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Outlook on the future role of robots and AI in material recovery facilities: Implications for U.S. recycling and the workforce

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Highlights

- Future recycling is likely to feature more use of robotics and AI in its processing
- The introduction of technology to recycling will impact workforce numbers and job types
- By 2050, policy support for recycling is likely to increase in the U.S.
- Scenario analysis of future paths for recycling enables refined techno-economic analysis

Abstract

This study offers a comprehensive discussion of the future role of robots and artificial intelligence (AI) in U.S. recycling under different policy environments and its impact on the workforce. The state of recycling in the U.S. is changing rapidly, with techno-economic developments transforming the efficacy and sustainability of recycling and the workforce it employs. This study describes the technical, social, and policy drivers that influence U.S. municipal solid waste (MSW) management and explores pathways for more sustainable outcomes by focusing on different technology options for the sorting of recyclables in material recovery facilities (MRFs). This study presents four distinct scenario storylines for U.S. recycling by 2050 that contrast recycling and robotic futures, particularly with MRFs that maximize material recovery, worker experience, and economic competitiveness, respectively. This study finds that a recycling scenario defined by strong policy support for recycling and the addition of increasingly flexible, collaborative technology in the form of robotics coupled with AI-driven vision systems, offers the greatest potential for better results. Less certain is the role of MRFs by 2050 based on the full cost for public actors and substantial changes in private industry. Insights from this study can directly inform future techno-economic analyses, technology decisions, and policy recommendations.

Keywords

Material recovery facilities (MRFs); recycling; municipal solid waste (MSW) management; future of work; experience of work; scenario storylines

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Section 1: Introduction

The recycling rate of municipal solid waste (MSW) is low in the United States when compared to other industrialized regions: 32% in the U.S. (U.S. Environmental Protection Agency 2020), 49% in the European Union (European Environment Agency, 2023) and even 57% in South Korea (Statista, 2023). Low recycling rates contradict the notion of a circular economy, represent a loss of valuable materials for reuse (Chertow and Gordon, 2019), and are associated with environmental costs for landfilling or incineration. There are two strategies to increase the amount of recycled MSW, namely 1) increasing the collection rates of recyclables (through increased access or better compliance of participating households) and 2) better sorting at material recovery facilities (MRFs), i.e., the plants that separate different recycling streams.

This study explores the second strategy by giving special emphasis to the emerging role of robots as complementary sorting equipment, and the impact of robot integration on the future workforce in MRFs. It does so through a broad framework that is organized into four themes: 1) the drivers of future recycling; 2) the impact of technology on recycling; 3) the impact of changes in recycling technology on workers; and 4) the role of business in defining the future of recycling. The following set of questions and responses introduces these themes. The four themes are then discussed in detail in Section 3 by developing a scenario framework that explores different technology options and levels of robotic integration into MRFs, and the

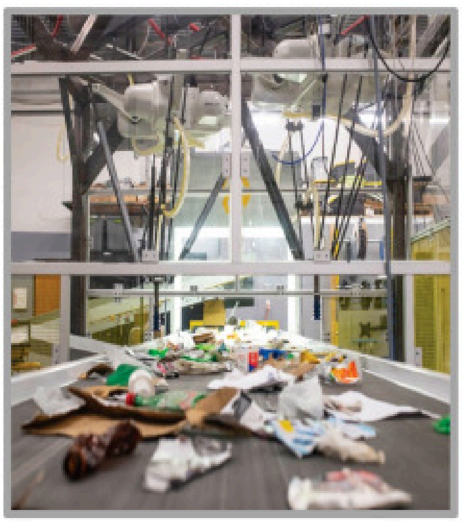
anticipated impact of these decisions on workers. Lastly, Section 4, "Discussion and Looking Ahead" builds on these insights for a final reflection on these questions.
Question 1. What are the most relevant threats and opportunities likely to influence the future of recycling?

Trends anticipated in this study are an ever-changing waste stream composition, growing levels of automation across waste collection and sorting, innovations (possibly disruptive) in materials and waste management, and a restructuring of MRFs so that less waste is diverted to landfills and incineration and more revenue is retained, including a growing interest in "secondary sorting" that extracts additional recyclables from MRF residues.
Question 2. In what ways does technology - especially the use of artificial intelligence and robotics - change the recycling industry?

Technology plays a central role in the waste management sector. After decades of only incremental advancements, recent years have seen dramatic developments in sorting technology, suggesting an active, fast growing, paradigm-shifting era of innovation. Driven by advances in optical sorting and AI, new monitoring and sorting technologies have emerged, such as automated waste composition/contamination estimation and vision-based safety systems for the detection of dangerous materials, leading to more efficient sorting equipment such as advanced robotic sorters.
Question 3. In what ways are workforce issues affected by changes in recycling, particularly at the interface of humans and robots?

The largest workforce change is expected to be a major decrease in the number of human sorters employed in MRFs. Even though a smaller number of humans can expect to have more complex jobs at MRFs, such employment requires new protocols and extra training which affects the workforce. The photographs in Figure 1 illustrate this shift, from human workers sorting waste for recycling (left, from Wikimedia) to robots but no humans sorting recyclables on the MRF line (right).
Question 4. How are U.S. businesses responding to the call for greater sustainability given climate and environmental challenges, and how do their responses influence the business models of waste management and recycling companies?

a) https://commons.wikimedia.org/wiki/File:Municipal_recycling_facilities,_Montgomery_County,_MD._2007,_Credit_USEPA_(14410405277).jpg



b) Fully automated MRF line

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Fig. 1. (a) Workers on the MRF line https://commons.wikimedia.org/wiki/File:Municipal_recycling_facilities,_Montgomery_County,_MD._2007,_Credit_USEPA_(14410405277).jpg ↗ ; (b) A MRF line utilizing robots

The importance of sustainability topics has surged for large companies. As one recent business article states, “Society’s expectations of business have changed more in the past two years than in the previous 20” (Polman and Winston, 2021: 1), a result of the visibility and threat of climate change. Companies are facing increasing pressure to cut waste, pollution, and emissions, and more efficiently use the resources already in circulation. This presents an opportunity for the recycling industry to align with current sustainability trends. This opportunity may be hastened by the rapid restructuring of the waste management industry through mergers and acquisitions, offering large companies increased market power by covering a greater portion of the waste supply chain.

