Solid Waste Authority of Broward County

TASK 9 - Innovative and Future Technologies White Paper

Solid Waste Disposal and Recyclable Materials
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1.0 INTRODUCTION

Effective materials management is at the heart of sustainable and resilient waste systems with lowest emissions and highest recovery. The Solid Waste Authority of Broward County (Authority) faces increasing waste generation, shifting consumption patterns, staffing issues, and intensifying environmental challenges, necessitating innovative solutions that enhance efficiency, reduce costs, and foster environmental stewardship.

This white paper explores the cutting-edge advancements in materials management, including the integration of artificial intelligence (AI) with all facets of the solid waste system supply chain, encompassing collection vehicles and systems, materials sorting technologies, landfill management including the use of solar photovoltaic systems on closed sites , emerging battery management practices, e-waste recovery systems, textile recovery optimization, and impacts associated with per- and polyfluoroalkyl substances (PFAS). It also examines advanced recovery methods for gases, ash outputs, biological digestion, and the beneficial reuse of process residues. These quickly evolving practices are transforming waste management, making it safer and efficient, increasing recovery rates, and reducing environmental impacts.

The SCS Team utilized deep and practical expertise in state-of-the-art equipment and systems, both hardware and software, and in solid waste and recovery methods and facilities to build this compendium and identify the latest emerging supply chain technologies for collection, sorting, recycling, and disposal. Where possible, the authors also used this expertise to analyze facility footprints and equipment, estimating capital expenses, and cost-per-ton ranges, and scalability. In addition, assessments of processing facilities include proof points for meeting local Authority requirements, recovery outputs, emissions ranges, automation potential, staffing needs, and other impacts.

Some key takeaways from this broad survey are especially important for the long term:

- Connectivity for all assets and players using the revolution being quickly implemented by solid waste managers through Web 3.0 (which provides premier tools, artificial intelligence, and blockchain technology) and the internet of things (IoT) is recommended immediately and through the planning horizon because it will be required to keep costs down and improve service in a rapidly growing and crowded County. The options presented are a small representation of the amazing number of choices the authority needs to make in the next five years. In addition, it is recommended the Authority maintain a strong and prioritized focus on compatibility and connectivity as part of knitting together the high diversion solid waste system it envisions in the future. Harmonization will also be required for both customer services (e.g., collection pick up types) across the Authority member municipalities, as well as data integration, with the latter requiring uniform programming, metrics, and information flow for best connectivity and maximum system improvement to work.
- A few newer 21st century versions of proven technologies are seeing the biggest gains in recovery of mixed waste and will be needed to get to the 75% diversion goal in Florida. These include the following:
  1. Backend organics solutions after capturing recyclables from the flow, which have shown operational resilience and the biggest jump in diversion as their use has expanded from in-vessel, aerobic or other compost methods to wet anaerobic digestion (AD).

2. Automation of dangerous and repetitive manual sorting jobs exposed to the mixed waste flows in a processing facility. New automated sorting protocols and devices have shown to increase recyclables captured, especially AI-assisted banks of optical sorters and air classification devices.
3. AI-assisted recirculation and sorting redundancy, a practice gaining steam in all waste sorting plants including single stream, to enrich mixed waste facility processing flows; thereby automatically capturing more recyclables that were previously missed and doing it better than manual sorting.
4. Conversely, the more capital and energy intensive technologies, including large-scale pyrolysis/gasification/hot hydrolysis/RDF thermal diversion, have had several failures and no sustained successes in North America, and they only seem to be sustained in highly regulated geographies with high landfill fees.

- More generally, the rapid, unprecedented rise of solid waste autonomous processes, which are now available or less than five years away, is all fueled by the new connectivity. From landfill life management to litter identification and abatement, to monitoring scales or even monitoring the entire solid waste collection service in real time, to the certain future use autonomous vehicles for some types of solid waste collection (just to name a few), these autonomous processes are transforming the way we think and manage waste; leading to lower costs, better safety, higher diversion, and less daily disruptions.

Through this compendium, tailored to the Authority's unique context, stakeholders will gain actionable options for solid waste collection, processing, recovery, and disposal. By leveraging these technologies, the Authority can establish a future-ready, sustainable materials management strategy aligned with its environmental and operational goals.

