (lead) (Singerling and Sangine 2017). In a series of reports published by the U.S. Geological Survey from 2011, the materials flow of several recycled metal commodities were detailed (Sibley 2011). Though the exact flows of different metals may differ, the recycling flow charts all have the same basic components, as summarized and reported by the U.S. Geological Survey (USGS) (***Figure 4***) (Sibley 2011).

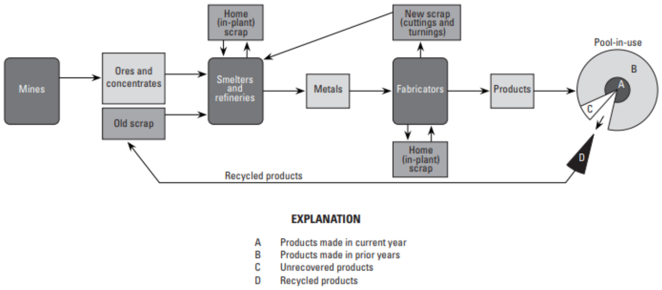

Figure 4: Generalized metals recycling flow chart first presented by USGS (Sibley 2011).

The data tracking metals recycling indicate that more can be done to expand recycling of key metal commodities in the U.S. Some notable successes in increasing recycling have already been achieved. For example, battery recycling legislation for lead-acid batteries has bolstered a robust recycling collection infrastructure. As a result, lead (88% of which was used in lead-acid batteries as of 2008) continues to be recycled at rates around 70%; in 2008, secondary lead accounted for almost 80% of the domestic lead consumption (Sibley 2011). Similarly, nickel recycling rates have been climbing since 1990. This is due to its relatively high value, technological advancements that improve the recyclability of nickel-bearing stainless steel scrap, waste management regulations spurred by concerns over the toxicity and carcinogenicity of nickel compounds, and the relatively recent availability of

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[1] Metals include: aluminum, chromium, copper, iron and steel, lead, magnesium, nickel, tin, titanium, and zinc

nickel in lithium-ion batteries which promise new opportunities for recyclers.

To push metals recycling further, there remains a technological need to improve the sorting process for old scrap processed at scrap yards (Seabrook 2008). In a typical process, old scrap is sent through a shredder where it forms a mixture of smaller chunks including several different metals and metal alloys, glass, plastic, foam, rubber, paper, etc. After the scrap is shredded, large magnets are used to extract and separate the ferrous (iron-containing) metals before sending this material to steel mills. The resulting mixture of nonferrous metals—typically aluminum, magnesium-based alloys, zinc, copper, and brass—is known in the industry as “Zorba” and is most often sent overseas where the labor cost to hand sort the Zorba into its constituent metals is significantly cheaper. In the event that prices for scrap metal are high, Zorba can be processed domestically using electromagnetic sorters which use eddy currents to separate large pieces of non-ferrous metals such as copper and aluminum are then employed or flotation baths which employ copious amounts of water to sort out the smaller pieces of nonferrous metals that sink to the bottom. Technical advancements in sorting such as alloy tagging combined with x-ray fluorescence spectroscopy could lead to more efficient sorting, a larger fraction of metals recovered from old scrap, and a reliable domestic supply of scrap material. In addition to technical upgrades, policies aimed to foster better reporting and to promote the recovery of valuable metals may also support better recycling practices.

III. Future of recycling

As the recycling industry grapples with the recent market disruptions and as end-of-life materials management becomes more critical, coordinated action among governments, producers, consumers, and technology markets will be essential. Current recycling models are unsustainable and greater responsibility for end-of-life management must be shared among consumers, producers, and governments. This is particularly crucial as the global population is projected to increase to nearly 10 billion people, with several large emerging markets anticipated to develop significantly over the next several decades. Demand and production of materials, particularly plastics, will likely climb with a concomitant increase in waste generation. Therefore, both near-term adjustments and long-term solutions to recycling and waste management must be addressed.

i. Revisiting the U.S. recycling model

Following China’s National Sword policy, the drawbacks of the U.S.’ single-stream recycling model became clear, begging the question if this model will be sustainable long-term. Policies that reduce contamination levels in the recycling stream and make recycling more accessible can help make these processes become more efficient. For example, several states and municipalities have invested in campaigns to reeducate customers on what is and what is not recyclable. Other municipalities across the U.S. have begun reverting their single stream recycling programs to dual stream in an effort to curb the contamination levels in their recycled materials (Koerth 2019; Roper 2018; Pyzyk 2018; Staub 2018; Rosengren 2018b).