The forces in play outlined in the questions and responses above stand to transform the recycling industry between now and 2050. However, the ways in which this transformation will evolve are less clear. This study develops a number of future pathways that could credibly guide developments over the next quarter century. It uses scenario storylines to develop snapshots of where the U.S. could stand in 2050 with respect to its recycling future. Given the considerable role of technology in recycling globally, it pays particular attention to how it could transform this industry. The study focuses on the implications of transformative technologies such as robotics and AI for improving workforce management, particularly in MRFs, and the efficacy of waste management by increasing the recovery of secondary materials and reducing the flow of waste to landfills. There is great interest among MRFs about how to increase the value of recycled material by adding sorting capabilities, enhancing AI recognition (including robots and vision systems as mentioned above), and adding catalogs of images numbering in the billions for identifying specific containers and packaging types (Leif, 2022).

To illustrate possible pathways that recycling and technology could take, this study complements a scenario framework (Van Vuuren et al., 2012) with discussions and interviews conducted with leaders in the recycling and technology industries, as well as with scholars studying the workforce. This leads to a descriptive set of SSP-based scenarios (Riahi et al., 2017) covering the broad range of factors influencing the future MRF landscape in the U.S. – from public policy to consumer and business demands for sustainability, to feasibility and cost of AI and robotics – without trying to quantify the substantial associated uncertainties. The resulting storylines discuss the implications of the kinds of materials being processed in MRFs, how those materials are used, how much and what type of technology might be deployed in MRFs, and how that technology will affect the MRF workforce. In combination, they highlight how future policy and technology decisions drive MRF economics and workforce decisions and vice versa.

Section 2: Methods

A two-step approach was used to identify plausible pathways towards a more efficient U.S. recycling system by 2050. The first step involved selecting a framework for mapping **sustainable futures** that allows exploring different pathways (scenario design). The second step involved identifying the **key drivers** that might influence the state of U.S. recycling in 2050. Both steps were informed through an initial stakeholder workshop, interviews with experts covering different aspects of U.S. waste management, complemented by an extensive literature search.

Figure 2 provides an illustration of the methodology framework used in this study, together with its main information sources.

Step 1: Selecting a framework for SUSTAINABLE FUTURES on the state of U.S. recycling in 2050.

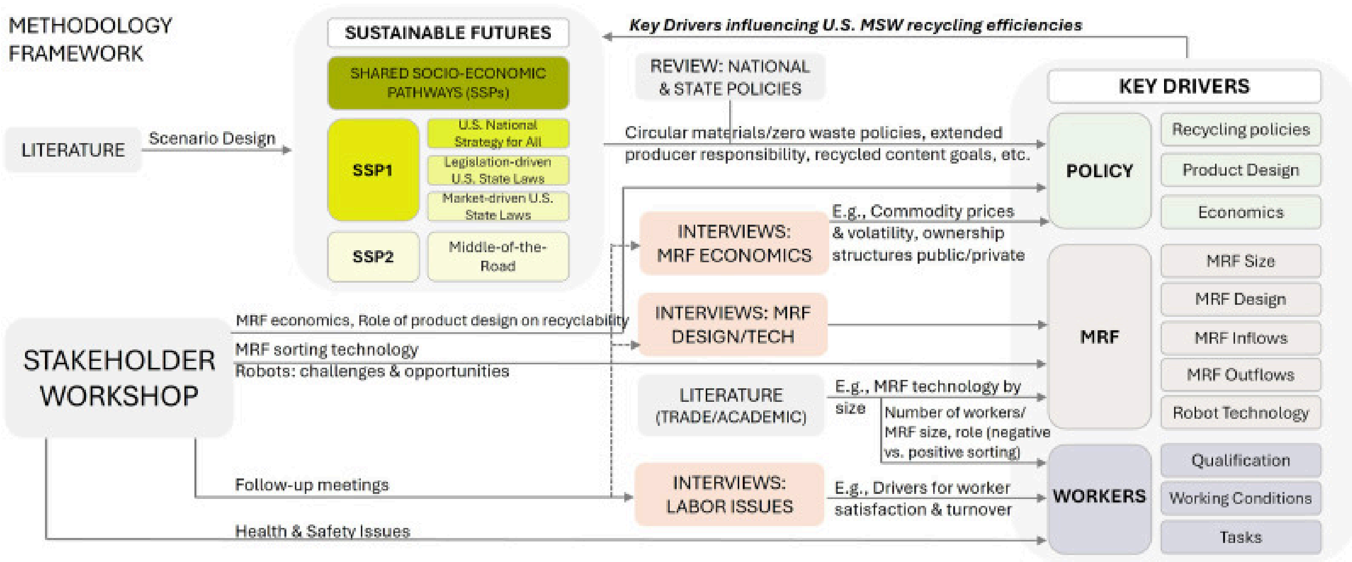

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Fig. 2.

This study uses a scenario framework to develop plausible storylines on future U.S. recycling pathways. Scenarios are descriptions of possible futures (Kosow and Gaßner, 2008), they are not predictions (Brewer, 2007). By highlighting important elements of a possible future, they draw attention to the key factors that will shape that future (Kosow and Gaßner, 2008). Scenario analyses have advanced the understanding of a range of sustainability challenges, including waste management (Meylan et al. 2018).

The shared socio-economic pathways (SSPs) are a set of five scenarios that span a relevant range of uncertainty in societal futures and describe plausible changes in aspects of society across demographic, economic, technological, social, governance, and environmental factors (O'Neill et al., 2017). They are widely used in sustainability studies and allow incorporating the key questions from the Introduction, namely the drivers of future recycling, the impact of technology on recycling, the impact of changes in recycling technology on workers; and the role of business in defining the future of recycling. Two of the SSP scenarios form the basis for the four scenario storylines presented here:

- SSP1 Sustainability (Taking the Green Road; low challenges to mitigation and adaptation)
- SSP2 Middle-of-the-Road (medium challenges to mitigation and adaptation)

Information from Section 3 (Literature Review and Status Quo) informed the four scenario storylines presented in Section 4, including different assumptions on key drivers and the level of anticipated MRF automation. More information on the SSPs, the original storylines of SSP1 and SSP2, and the history and application of scenarios is presented in the Supporting Information (Section S2).
Step 2: Identifying the KEY DRIVERS that might influence the state of U.S. recycling in 2050.

Key drivers were categorized into three groups: policy, MRF technology, and worker aspects. An initial two-day in-person workshop covered the key stakeholders driving U.S. recycling outcomes: MRF operators, MSW handling companies, metal recyclers, manufacturers of robotic/AI solutions for MRFs, waste management finance professionals, consumer goods manufacturers, policy makers, and academics focused on robotics, sustainable materials and waste management, public health, worker safety, and the psychology of work (a total of 30 experts). The workshop provided valuable insights into the impact of recycling policy on different industry groups (original equipment manufacturers [OEMs], recyclers), MRF economics, the role of product design in recyclability, pros and cons of different MRF sorting technologies (including different setups of robots coupled with AI-driven vision systems in MRFs), and health and safety issues of MRF workers.