2.0 COLLECTION SYSTEMS INNOVATION & TECHNOLOGY

2.1 ALTERNATIVE FUEL COLLECTION VEHICLES

The solid waste collection vehicle landscape is shifting as the industry adopts alternative fuel collection vehicles to replace the traditional use of diesel fuel to meet the market demand for more sustainable solid waste management practices and improved operational effectiveness, including reduced emissions and smart fleet management.

2.1.1 Compressed Natural Gas/Renewable Natural Gas Collection Vehicles

Many solid waste collection vehicle fleets throughout the United States have transitioned to compressed natural gas (CNG) as a fuel source. This transition has helped both offset a company's carbon footprint and fleet maintenance costs. With CNG being the first step in a cleaner operating vehicle, many major manufactures offer a CNG fueled vehicle straight from the factory. However, cost remains a factor in upgrading a fleet to CNG by either buying a new CNG truck, which costs more than a diesel, or retrofitting an existing diesel fleet to CNG. The other cost factor that needs to be addressed is fueling. CNG, in the long run, is cheaper than diesel, but putting in a CNG fueling infrastructure is a major upfront cost to fuel a fleet.

Some solid waste collection companies are starting to explore using renewable natural gas (RNG) to fuel their CNG fleets. Companies that operate both collection vehicle fleets and landfills are now using the methane that landfills produce to fuel CNG fleets. Using RNG helps reduce one's carbon footprint even more. However, the major consideration with this option is the major up-front cost needed to construct an RNG facility at a landfill.

2.1.2 Electric Collection Vehicles

Electric solid waste collection vehicles are coming down the pike. Several fleets have been testing the use of electric trucks within their existing fleet. Unlike diesel or CNG, a large portion of the truck weight is going to be the battery to power the truck. Thus, creating a major drawback limiting the range that current battery powered trucks offer. Several major manufactures are now offering electric trucks as a production vehicle. The trucks themselves cost much more than a diesel- or CNG-powered truck, making fleet conversion a slower process. Also, like all other alternative fuel types, there is a large upfront cost to build the infrastructure to charge the fleet at headquarters and for the emergency charging capabilities that are needed to take into the field. With refueling electric trucks, time is going to be a factor when recharging these trucks.

2.1.3 Hydrogen Fuel Cell Collection Vehicles

Solid waste collection vehicles that operate on a hydrogen fuel cell are still in their infancy within the United States. Only one (1) company currently manufactures a hydrogen fuel truck in the United States. In other parts of the world, hydrogen collection vehicles are used to collect waste. Hydrogen fuel production isn't widespread in the United States, thus limiting the area that these collection vehicles can operate. Notably, hydrogen-fueled collection vehicles have a greater operating range than electric collection vehicles. Hydrogen-fueled collection vehicles also offer a fleet to have zero-tailpipe emissions when operating. Like CNG and electric trucks, a major upfront cost is going to be building a refueling infrastructure to supply a fleet with fuel.

2.2 THE NEW CONNECTED MONITORING AND SENSOR SYSTEM AND SOLID WASTE MANAGEMENT (WEB 3.0 AND IOT)

2.2.1 Solid Waste Management Technology: A Transformational Shift

Two major technological trends are revolutionizing solid waste management by seamlessly connecting system actors, local monitoring devices, and daily processes in unprecedented ways.

2.2.1.1 Web 3.0 Technologies

Web 3.0 represents an evolving infrastructure that integrates smart, connected applications across users, devices, the cloud, and edge computing specific to solid waste systems. This interconnected or "internet" leverages real-time inputs from all system components to deliver consistent and reliable data, enabling automatic and rapid adjustments that enhance efficiency and reduce costs. As the foundation for advancements in artificial intelligence (AI), blockchain technologies, and 3D graphics, Web 3.0 aims to decentralize systems while ensuring safer, self-regulated transactions. In the solid waste industry, Web 3.0 infrastructure adapts dynamically to predictable waste management practices, optimizing processes, and fostering innovation.

2.2.1.2 Internet of Things (IoT)

The IoT facilitates centralized control over diverse components of the solid waste system through internet connectivity. This includes real-time communication across stakeholders—customers, supervisors, municipal personnel, facility managers, third-party contractors, drivers, salespeople, etc.—and integration with devices such as on-board computing truck driving pattern recorders, smart phones, scales, monitoring cameras, sensors for heat and gas detection, truck and facility computerized maintenance management systems (CMMS), public emergency management systems, etc. These IoT-enabled technologies create a cohesive and intelligent feedback loop from these disparate devices that surpasses manual management of predictable events, forming a secure data-driven network to enhance safety, efficiency, and automation across all facets of waste operations.