For materials like metals and glass which are already more easily recycled, policies have served an important role on the supply side in diverting these materials from waste streams. Bottle bills for glass bottles or buyback programs like those for used lead acid batteries have proven immensely successful in establishing a formal collection system that uses a series of deposits to incentivize retailers, distributors, and consumers to participate in the recycling process. A study published by the Container Recycling Institute (CRI) found that recycling rates for aluminum, plastic, and glass containers in states with a bottle bill were, on average, almost twice as high as those with other types of programs (Gitlitz 2013).

In addition to increasing recycling rates, the same study found that the recyclability of certain materials was enhanced. This was particularly true for glass, a material uniquely impacted in single-stream recycling programs. The CRI report found that in 2010, only 60% of glass bottles collected in single-stream curbside recycling programs were recycled into new bottles compared to 98% of glass returned in states with bottle bills.

Increasing access to recycling programs has also been shown to lead to successful recycling programs (Marshall et al. 2017). A few common characteristics of the most successful recycling programs, as measured by pounds of recycling per household per year, included: single-stream curbside programs with automatic (e.g. no opt-in action required) collection and large, wheeled carts with lids. The most important factor for higher community recycling rates, however, was the level of involvement of the local governments. Communities that took action to incentivize recycling (e.g. franchising or licensing agreements with waste haulers to bundle garbage and recycling services, or mandates that automatically extend recycling to all households) had higher recycling rates.

As recycling models continue to evolve and expand in the future, robust data collection will be necessary to track program progress. Furthermore, studies that target recycling in multifamily or apartment complexes can help identify additional policy opportunities to expand recycling to this relatively underserved demographic. Finally, incorporating recycling services that connect rural communities with more established recycling hubs may lead to higher participation rates across the U.S.

ii. Designing materials for end-of-life

Materials that can retain their value and can be upcycled into high-value products are more likely to be recycled. This is the case for many metals, including steel, aluminum, and titanium, as well as glass, which has significant environmental benefits. Plastics, however, suffer from poor recyclability due to their unique chemical structures and difficulties in processing. Plastics recycling will need to expand to include: chemical recycling (reverting polymers to their original monomers at moderately high temperatures and in the presence of a catalyst), the development of compatibilizers to improve the processability of commingled plastics, and plastic polymers that are generally more amenable to recycling into new materials or new plastics that will biodegrade, thereby minimizing plastics accumulation in the natural environment (Garcia and Robertson 2017; Stein 1992; Ignatyev, Thielemans, and Vanderbeke 2014; Agarwal 2020; Gross and Kalra 2002).

However, technology can only take plastics recycling so far; actors at every stage of the supply chain must play a role. Upstream product developers might consider the design and resin choices of their plastic packaging, collaborating with recyclers to maximize the value of the packaging at its end of life and increase transparency along the entire value chain. In new collection models, like the "milkman model", consumers buy their favorite products online and pay a small deposit; when they have finished using the product, the consumers return their empty containers or products to a courier or drop off the containers and products at select store locations (Franklin-Wallis 2019). This encourages packaging design that is durable, rather than dispensable, and makes consumers more active participants in the recycling process.

iii. Advanced sorting systems

Investing in technical solutions that enable efficient sorting will be key to increase recycling efficiency across all classes of materials, from metals to plastics. Improving metals sorting could include using trace elements in alloys that, at end-of-life, will be easier to identify using sorters that employ X-ray fluorescence, for example. Plastics and paper recycling are plagued by inefficient sorting from a mixed stream and a degradation in their properties after each cycle. In this vein, new technologies and robotic sorters combining artificial intelligence systems and deep learning to scan and identify different materials can augment the processing capabilities in today's MRFs ("Max-AI® In Action" n.d.; Rahimi and García 2017). These systems will require large upfront capital investments, providing an opportunity for public and private partnerships to help de-risk the technology development and scale advanced sorters.

iv. Corporate social responsibility

These collection initiatives might be considered as part of a broader Company Social Responsibility (CSR) strategy in response to mounting pressure from shareholders, consumers, and regulation agencies to develop sustainable supply chain management practices at each stage of the value chain. Recently, CSR initiatives have increased dramatically—93% of the largest 250 global companies have published CSR reports (Hickle

2017). However, less than half of the companies analyzed in one study cited specific goals in their CSR strategies or addressed supply chain management, instead prioritizing water conservation, climate change, and internal waste reduction (Hickle 2017). The efficacy and breadth of CSR strategies, particularly for end-of-life handling, will depend on the voluntary actions taken by individual firms.