Following the workshop, a set of carefully selected interviews were conducted with experts on MRF operations, MRF technologies, and plastics recycling technology as well as on waste management, the circular economy, and recycling more broadly. Over a period of two years (2020-22) some experts were interviewed repeatedly to ask for their feedback on new information or new technology developments. Interviews highlighted the impact of fluctuating commodity prices on long-term planning, the economic challenge from different ownership at the collection (often cities/towns) and separation (MRFs) level of recyclables, and the drivers of worker satisfaction and turnover. More information on the workshop and interviews appears in the Supporting Information (Section 1).

The review of the academic literature was complemented by a review of the waste management trade literature, which tends to be more up-to-date regarding the latest technology trends (Section 3.2). Through an iterative process, the gained insights on MRF economics and the factors influencing technology selection, worker retention rates, and overall material recovery efficiencies were used to develop the four scenario storylines presented in this study.

Section 3: Literature Review and Status Quo

In the following sections, the literature on how MRFs and their labor forces are evolving over time is examined, followed by a review of the development of technology in MRF operations with a focus on waste collection and the role of AI and robots. These sections highlight the ways in which the labor and technological landscape is tightly bound up in and determinative of the future of MRFs.

Section 3.1: MRF Evolution and the Workforce over Time

Academics and practitioners are increasingly interested in the development of technology for recycling and processing. Particular attention has been paid to the implications of advancing technology for the workforce, with an emphasis on the benefits to MRFs of relying less on human labor (Hayes, 2021). Today's MRF managers face a range of operational challenges, including contamination of waste streams and limited recovery of recyclables (King County Waste Monitoring, 2020), health problems (Poole and Basu, 2017), safety risks (Neilson, 2019), and high employee turnover (Rosengren, 2018).

The evolution of MRFs to meet these challenges and changes in technology, policy, and waste itself (Offenhuber, 2020) raises important questions about how the work of recycling will happen, and what happens to workers involved as technology remakes the landscape of MRFs.

The appeal of technical solutions to MRF operators is clear. By deploying robotics and optical sorting systems, MRF operators can supplement a labor force that has been hard to attract to this "dull, dirty, and dangerous work" (Gibson, 2020). Existing robotic systems already offer processing (or "picking") speeds two times (Kingson, 2023) to ten times (Hayes, 2021) greater than human labor. Technological developments will likely increase speeds even further (Pyzyk, 2019). AI and robotic "labor" are predictable and incur fewer expenses beyond fixed costs, maintenance, and repairs, enabling MRF operators to extract more value from materials (Waste Management, 2021). Transitioning from traditional rear-loading collection trucks (at least two workers) to automated side-loaders (one worker), the company "WM" (the country's largest waste handling company, recently renamed from "Waste Management") increased productivity by 30% (Waste Management, 2023) and reduced labor costs paid to temporary worker agencies – approximately $75,000 to 100,000 per truck annually (Waste Management, 2022).

Studies on the impact of automation and robotics on jobs primarily focus on the manufacturing sector (Holzer, 2022), attempting to understand whether technology acts as a substitute or complement to human workers (Li et al., 2023). Some studies find declines in wages (Acemoglu and Restrepo, 2020) and employment rates, at times identifying more severe impact on low-skilled employees (Graetz and Michaels, 2018). Others observe negligible changes or net increases in employment (World Economic Forum, 2020), including for unskilled labor (Klenert et al., 2023).

The existing literature has not attempted to determine if a decrease in the number of low-skilled roles at MRFs due to robotics and AI may ultimately benefit workers. On the one hand, MRFs in the U.S. employ almost 25,000 employees, spending $1.5 billion on wages annually (U.S. Bureau of Labor Statistics, 2022). The mean annual wage in 2022 was $62,000; however, wages can vary dramatically between states and operators (from $18,000 at a local government MRF in Tennessee, to $77,000 at a private facility in Delaware). This indicates economic impacts of job loss could vary across the U.S.

On the other hand, the workplace literature seems to be coalescing around a recognition of the risks and challenges MRF workers face (Pellow, 1998). Occupational hazards include flammable and hazardous contaminants in the recycling waste stream (King County Waste Monitoring, 2020), heavy manual handling (Poole and Basu, 2017), and exposure to airborne contaminants, heavy metals, and organic pollutants (Econie and Doherty, 2019). MRF workers face risks from working with moving machinery, and exposure to extreme temperatures, loud noise, vibrations, and repetitive movements in awkward positions (Graham et al., 2015). In 2020, non-fatal occupational injuries and illnesses (5.1 per 100) were almost double the national average (2.9 per 100) (U.S. Bureau of Labor Statistics, 2020). Fatalities occur regularly (Heffernan, 2023).

High turnover is indicative of the largely undesirable nature of the roles. The City of Atlanta's short-staffed waste collection operations only see roughly 60% of their workforce each day (Paben, 2021). Resource Recovery Solutions estimates that sorter positions turn over roughly monthly (Van Dyk Recycling Solutions, 2020). As such, the recycling industry relies heavily on temporary workers, especially for sorter positions (Rosengren, 2019). The company WM uses temporary workers for around fifty percent of sorting positions. The literature widely agrees that temporary workers are particularly vulnerable (Morris, 1999), lacking access to job security, benefits, and legal protections, and facing elevated health and safety risks (Econie and Dougherty, 2019).

This raises the question, would reducing low-skill positions ultimately benefit existing MRF workers? Although the precise nature of the impact of robotics and automation on the workforce is still to be determined, the industry transition and job impacts have already begun. Republic Services halved labor requirements in a new automated recycling center in 2019 (Rosengren, 2019). WM is accelerating automation roll-out, obtaining approximately 30% lower labor costs, 18% lower operational costs, and a 40% improvement in key safety metrics at fully automated facilities (Waste Management, 2023). Over four years, it anticipates reducing total truck collection positions by 2,000 and MRF roles by 1,000 to 1,200 (Waste Management, 2022).

While some forecasts assume that technology will replace human labor in the recycling industry (e.g., Hayes, 2021), there are pathways to engaging workers in the maintenance and utilization decisions for robotics that could both increase efficiency and support deeper technical training and skill-building. As technology develops, AI is likely to play a larger role in MRFs, "controlling various robotic, optical, and other sorting equipment and making autonomous decisions" (

Gibson, 2020). MRF managers have a choice in how to handle this transition. The workforce impacts at mission-driven, non-profit MRFs, such as Eureka Recycling (Seldman, 2020), can differ significantly from a traditional operation. There is an opportunity to provide living wages, eliminate temporary labor, retrain workers, and promote from within. Robots could complement and enhance the human workforce, rather than simply replace it. The impact of the technological landscape on the content and availability of jobs in MRFs is thus critical to understand and could reduce the physical dangers and strains traditionally represented by this work (Bashir et al., 2022).