2.2.1.3 Innovative Tools Driving Transformation

By leveraging Web 3.0 tools like blockchain for secure transactions and AI for real-time decision-making, solid waste management processes have become more responsive to industry challenges. Low power connected devices are being deployed across supply chains, fundamentally altering system operations. Edge devices—such as locators, sensors, and data aggregators—enable comprehensive monitoring of diverse activities, from collection system operations to machine performance, to environmental outputs. These devices can even detect critical intervention needs and, in some cases, initiate corrective actions autonomously.

Emerging platforms and applications now monitor and manage key assets and systems, including fleet vehicles, landfill capacity, air pollution controls, gas detection systems, and route optimization. These tools facilitate real-time communication between field devices, central computers, and mobile applications, empowering managers to address deviations promptly.

2.2.1.4 Capabilities Enabled by Smart Waste Technologies

Real-time outputs from smart waste systems now deliver actionable insights, such as:

- Reminding maintenance teams of scheduled upkeep and alerting them to repair needs.
- Adjusting collection schedules based on service demands.
- Analyzing changes in waste streams, including weight and soon, composition.
- Diagnosing preventative maintenance requirements for equipment.
- Notifying key personnel of abnormalities or urgent issues in the system.

The integration of “machine-to-machine-to-decision-maker” communication, underpinned by AI and IoT, is driving unparalleled efficiency in solid waste management. Staying informed about advancements in this infrastructure is essential for long-term planning and should be incorporated into procurement processes to ensure sustainable and effective operations.

2.3 ARTIFICIAL INTELLIGENCE (AI) FOR SOLID WASTE COLLECTION

2.3.1 Introduction

Artificial intelligence (AI) is transforming municipal and commercial solid waste systems by leveraging machine learning, data analytics, and predictive modeling to enhance operational efficiency and decision-making. AI-assisted technologies are increasingly employed to address key challenges and optimize performance in the following areas:

- **Optimizing Resource Allocation:** AI enables the development of efficient waste collection routes, reducing fuel consumption and labor costs.
- **Automating Repetitive Tasks:** By automating dangerous and repetitive manual processes, AI reduces workplace injuries and addresses high turnover rates.
- **Predicting Waste Generation Patterns:** AI can analyze and predict household and commercial waste generation rates by geographic or industry classification, aiding in capacity planning and resource deployment.
- **Dynamic System Responses:** Real-time data and AI-powered responses enable systems to adapt to changing waste compositions, improving diversion rates and material recovery efficiency.
- **Enhancing Supervision and Productivity:** AI-driven real-time location mapping improves oversight and productivity of collection services.
- **Resolving Disruptions:** Automated monitoring helps identify and resolve service disruptions, ensuring timely customer service and minimizing inefficiencies.

2.3.2 Addressing Specific Operational Challenges

AI is particularly well-suited for addressing persistent inefficiencies in waste collection systems, such as in the following ways:

- **Container Monitoring:** Overfilled or underutilized collection containers increase collection times. AI systems can monitor fill levels in real time, enabling more efficient container use.
- **Predicting Service Demands:** Socioeconomic changes often alter waste generation patterns. AI can forecast future needs based on demographic and economic trends, allowing systems to adjust proactively.
- **Driver Risk Profiles:** Driver behavior affects service reliability. AI can analyze driving patterns to detect risks, reducing accidents, missed pickups, and service disruptions.
- **Recyclable Composition Analysis:** The dynamic nature of recyclable material streams requires constant updates. AI-powered image recognition, combined with extensive databases, offers real-time composition analysis at a fraction of the cost of traditional waste studies.
- **Infrastructure Planning:** AI demand forecasting models can predict long-term capacity needs for disposal and processing facilities, replacing costly and time-intensive studies.

2.3.3 Strategic Integration of AI

The integration of AI into solid waste management systems is advancing rapidly, and the next three to four decades will see unprecedented adoption of these technologies. To maximize the benefits and minimize start-up costs, the following strategic steps are recommended:

1. **Standardizing Service Offerings:** Harmonize current collection, processing, and disposal approaches across the Authority to enable effective implementation of AI tools by making the Web 3.0 connectable and developing the local solid waste system IoT.
2. **Prioritizing Data Integration:** Ensure comprehensive and accurate data collection by aggregating diverse inputs from sensors, scales, recorders, and other technologies. Coordination across municipalities and private contractors will be critical.