It is here where Extended Producer Responsibility (EPR) policies and regulations can supplement voluntary company practices to ensure that all corporate activities adhere to the same minimum standard for sustainable activities and internalize environmental or social externalities (Hickle 2017; Cai and Choi 2019; Diggle and Walker 2020). When designed correctly, EPR policies can promote sustainable practices and encourage producers to internalize post-consumer disposal costs. In their review of the EPR literature, Cai and Choi highlight several innovative proposals related to EPR systems in five areas, including policy, product, process, supply chain, and technology (Cai and Choi 2019). Some of the most notable EPR policy proposals include life cycle analyses (LCAs), legislation to curb illegal and informal recycling, using real-world data to assess the efficacy of policy initiatives, and creating inter-country alliances to better track the international trade networks for recycled materials. The last point is particularly critical, because the emergence of large recycling markets have made tracking recycling shipments more complex. Future EPRs that aim to close the loopholes in international trade markets may play a role in preventing illegal recycling shipments, particularly to developing countries where recycling is less regulated, informal and illegal operations are common, accidental release to the environment is more likely, and where recycling processes pose serious environmental and social harm to the local populations ("We Found UK Plastic Waste in Illegal Dump Sites in Malaysia" 2018; Laville 2018; "US Plastic Waste Is Causing Environmental Problems at Home and Abroad" 2018; "How Mountains of U.S. Plastic Waste Ended up in Malaysia, Broken down by Workers for $10 a Day" 2018; "China's Ban on Trash Imports Shifts Waste Crisis to Southeast Asia" 2018). International frameworks for tracking and reducing hazardous waste movement between nations like the Basel Convention provide a starting point for future policies, empower both producers and governments to address the end-of-life waste management, and offer an opportunity for innovative solutions which help sustainably increase global trade markets.

v. The importance of considering life cycle of materials

Without considering the entire life cycle of any given material class, policies run the risk of exacerbating negative environmental impacts. Perhaps the most popular policies that were enacted following China's National Sword policy aimed to significantly reduce or completely remove plastic bags ("State Plastic Bag Legislation" 2021). However, numerous life cycle assessments suggest that, over the entire life cycle, plastic bags have a lower global warming potential per trip than common alternatives, including paper bags (Kimmel 2014; Ahamed et al. 2021; Great Britain and Environment Agency 2011). One study looking at the environmental impacts over the life cycle of several grocery bag options found that to achieve a lower environmental impact than a typical plastic grocery bag, paper bags or more durable reusable plastic bags must be reused at minimum 4 times (paper bags) and at maximum 13 times (non-woven polypropylene sacks with a plastic bottom insert) in order to have an equivalent global warming potential to single-use plastic grocery bags (Kimmel 2014). In other words, policies designed to limit plastic bag use might be exacerbating climate impacts unless additional policies are in place to encourage re-use of plastic bag alternatives as much as possible. These unintended consequences can be mitigated, but only if the environmental impacts of materials and their alternatives are quantified over their entire life cycle.

IV. Conclusion

The conclusion of World War II and the availability of cheap oil propelled the U.S. into an age of consumerism and growth. Hidden in the shadows of this prosperity, however, was a growing waste problem that would soon engross the country in a discussion about the final fate of our waste. The first formal recycling model was introduced as a way to reduce waste in municipalities. The combination of switching to single-stream recycling, targeted advertising from the plastics industry that promoted plastics as a recyclable material, and an overreliance on a single recycling market stifled innovation and left the recycling market vulnerable to major global disruptions. Recycling will be a key cornerstone for building a circular economy in the future, but it will require actors along the entire supply chain to have a vested interest in minimizing the social and environmental impacts of their activities. Building in end-of-life management strategies should be a top priority for CSR initiatives and can be reinforced by EPR systems. There are many opportunities for innovative and impactful solutions that promise significant economic, societal, and environmental reward.

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