Section 3.2: Technological Advances in Collection and MRFs with a Focus on AI and Robots

Over time, many technologies have entered the market intended to improve the environmental, operational, and economic efficiency of waste management systems. The applications of these innovations include waste monitoring, collection and transportation, and sorting as the key elements of recycling.

Regarding the operations that surround the waste sorting process, one of the costliest aspects is the collection and transport of waste from communities to waste sorting and disposal facilities (Abdallah et al., 2019). Today's Fleet Management Systems can reduce costs as well as emissions associated with the collection and transportation of waste management (Salhofer et al., 2007). Sophisticated systems use sensor networks to optimize vehicle routes, increasing driving safety and efficiency (Golbaz et al., 2019). Geographic information systems (GISs), radio-frequency identification (RFID), ultrasonic sensors, and odor receptors have found applications in waste monitoring in trucks and bins (Golbaz et al., 2019). Such technologies could make multi-stream recycling more feasible and profitable. Similarly, sorting-in-place solutions such as smart bins (e.g., Baras et al., 2020) can help reduce contamination levels in the waste stream and make multi-stream recycling easier and more appealing for the public.

Regarding the operations inside MRFs, artificial intelligence provides novel opportunities in waste management, especially for optimizing the sorting process and developing new, effective sorting equipment. Detecting and forecasting waste bin levels (Golbaz et al., 2019) and optimizing process parameters (e.g., conveyor speeds and workforce allocation within the MRF) hold great potential to reduce inefficiency on facility floors (Abdallah et al., 2020). Studies have also elaborated on the use of collaborative robots that work together with people and recycling equipment that is reconfigurable (Alvarez-de-los-Mozos and Renteria, 2017). These systems can adapt to the characteristics of a changing waste stream by modifying the process flow in a recycling facility and improving its efficiency (Barwood et al., 2015).

The role of AI in developing new sorting equipment is expanding, as vision-based waste classification methods grow in their effectiveness thanks to recent advancements. Algorithms are trained to interpret visual data such as digital images and videos to identify the material types of recyclable items. As can be seen in Figure 3, these algorithms typically receive a color image and output the types of items along with their locations.

Fig. 3. Waste classification algorithms identifying the types of recyclables in the ZeroWaste data set (from Bashkirova et al., 2022)

These algorithms are in the category of “supervised learning.” They “learn” based on training data labeled by humans, as opposed to “unsupervised learning” that analyzes data without human input. In the current state of the art, these algorithms require tens of thousands of training samples for each recyclable type. Once the algorithms are trained, they can be utilized in waste monitoring solutions, such as identifying contamination levels at sorting lines. The algorithm can also be combined with physical sorting solutions, including optical sorters or robots that are doing the sorting (Gibson, 2020). Recently, researchers presented the first publicly available labeled image dataset collected from a MRF (Bashkirova et al., 2022), advancing the development of waste classification algorithms. Another dataset collected in a laboratory setting was also recently published (Koskinopoulou et al., 2021).

Coupled with the above-mentioned waste classification algorithms, robotic solutions are emerging in MRFs. The most popular robot type for this application is the **centralized and fixed** robotic solutions using delta robots (AMP, 2022), as seen in Figure 4. The robots are installed and fixed on a conveyor belt and the robotic workspace is completely isolated from humans via a cage for worker protection. These robots are equipped with suction cups and reportedly provide approximately 100 picks of recyclable items per minute. Another type of solution is **Modular and flexible** robots (see Figure 5) that do not need to be fixed and can be placed at a worker post as needed. They are essentially designed for safe human-robot collaboration and can work next to human workers without needing a cage. However, these robots are known to be significantly slower than the fixed delta robot solutions, having only 10-20 picks per minute. As a result, these robots currently have a very limited market share.

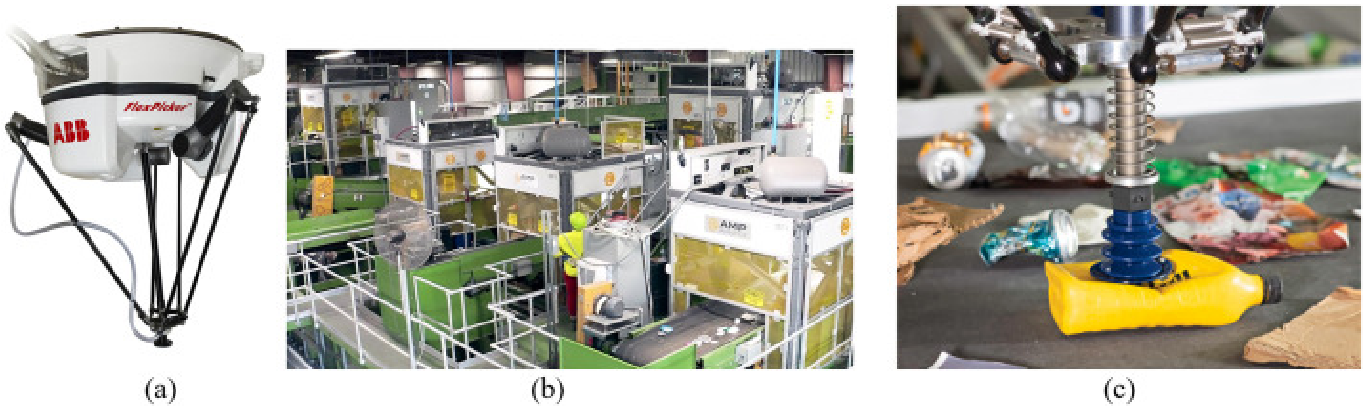

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Fig. 4. (a) Robots made by AMP Robotics in a MRF; (b) a centralized and fixed Delta Robot; (c) a suction cup picking up a recyclable item (from AMP, 2022)

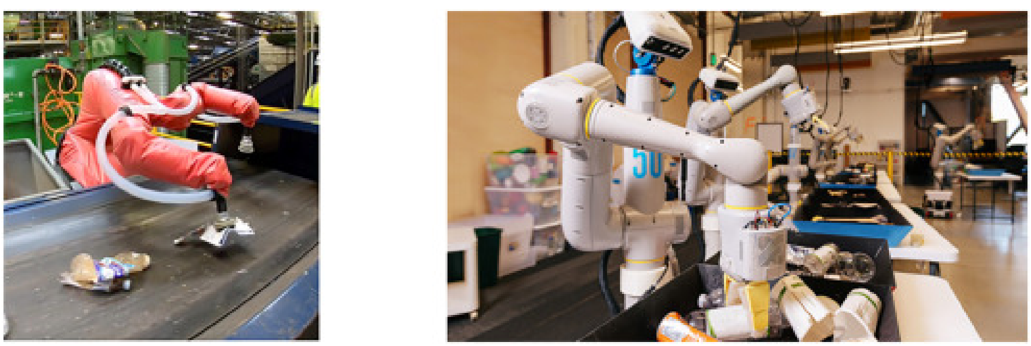

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Fig. 5. Examples of modular and flexible robots