2.3.4 Overcoming Data Bottlenecks

Effective AI deployment depends on robust data integration. The Authority must address challenges associated with aggregating diverse datasets, including real-time operational data and historical records. Standardizing service offerings, metrics, and parameters will ensure that AI systems deliver actionable insights, reduce lead times, and minimize costs.

When implemented correctly, AI-driven systems can significantly enhance efficiency, public satisfaction, and cost-effectiveness. They also provide critical oversight for contracted services, helping to maintain competitive service rates while achieving high levels of operational performance.

2.3.5 Key AI Innovations to Consider

Several emerging AI technologies and technology solutions are poised to revolutionize solid waste management. These innovations should be evaluated by the Authority for their potential to streamline operations and improve outcomes.

Table 1 presents key AI innovations by category and function, including on-board, connected computing in collection and transfer vehicles, which are being universally adopted:

Table 1. Key AI Innovations

CATEGORY	FUNCTIONS
Smart Bin Systems include public place disposal, litter, and recycling access points and commercial receptacles used in conventional collection, i.e., roll-off and compactor systems, Front End Loader yardage containers, automated curbside cart systems, and integrated bin/compactor public venue systems are also included. • Types of smart bin technologies: o Low Power Wide Area network (LPWAN) and message cueing telemetry transport systems (utilizing a broker) can send signals and data long distances while consuming low power. o Bluetooth systems can send signals to a nearby hub or worker. o GSM Global mobile communication allows bins to send signals and data to each other and hubs at fast rates of speed.	• Optimizes collection through real-time monitoring of levels of waste within different container types. Sends a signal when containers are full for automatic collection scheduling. • Can bill customers automatically when containers are overfilled, and/or itemize services delivered, i.e., for each collection. • Identifies types of materials collected, i.e., information on volumes, mass, and composition (the latter, just now hitting the market).
Route and System Optimization Systems monitor route, stop, and disposal travel times. They also unload and cue times, fuel consumption, and service disruptions, and provide useful feedback to enhance productivity.	Data sets (e.g., historical and daily traffic patterns and conditions), collection data (e.g., fuel consumption per day and driver), GPS tracking, and weather forecasts are used to adjust routes.
Dynamic Scheduling Systems adapt to changing waste generation patterns and allocate productivity changes in solid waste service systems, routes, hours of operation, and times.	• Allows optimal planning and adjustment of waste service schedules based on real-time data. • Longer term, targeting, and availability of waste services will become adaptive and more powerful through continuously analyzing these data sets along with current and historical traffic conditions on Broward County's crowded road systems, weather forecasts, and population density.
Demand Prediction Technology updates planning systems for future service coverage and the need/placement of hub and spoke solid waste facilities for further processing and/or disposal by using various data sources and algorithms. Also incorporates data from sources such as social media, online platforms, etc.	• AI analyzes collected data sets and makes accurate predictions considering demographic factors, waste generation rates, spike events, and holidays to forecast waste generation. • Technology is used to plan for efficient hub and spoke transfer station, processing, and disposal facilities.

CATEGORY	FUNCTIONS
On-Board Computing/Monitors fixed, 'connected' devices installed in the cabs of collection vehicles which show where drivers/vehicles are physically located, assigns work (missed collection point), and collects the service history of the vehicle and driver. Most importantly, it is tied into fleet maintenance hardware which can tell technicians when and what services and repairs must be made based on vehicle behavior, mileage, or incident.	• Produces daily metrics for each driver, pick up, and route. • Produces historical activity and route records. • Can prepare customers for arrival time and answer questions on historical or yet to be performed services. • Can alter route coordinates and pick up points in real time for reacting to traffic or workload anomalies. • Can start the billing processes for completed services automatically by sending service completion signals to accounts receivable through the portal.

The leading national private waste management companies are rapidly adopting these advanced systems, including other AI-driven tools, to optimize resources, streamline logistics, and enhance scheduling efficiency. These companies have heavily invested in centralized, interactive data portals to manage customer and operational processes, leveraging AI to identify trends and insights that improve both service quality and financial performance.