Potential Future Advancements impacting Fixed and Flexible Paradigms: This study discusses the potential impacts of the two types of robotic solutions described above: **centralized and fixed robots** and **modular and flexible robots.** The discussion covers how these different types of solutions will potentially be impacted by near-term advancements in robotics and explores the economic and operational advantages of each solution. The main difference between these technologies is the level of possible engagement for non-experts with the robot. Typically, MRF workers are not permitted near centralized and fixed robots and cannot customize the robots and AI technology themselves. In contrast, MRF workers are able to customize and safely work next to modular and flexible robots. Near-term technological advancements are expected to benefit both of these paradigms, but significantly more so for modular and flexible robotic solutions. As mentioned above, there is a significant difference between the picking speeds of fixed and flexible robots. This gap is expected to narrow with more capable modular robot technologies. Recent progress in collaborative robotics research (Proia et al., 2021) suggests that modular and flexible solutions will become faster, more capable, and safer over time (Vicentini, 2020).

Improvements are also expected for vision-based waste classification algorithms. These systems would be more capable of processing different sensory data (e.g., hyperspectral imaging as studied in Tehrani and Karbasi, 2017), which would benefit the prediction accuracy of both fixed and flexible robots. The classification algorithms are also expected to be more “sample efficient” in that they would require less labeled training data to achieve highly accurate classification. This advancement would specially make the modular and flexible robots a desirable option, as it makes it easier for MRFs to train, customize, and repurpose their own robots.

Therefore, while these technological innovations seem to be promising solutions to issues in waste management, it is important to recognize that these technologies represent future solutions, with the most promising ones moving into mainstream research and development (R&D) and pilot phases. Even though most of these aspects are difficult to predict, it is important to imagine possible futures for the waste management sector, which the scenario-based approach in Section 4 aims to do.

Section 4: Scenario Storylines for the Future of MRFs

The following scenario storylines were developed based on interviews and extensive conversations with representatives from across the waste management industry and are meant to stimulate informed discussions among decisionmakers in industry and government alike. The storylines are based on the technology discussions described in Section 2 (see also SI).

To improve the understanding of possible pathways toward more circular material systems, this study develops three sub-scenarios for SSP1, in addition to the SSP2 scenario: one scenario that is guided by a comprehensive national sustainability strategy implemented equally across all 50 U.S. States (SSP1-natl), and two scenarios that are characterized by an ambitious national sustainability strategy that leaves its implementation to individual states, leading to a set of states with strict environmental legislation (SSP1-legisl), and a set of states that favors market forces over government regulation (SSP1-market). An overview of the key drivers of the four scenarios is provided in Table 1, including various policy options for waste management, different MRF designs and technologies, and the implications for the workforces required in each.

Table 1. Overview of key drivers influencing future recycling operations for the four scenarios, grouped into policy environment, size and set up of the material recovery facilities (MRFs), and implications for workers

Possible MRF environments in 2050			**POPULATION DENSITY**			**SCENARIOS**		
			URBAN	**RURAL**		**SSP1**		
			high volumes, sophisticated sorting tech, Mix C-fixed/M-flex,	**low volumes, little sorting tech**		**National strategy for all**	**National guid State laws are**	
				Use of robots				
				NO	**YES (M-flex)**		**Legislation-driven**	**M c**
Policy environment (Federal/ State)	Recycling policies	Strict material recovery goals (recycling targets by material class)	(no difference urban-rural)			high	high	r
		Collection of recyclables maximized				no	yes	r
		Landfill tax				yes	yes	r
		Pay-as-you-throw (PAYT, penalizes waste, incentivizes recycling)				yes	yes	r
		Extended Producer Responsibility (EPR) laws				yes	yes	r S
		Targets on residuals in recyclables (currently 25%)				<10%	<5%	<
	Product design	Design for recycling (less material mixing)				yes	yes	y
	Economics	Commodity prices				high	high	h

		Tax on primary raw materials (leading to higher commodity prices for recyclables)				yes	yes	y
		Minimum Wage				high	high	r
MRF	Size	Small/medium/large	Large	Small/ Medium		S/M/L	S/M/L	S
	Design	Mix of small & large MRFs guarantees maximum material recovery	NA			yes	yes	y
	Inflows	Single- vs dual-stream	(no difference)			Single	Dual	S
		Specialty MRFs are common (film only, plastics only, etc)				yes	yes	y
	Outflows	Residuals low <5%, medium 5-15%, high >15%	low	low	medium	medium	low	r
	Robot technology	Centralized & Fixed (C-Fixed) Robots	yes	**no**		mix depends on rural vs u		
		Modular & Flexible (M-Flex) Robots	no	**no**	**yes**			
		Other sorting tech exists (optical, magnetic, Eddie-current, glass breakers)	yes	no				
		Robotics speed (picks per minute)	high	NA	medium			
		Robotics accuracy	high	NA	medium			
		Presort (yes/no)	yes	NA	no			

		Positive picking (yes/no)	no	NA	yes			
Workers	Qualifications	Predominantly medium-skilled jobs (focus on maintenance & supervision of technology)			yes	yes	yes	r
		Predominantly low-skilled jobs (focus on manual sorting)		yes		no	no	y
	Working conditions	Job satisfaction		low	high	high	high	l
		Absenteeism (sick rate)		high	low	low	low	h
		Retention rate		low	high	high	high	l
		Job safety (presort yes/no?)		low	high	high	high	l
	Tasks	Presort	some	yes	some	some	some	y
		Positive picking	yes	yes	no	no	no	y
		Negative picking (quality control)	no	yes	yes	no	no	y

Set-up options for integrating robots into MRFs and implications for workers. Each proposed scenario must also account for major differences in how robotic solutions tend to be organized in the recycling industry. In this study, the implications of two different robotic solutions are investigated: 1) Centralized and fixed robots; and 2) Flexible and modular robots (see overview in Table 2). In **centralized and fixed robotic solutions** (referred to as **C-Fixed**), robotics companies install and maintain their products with minimal intervention from MRF employees. These robots are installed within safety cages that isolate their work environment, and they are fixed, so that MRF employees cannot move or modify them. MRFs then employ an item classification algorithm that is provided from a central hub of the robotics company. These robots might have an interface for MRF employees to enter the type of items they want sorted, but MRFs do not control the item classification algorithms. The interaction between the MRF employees and the robotic systems is minimal in C-Fixed systems. Typically, robotics companies send a technician to the MRF to address any technology issues, which serves to minimize the role of MRF employees. Fewer sorting jobs result from the introduction of robotics, and many of the remaining MRF jobs are low-skilled and feature low job satisfaction and autonomy, thus driving up absenteeism and turnover.