Additionally, they are integrating smart applications on customer devices, such as home computers and smartphones, featuring multilingual capabilities and other user-centric tools. These apps feed data into AI systems, enabling continuous learning and adaptation to user behavior, which enhances operational management and customer feedback.

To ensure alignment with industry advancements, this plan recommends that future procurement activities by the Authority prioritize service providers with demonstrated capabilities to integrate AI technologies. Providers should be evaluated based on their ability to adapt AI tools over contract periods and their capacity to grant the Authority access to collection and processing data through AI-enhanced platforms. This approach will enable the Authority to monitor system-wide operations effectively and leverage data for informed decision-making.

2.3.6 Collection System Tools

2.3.6.1 Interactive Community and/or Authority-wide Waste Services Portal

One of the most promising advancements in solid waste management technology is the rapid development of comprehensive municipal waste enterprise software suites, often referred to as "portals," which are increasingly incorporating AI and machine learning capabilities by utilizing Web 3.0 connectiveness. These platforms integrate customer and management tools via desktop and mobile applications, creating a seamless connection to the central portal.

These systems automate and digitize customer-facing processes while providing real-time feedback loops for scheduling, notifications, and service monitoring. Besides on-board computing, other devices in key points in the supply chain also have critical features, which include the following:

- Productivity monitoring (scales, pre-trip handheld checklist devices, maintenance and shop productivity)
- Real-time updates on service delays and disruptions (public service announcement platforms, community information relay)
- Scheduling of additional or specialized services (customer smart phones, route manager tablet)
- Notifications for service delivery and adherence to service parameters (customer smart phones, route manager tablet)
- Automated monitoring of service quality and payment processing customer smart phones, route manager tablet)
- Instant cost assessments (customer smart phones, route manager tablet)
- Payment and invoice notifications (customer smart phones)

The overarching goal of these platforms is to unify system data and processes into a single, cohesive framework, enhancing efficiency and value. Over the planning horizon, AI-driven portal platforms are expected to play a critical role in managing the complexities of system inputs and outputs. They will leverage features like multilingual support to effectively serve diverse customer communities such as Broward.

Table 2 presents enterprise-wide technology platforms and applications, which are set to deliver advanced functionalities across a wide range of categories.

Table 2. Enterprise-wide Technology Platforms and Applications

CATEGORY	FUNCTIONALITY
Customer Waste Behavior Monitoring	Monitors set outs, participation, contamination in recycling bins, litter at bin sites, volume/weight limit reporting, enforcement events, etc. Phone and computer apps send reports, notifications, and other feedback to the actors in the system (customers, private service providers, and system managers). The collected behavior data and outcomes can perform the following: Signals for pick-up of full bins. Send notifications, warnings, suspensions of service for abuse, contamination, litter, or non-payment.

CATEGORY	FUNCTIONALITY
	Can bill automatically when containers are overfilled, and/or itemize services delivered (i.e., for each collection). Also, can bill additional charges (e.g., pay as you throw volume limits exceedance). Collection periodicity sums the amount of collection signals and how full the containers are from the stop.
Notification Systems for efficient delivery of services and customer behavior modification. Streamlined notification system that will drive higher and proper levels of participation in programs	These systems can report/alert customers to the following: Regular and special hours for waste services (daily/weekly), which will increase participation in diversion and special waste services Weekly service reminder dates and times Service disruptions Service changes Service reminder notifications Collection of set out and participation data Exceedance of allowable limits for solid waste, recycling, and yard waste Contamination in the recyclables, including warnings and suspension of service Composition information: nascent and quickly developing ability for smart trucks with cameras and/or smart bin identification technologies to collect composition data Notification of longer periods for special collections for bulky waste, and other separated materials (batteries, clean bag-in-bag film, textiles, and household hazardous waste, or e-waste) Special Collection ordering and notification of time of service Storm response schedules in real time
Waste System GPS Real-Time Monitoring and Mapping Systems are a "control tower" for daily services monitoring and management	Oversight management for actors in the waste management supply chain, including contracted privately and municipally run collection and disposal systems.