Table 2. Comparison of centralized and fixed vs. modular and flexible robots in MRF settings

Robots in MRFs	**Centralized & fixed**	**Modular & flexible**
	(C-fixed)	**(M-flex)**
Placement	Permanently installed (fixed), surrounded by safety cage	Flexible, easy removal and attachment to different workstations
	Workstation is independent of human sorters	Collaborative work of robots and humans is possible
Size	1 cage corresponds to 2-4 worker stations	Similar to 1 worker
Performance metrics	<100 picks per minute	10-20 picks per minute
Cost	Higher	Lower, allowing greater flexibility per given investment as to target streams
Sorting decisions	Centralized	Local (at MRF)
	Item classification algorithm provided by robotic company	MRF decides on sorting priorities, with flexibility to react to seasonal variations (e.g., related to commodity prices, composition of recyclables, or weather)
Worker agency	Minimal, limited to selecting the type of material to be sorted	Engaged through decisions on location, sorting priorities, and basic maintenance
	Predominantly low-skilled jobs (lower job satisfaction, increasing turnover)	Increases technical skill-set, offering career paths within MRF (higher worker satisfaction, decreasing turnover)
Repair	Off-site	On-site
	(sent back to robotics company)	(except for major repairs)

Modular and flexible robotic solutions (referred to as **M-Flex**), in contrast, feature a higher degree of modularity and flexibility. MRFs have more control over the robots' functionality and locations, with MRF employees moving the robots to any part of the plant they want and teaching the robots which items to focus on and how to sort them. The technology could also provide recommendations to employees, suggesting which items or streams require their attention (e.g., in response to fluctuating commodity markets), or adjusting conveyer speeds. These robots are also simpler and easier to maintain, with the majority of problems able to be solved by in-house MRF technicians. M-flex robotic solutions increase the technical skills needed by MRF employees, who maintain the robots in-house. Such a development could support the creation of career paths for MRF employees, thus boosting satisfaction and decreasing turnover. In addition, more employees may be necessary to oversee a variety of sorting stations of different materials, which could support additional hiring and employment.

Each of the four scenario storylines discussed below reflects the fact that recycling access in the U.S. continues to differ greatly between urban and rural areas. **Urban areas** typically have access to large MRFs with modern sorting technology (e.g., magnetic and Eddy-current separation of metals, optical sorting, glass breakers), and are more likely than rural areas to use C-Fixed solutions coupled with AI to assist both with positive sorting and quality control at high picking speeds achieved with high accuracy. In contrast, MRFs in **rural areas** are small- to medium-sized with less technology, which favors the use of M-Flex solutions that can be set up in a modular way, allowing for easy changes in sorting location depending on volumes and commodity prices. Sorting is more efficient in larger than smaller MRFs, leading to lower residual rates in large MRFs. The authors expect that rural areas that currently do not have access to recycling might gain MRF access through the build-up of hub-and-spoke systems that are optimized for transportation.

Scenario #1, SSP1-natl: The National Sustainability Scenario creates a strong legislative foundation for efficient recycling across the country, aimed at creating a circular economy that values recyclables as competitive raw materials for future manufacturing. National targets for material recovery are high for each material class and are achieved through a combination of policy instruments: taxes on greenhouse gas (GHG) emission-intensive primary raw materials and on landfills, extended producer responsibility laws, and pay-as-you-throw incentives at the household level. Commodity prices of recyclables are high, justifying investment into efficient sorting technologies. Industry supports these goals and increasingly considers Design for Recycling as an important tool. The collection at the household level continues to be predominantly single-stream, reflecting the high capital investments that have been made ("lock-in"). The efficiency of MRFs is measured by the cleanliness of their output streams, and the current 20-25% residuals are reduced to under 10% in this scenario. The efficiency of MRFs is measured by the cleanliness of their output streams, and by 2050 the current 18% (Toto 2018) to 25% (Collins 2012) residuals are reduced to under 10% in this scenario. To meet the strict sorting criteria, MRFs employ a combination of traditional and novel sorting equipment (including robots), coupled with AI. MRF employees are responsible for ensuring cleanliness of the output stream, and thus work on pre- and post-sort stations to supplement the available technology. Employees work collaboratively with flexible robots in order to accomplish 10% residuals efficiently and are also responsible for maintenance of simple technical equipment. Job satisfaction, autonomy, and safety are constrained to the extent that most workers are simply engaging in sorting work. Employees with responsibilities for maintaining technical equipment and supervising workflows enjoy more satisfaction, autonomy, and safety.

Scenario #2, SSP1-legisl: The Legislation-Driven Sustainability Scenario is similar to SSP1-national but more ambitious. It envisions a world in which policies incentivize virtually any activities that lead to a circular economy of valuable materials. Original equipment manufacturers (OEMs) produce products and packaging under Design for Recycling principles, consumers are well-educated and separate different materials at home for multi-stream collection, and MRFs operate such that residuals in their output are strictly limited, leading to clean recycling streams with residual rates below 5% (RRS, 2015) that are of high value to the post-consumer materials market. Namely, to ensure higher recycling rates, the sorting of recyclables starts at the household level as dual-stream collection of paper/cardboard and containers (plastic, metal, glass), resulting in much cleaner recycling input streams for MRFs compared to single-stream collection. The collection of recyclables is further maximized by easy access to collection for all households (including in rural areas), businesses, and public areas. This scenario depends heavily on consumer collaboration, achieved through education and source separation at the household level. With a clean material income stream, the MRF produces recyclables of high quality (i.e., little contamination, few residuals), leading to higher sale prices and better marketability for the recyclables. Sorting processes are straightforward and can be largely automated, and employees are more likely to focus on maintenance of technical equipment and the supervision of the operation, both of which represent higher-skill duties than sorting work. Thus, higher levels of autonomy, job satisfaction, and safety are supported.