CATEGORY	FUNCTIONALITY
	Provides GPS placement of mobile assets in a real time mapped location that updates like an airplane control tower monitor. It includes identification of bottlenecks, alternate route, recurring traffic patterns, accidents, and cue time issues. Interacts with mobile phone customer apps to confirm missed pick-ups from mapping records and confirms consequent pick-up scheduled due to missed pick-ups for both residential and commercial sites (if required). The System has been shown to reduce missed calls due to accurate recording of collection. Driving behavior identification and unsafe acts Re-routes in real time to some of these factors Interactions between private service providers and municipalities and back up evidence for evaluating performance

2.4 SMART WASTE MANAGEMENT APPS

2.4.1 Introduction

“Smart” waste management software and applications are systems which use edge device technology to make the solid system more efficient, cost-effective, and environmentally friendly. Most of these systems sport the latest high-level machine tool, the Internet of Things (IoT), a monitoring technology that collects and tracks real-time data to help optimize waste collection and future planning.

Many of these applications have been built as aids to communities and their waste customers and offer one or more functions listed below. The newer ones interact with an integrated waste portal for more accurate real-time information and notifications, and to provide feedback on each function’s usefulness. Some of the emerging popular applications and their functions are presented in **Table 3**.

Table 3. Smart Waste Management Apps

FUNCTION	EXAMPLES
Simple and Special Collection Schedules, Notices, and Reminders for Consumers	These applications are most effectively utilized when integrated with real-time, continuously updating enterprise portals, although some may rely on static, pre-programmed information. Many of these apps also provide access to additional resources through links to external websites, such as Call2Recycle, where drop-off centers for batteries can be found or Goodwill for textiles and re-use of household goods. A sample of this widely used format by the private sector is from Evergreen Disposal.
Program Recyclables Accepted	The Recycling Partnership's App for recycling identification, "Recycle Check." This app, and other similar apps, offers the ability to enter a zip code or allow location permissions and receive a clear, yes-no answer about whether to recycle a specific item where you are located. It also enables consumer brands to navigate the complex recycling landscape, reduce label changes, and leverage existing labeling systems. Communities like St. Johns County, Florida use "Recycle Coach."
Access Points for Hard to Dispose, Special Wastes, or Recycling (dead animals, batteries, HHW, tires, bulky, carpet, e-waste, paint)	Earth 911's iRecycle app offers more than 1,600,000 ways to recycle more than 350 materials in the United States. Also, these apps link outside resources like the Call2Recycle database with links to the closest appropriate drop-off location for the item a consumer is attempting to recycle.
Apps that Read RFID Tags in Household Carts	• Used to improve management of carts and performance of recycling, food waste, and yard clipping programs (Greenwalt, 2016). • Management of inventory for expensive roll out carts. Utility: an RFID tag is placed into a roll out cart during manufacturing. When the cart is delivered, the RFID tag is scanned by an app to register that it's been delivered and the type of cart (garbage, recycling, organics, etc.). The RFID tag includes the serial number, coordinates (where the cart was scanned), and time stamp (when cart was scanned) and sends data to a waste portal. This allows real-time

FUNCTION	EXAMPLES
	monitoring of cart delivery and rollout. Anytime the tag is scanned, the information is automatically updated through transmission to the waste portal. • Another interesting use of RFID in carts is to monitor the set-out participation rates of services, like recycling. By knowing the number of carts participating, the zip code of the carts (geo-location), and the daily weight of the truck, the amount recycled per household can be obtained through the data upload. Participation can be managed as well. In this case, the app reader is placed on the automated truck arm and registers that the cart has been lifted from the assigned household.

2.4.2 Other Available Collection System Tools

2.4.2.1 Automatic Vacuum Systems for New Developments

In pneumatic refuse collection systems, waste or recyclables are deposited into inlet ports and transported over long distances through a network of pipes to a central collection station. This system uses negative pressure fans to generate airflow, which enters the pipes at atmospheric pressure, trapping and conveying solid waste to the collection point. At the station, the waste is compacted into sealed containers for further handling (VL Swedish Environmental Research Institute, n.d.).

Studies conducted in Asia and Europe have demonstrated that these systems perform most effectively in dense urban centers. They are typically integrated into the design of new developments or major refurbishments, particularly in settings with limited space for traditional waste storage and truck management, such as large multi-family residential complexes or high-rise business districts (Preville, 2020; Hidalgo et al., 2018).

This technology could be a valuable consideration for future development requirements and building codes in Broward County, potentially reducing traffic congestion and enhancing waste management efficiency.

2.4.3 Future Autonomous Vehicle Collection Technologies

The AI-assisted autonomous vehicle garbage collection and transfer vehicle technology is on the cusp of becoming a reality, with widespread implementation expected within the next two decades. They are most certainly going to be available and widely used during the period of this plan and may be the preferred method for many parts of the supply chain logistical needs, including regular collection and transfer logistics, special collections, public park and beach collection, etc. As this technology advances, understanding its current capabilities and potential is essential for informed planning and adoption.

2.4.3.1 State of Development

AI-driven garbage collection vehicles are among the most researched innovations in waste management, with significant progress made in recent years. Companies like Tesla, Volvo, and Mack Trucks have developed prototypes tested in a variety of environments, including complex urban settings (Szczepanski, 2019; Yin et al., 2022). These vehicles utilize advanced technologies, such as 360-degree monitoring cameras and sensors, to detect and immediately stop for humans, pets, vehicles, and other obstacles, ensuring safe navigation.

Volvo has reported that its autonomous trucks are designed not only to enhance safety and efficiency, but also to improve sustainability. By leveraging machine learning, these vehicles optimize steering, speed, and other operational parameters, which reduces emissions and fuel consumption (Ackerman, 2017; Dyllan Furness, 2017). As the technology matures, route optimization and efficiency are expected to increase, reducing collection times, missed pickups, and overall costs.

2.4.3.2 Addressing Industry Challenges

Autonomous garbage collection offers a solution to several persistent challenges in the waste industry:

- **Eliminating Human Risks:** The waste collection process is inherently dangerous, particularly for workers who walk alongside trucks to manually collect waste. Removing humans from these hazardous roles significantly reduces injury risks.
- **Improving Efficiency:** Traditional collection routes often follow inefficient patterns due to ingrained practices rather than optimization. Autonomous vehicles, guided by AI, eliminate these inefficiencies, ensuring routes are collected in the most cost-effective manner.
- **Solving Labor Shortages:** Many waste collection companies face ongoing staffing issues, especially with legacy rear-loading vehicles requiring manual labor. AI-assisted vehicles reduce the dependency on human workers, addressing this staffing shortfall.

2.4.3.3 Safety and Sustainability Benefits

Modern collection vehicles already mitigate some risks through automation and semi-automation. However, fully autonomous systems represent the next step in removing the human element from dangerous repetitive tasks. By integrating AI for servicing individual waste bins autonomously, these vehicles enhance worker safety and streamline operations. Over time, their ability to learn and adapt for performance optimization will lead to further reductions in emissions and operational costs, contributing to a more sustainable and efficient waste management system.

As this technology reaches scalability, its adoption is expected to accelerate, transforming waste collection into a safer, more efficient, and sustainable process over the next 20 years.

2.4.3.4 State of Play

While autonomous waste collection technology is advancing rapidly, its application in large-scale waste systems remains unproven. Despite manufacturers expressing confidence in its scalability, widespread implementation is estimated to be five to 10 years away. Challenges such as public concerns about autonomous vehicle safety, potential malfunctions, and institutional resistance will need to be addressed before the technology gains broad acceptance. Currently, AI is improving safety immensely by providing drivers with lane correction and pre-crash notifications in real time. It is expected that full automation, in any event, will be an evolution much like what is happening in the airline industry; however, given the potential savings and money involved, its implementation will move more quickly.

This plan recommends proactively recognizing and planning for the integration of autonomous vehicles into both public and commercial waste collection systems. Preparing now will ensure readiness as the technology becomes viable and widely available.

2.4.3.5 Specialized Autonomous Waste Collection Technology

In addition to large-scale autonomous collection vehicles, specialized systems are being developed and tested worldwide for institutional and public areas, such as factories, parks, and beaches. These systems often take custom forms and focus on specific tasks.

One example is a small robotic collection vehicle, similar in concept to “Wall-E.” These robots are designed for limited routes and are dispatched when a collection container sensor signals that it is full. Equipped with 360-degree cameras and sensors, the robot navigates to the container, avoiding obstacles and maintaining safe distances from humans and animals. It then unloads, compacts the waste into a storage area, and transports it to a central transfer point.

Additionally, autonomous litter robots are being deployed for tasks such as lot sweeping and litter collection. Some of these robots are equipped to identify and collect floating debris, addressing significant waste management challenges in waterways like those in Broward County (Lee et al., 2024). While these specialized systems are expected to scale more quickly than route-based vehicles, their widespread adoption is on a shorter timeline.