Scenario #3, SSP1-market: The Market-Driven Sustainability Scenario assumes that sustainability measures are driven by market forces, complemented by national targets that are more ambitious than SSP2 but that do not reach best available technology across all facilities. Market-driven regions of the U.S. have no landfill taxes, extended producer responsibility laws, or pay-as-you-throw laws. By 2050, recycling streams are allowed to have a maximum residual rate of 15%, which is more ambitious than today's average residual rate of 18% (Toto, 2018) to 25% (Collins, 2012) but still higher than what is technically feasible (<5%) (RRS 2015). Industry is highly motivated to increase recycling and produce clean recycling streams as part of their overall circular economy strategies. The manufacturing industry considers sustainability a competitive advantage and creates packaging with Design for Recycling in mind (e.g., minimizing multi-materials, reducing the number of plastic grades used in packaging). As robots and AI improve, recycling companies are willing to invest in more specialized "secondary" MRFs that focus on a select set of materials with specific end markets (e.g., plastics. Hood-Morley 2020 , Musso et al. 2022). As in SSP1-natl, MRF employees are responsible for ensuring cleanliness of the output stream, and thus work on pre- and post-sort stations to supplement the available technology. Employees are also responsible for maintenance of simple technical equipment. Job satisfaction, autonomy, and safety are likely to be constrained to the extent that workers are simply engaging in sorting work. Employees with responsibilities for maintaining technical equipment and supervising workflows enjoy more satisfaction, autonomy, and safety.

Scenario #4, SSP2: Middle-of-the-Road (medium challenges to mitigation and adaptation). Recycling continues to be an afterthought in material management, with the MRF income stream originating from single-stream collection at households, with no policies that would regulate the cleanliness of the MRF output streams. Separation technology varies widely across MRFs but has in common that it is highly flexible, allowing the MRF to change the configuration based on seasonal input stream and commodity price fluctuations. Strong economic pressure leads MRFs to maximize automation so as to reduce vulnerability to worker shortages and the risk of increases in the minimum wage. As more technology is brought into MRFs, employees become more focused on pre- and post-sort processes, which can reduce injuries related to rapid sorting but would not alter the low level of variety in the work, nor would it help to create career paths for employees within MRFs. Jobs are mostly low-skill, leading to continued high turnover and low worker satisfaction.

The setup of the four scenarios illustrates the importance of policy decisions for recycling outcomes. The current recycling landscape in the U.S. varies widely across the 50 states in terms of existing policies (e.g., landfill tax, mandatory recycling schemes) and recycling rates for the major commodities (Eunomia, 2021). Equally important are decisions on ownership and responsibilities for collection (public vs private, town vs. MRF) and MRF operation (for profit vs not for profit) (Ecology Center, 2023).

Section 5: Discussion

Having reviewed the building blocks of the study in earlier sections, this section returns to the original four questions presented in the introduction, now incorporating the insights gained about the topics discussed. These questions regard recycling and waste management, current and new technologies influencing material recovery facilities (MRFs), stationary and flexible robots and the human interface, and how a scenario storyline framework helps to visualise how different policy environments could influence MRF technology, recycling outcomes, and worker satisfaction and turnover.

1. **What are the most relevant threats and opportunities likely to influence the future of recycling, including substantial changes to waste stream composition, automation, restructuring of MRFs, and innovations in materials and waste management in the U.S. to 2050?**

MRFs face two key challenges: (1) a continuously changing income stream, reflecting seasonal fluctuations and frequent changes in consumption patterns that affect the composition of recyclables ("the evolving ton"), and (2) strong price fluctuations in the commodity markets that can discourage investments into better separation technology since it is unclear for how long financial benefits of new technology will persist. An opportunity for more efficient material recycling stems from manufacturers increasingly recognizing the effect of their design decisions on product recyclability, particularly if commodity prices for recyclables can be prevented from dropping below the minimum required by MRFs to make their operations profitable. Furthermore, the cost of collection can be reduced by using optimization tools in transportation logistics (Das and Bhattacharyya, 2015; Nguyen-Trong et al., 2017). Such transportation logistics models also help determine the optimal location, size, and layout for future recycling facilities. We expect substantial differences in MRF design between urban and rural areas, with smaller MRFs in rural areas generally opting for a flexible setup of sorting technology (e.g., choosing flexible over fixed robots). Novel collection systems that automatically divert recyclables from non-recyclables (smart bins; Noiki et al., 2021) can also help increase the total share of recyclables while reducing their level of contamination.

2. **In what ways does technology, especially the use of artificial intelligence and robotics, change the recycling industry?**

After several decades of slow growth, MRFs have become the central intermediary from MSW collection to commodity markets. MRFs created a channel to bring recycling from collection to sorting and then to the market. The impact of AI and robotics technology on MRF operations is multifold as both these domains are having breakthrough processes. The progress in AI is an enabling factor for many new monitoring and sorting technologies, such as automatic waste composition/contamination estimation, vision-based safety systems detecting dangerous materials, empowering existing sorting equipment (e.g., optical sorters), and developing advanced robotic sorters. Future advancements in AI are expected to increase waste classification accuracy and reduce the amount of data required to train these systems. In addition, automatic training processes (e.g., observing human sorters and learning from their actions) are expected to reduce the amount of manually-labelled training data. It is also expected that various advancements in material science can aid the performance of the AI algorithms. An exciting example on this front is "digital watermarks" (Plastics Today, 2022) that are invisible to the human eye, but can be detected by computer vision systems, providing additional assistance for the AI algorithms to identify the type of recyclable. Recent advancements in robotics – mostly powered by AI – are enabling their use beyond traditional "controlled/structured environments" (e.g., carefully designed and adjusted manufacturing lines) and provide a trajectory for allowing their use in "unstructured/uncontrolled environments" (e.g., homes, offices, hospitals, public streets). As such, robots are becoming more capable of operating in dynamic and cluttered environments and adapting to the changes in their tasks and operating conditions. These improvements bring many advantages, and make the use of robots feasible in MRFs, since they are getting increasingly better at handling the level of clutter and changes inherent to waste conveyors. In addition, research efforts are increasingly dedicated to M-Flex robots, targeted to enhance human-robot collaboration as well as the safety and flexibility of these systems. Accordingly, it is expected that these robots will be more capable, accurate, and efficient in the near future, allowing for collaborative schemes such as M-Flex type robots in the near- to mid-future. Indeed, early techno-economic analyses have shown that including robots in MRFs is often economically competitive, with higher efficiencies expected as the technology matures (Rahman and Reck, 2024).

3. **In what ways are workforce issues affected by changes in recycling, particularly at the interface of humans and robots?**

The scenarios considered here have serious implications for the organization of labor in the recycling industry. While the introduction of technology and robotics has long been held up as a threat to jobs in this sector (Hayes, 2021), the presented scenario storylines point to some areas of hope for workers in the modern MRF landscape. For example, to the extent that the use of flexible technology enables workers to focus on tasks and roles that are more satisfying, engaging, and skill-based, both workers and MRFs will benefit. A future for MRFs that features the ability to use technology adaptively as the needs of the season, region, or even weather dictate is one that enables workers to be involved in the adaptations necessary to lines, sorting functions, and robotics use. Rather than being adjacent to robots and doing similar motions and picks, a future in which workers can shape the location and focus of robots dynamically is likely to increase not only safety on the job, but complexity, autonomy, and satisfaction as well (Ryan and Deci, 2000).

The adoption of technology that enables workers to take on more complex and autonomous tasks accomplishes two aims. First, it helps to put workers on a path to increased learning on the job, potentially creating promotion and career tracks as they develop in the MRF. Second, access to work that is more complex and in which employees can develop should boost employee satisfaction and engagement (Hackman and Oldham, 1976). As the Gallup Organization notes in a meta-analysis of business units from a range of industries, the effects of increased employee engagement are profound (Harter, 2022). For example, among business units featuring high levels of employee engagement, absenteeism is reduced by 41% while productivity climbed by 17%. Further, workers who feel more engaged are 24% less likely to turn over in high-turnover organizations like MRFs (Harter, 2022). Looking at the directions in which MRFs could evolve by 2050, strategic decisions about how to incorporate technology (whether AI, robots, or other forms) could augment, and not reduce, the quality of work for MRF employees.

4. **How are U.S. businesses responding to the call for greater sustainability given climate and environmental challenges, and how does their response influence the business models of waste management and recycling companies?**

Companies striving for sustainability and a circular economy are working on simplifying the packaging of consumer goods as a means to increase the recycled content of their packaging materials: designing less complex packaging materials increases the probability for their successful sorting into cleaner recycling streams that meet the specifications as a secondary feedstock in manufacturing. For MRFs, the growing demand for more and higher quality recycled materials leads to growing capacities and increasingly sophisticated sorting technologies, while seeking to minimize collection costs through optimized MRF locations and optimized transportation routes. Secondary sorting (e.g., through AI-driven robots) for lower value materials at the primary MRF or at succeeding sorting plants offers an opportunity to further reduce landfilling costs while increasing overall recycling rates for MSW (BusinessWire, 2022).

The quest for larger MRFs is reflected in the restructuring of the industry through mergers and acquisitions – over $4 billion in such activity in 2022 alone – offering large companies increased market power through involvement in a greater portion of the waste supply chain, including the opportunity to "develop domestic end markets for lower value material" (Paben, 2022). Some business customers may decide to process recycled materials themselves rather than rely on MRFs for the sorting, either for greater profitability or even to hedge against materials scarcity. Companies in other industries that interact with the waste industry are trying to reuse and reduce waste for both economic and environmental reasons. Apple, for example, has reduced the amount of plastics in packaging by 75% since 2015, and the company recently announced that recycled materials accounted for nearly 20% of the materials in its products in 2021, the highest in the company's history (Chaudhry, 2022).

Section 6: Conclusion

Several factors make an outlook on the future of MRFs particularly complex. First, the MRF landscape in the U.S. is in a process of consolidation, with a limited number of large companies acquiring and controlling a growing number of smaller entities. Second, changing policies around the production of recyclable goods means that the materials on which MRFs may focus is a shifting target, with major implications for the technology that would be most useful and the economics that would shape the revenue from recycled materials above labor and processing costs. Third, the Covid-19 pandemic has highlighted the changing labor landscape in the U.S., with anecdotal reports from MRFs that up to half of their workforces left during the pandemic without having been replaced. The pandemic may have accelerated the embrace of technology as a way to compensate for soft labor markets that left MRFs understaffed.

Like other sectors, the recycling industry and MRFs in particular are benefiting from advancements in AI as the technology helps make waste classification and sorting more accurate, while also reducing the amount of data required to train sorting systems. When considering the future of MRFs, perhaps the most difficult element to account for is the element of surprise. The sudden development of a breakthrough technology, a new market for recycled or reconstituted goods, or a new law or environmental policy could render the presented scenario storylines less relevant. Given the overwhelming focus of the MRF environment on financial considerations, a significant advance in new technology (whether robotics, optical sorters, AI, chemical recycling, etc.) that makes the economics of running MRFs more or less favorable would transform the competitive landscape and all but guarantee broad adoption. While the presented scenario storylines are useful under assumptions of normally evolving technology and markets, the possibility of transformative development should not be underestimated.

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Declaration of Competing Interest

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

The following are the Supplementary data to this article:

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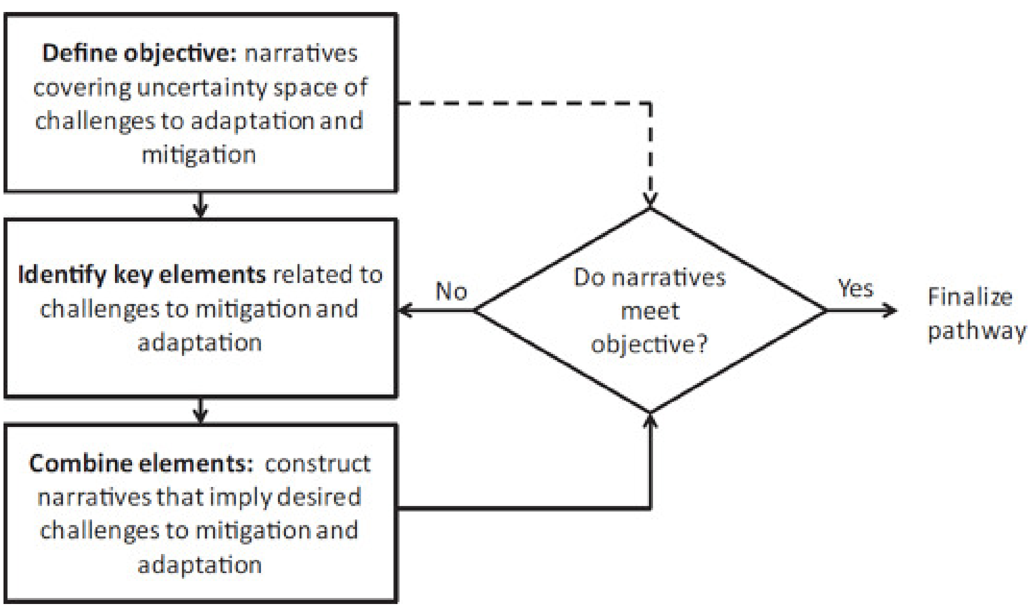

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Data availability

No data was used for the research described in the article.

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