2.4.3.6 Addressing Physical Strain in Waste Collection

Autonomous waste collection vehicles also offer the potential to address the physically demanding tasks faced by waste collection workers, particularly those operating front-load vehicles. In urban areas, drivers often need to exit their vehicles to manually move heavy dumpsters—ranging from two- to four-yard containers and weighing more than 500 pounds—over uneven surfaces in various weather conditions.

An AI-assisted autonomous collector capable of maneuvering dumpsters to and from the truck would eliminate this labor-intensive and hazardous task. This innovation would not only improve worker safety, but also save significant time. By reducing the need for drivers to repeatedly exit and re-enter the cab to service multiple dumpsters, these systems could increase efficiency and reduce exposure to dangerous conditions.

As autonomous technologies continue to develop, their integration into specialized and large-scale waste collection systems will provide safer, more efficient, and sustainable solutions, positioning municipalities and service providers to meet future demands effectively.

2.5 SCALE SYSTEMS INNOVATIONS

2.5.1 On-Board Scale Systems

Since the passage of RCRA Subtitle D in 1975, most of the U.S. has transitioned to measuring solid waste by mass (tons) rather than volume (yards or truckloads) to comply with solid waste management plans and permit requirements. This shift, driven by increasing disposal fees tied to stricter landfill and incineration regulations, remains a key trend in the industry. Notably, while disposal fees in North America stabilized from 2017–2023, states relying on waste-to-energy (WTE) facilities—such as Florida—continue to experience rising tipping fees, as noted by the Environmental Research and Education Foundation (EREF).

In response to these rising costs, both private and public sectors have adopted **on-board scale systems** to ensure accurate cost recovery. These devices, mounted on truck bodies or lifting arms, measure the weight of individual waste containers during collection. By integrating this data into route management systems and solid waste platforms, these scales eliminate manual processes and provide real-time information.

The benefits of on-board scales extend beyond cost recovery. Charging customers based on weight rather than container size incentivizes waste reduction and recycling. Managers can use integrated apps to notify customers when their waste output increases, particularly effective in addressing food waste. These systems can also periodically weigh smaller residential containers without significantly affecting route productivity.

Additionally, on-board monitors enhance truck safety by signaling when a truck is full, preventing overloading. Data collected by these systems can be analyzed by industry classification (SIC code) or residential zip code, enabling targeted interventions to reduce waste in specific areas. The combination of efficiency, safety, and actionable data makes on-board scales a transformative tool in modern waste management.

2.5.2 'Remote' Truck Scales

Historically, solid waste facilities have faced challenges with long lines at truck scales, leading to inefficiencies for both facility operators and collection truck operators. A decade ago, scale operations were labor-intensive, requiring multiple employees to manually record weights and process tickets for each truckload.

Modern **remote truck scale systems** have revolutionized this process. Utilizing edge technologies such as RFIDs and sensors, these systems automatically identify trucks and their associated accounts when they enter the weighbridge—the platform that measures truck weights. Precise weight data is uploaded directly into the integrated waste system platform, eliminating manual data entry and reducing on-site staffing needs.

These advanced systems offer numerous operational benefits, such as the following:

- **Automated Workflow:** Drivers receive unloading instructions via an on-board computer or from a scale attendant, streamlining the tipping process.
- **Data Integration:** Tagged weight data can be compared with on-board scale measurements, enabling analysis of waste flow patterns by time of day or day of the week.

- **Remote Management:** Facilities can be monitored by a single attendant overseeing multiple sites remotely, much like an air traffic controller.
- **Enhanced Safety:** Cameras monitor truck activity on the weighbridge, ensuring operational safety.

By reducing time on the weighbridge, these automated systems improve fleet efficiency, reduce fuel consumption, and lower operating costs. Furthermore, integration with IoT technology allows for real-time adjustments and enhanced management of waste facilities and fleets. With proper planning, remote truck scales provide a critical foundation for cost-effective and efficient waste management operations.

2.6 COLLECTION SYSTEMS AND DISPOSAL SITE MANAGEMENT AND MONITORING WITH DRONE TECHNOLOGY

When visiting a landfill, one might expect to see the ubiquitous high visibility safety gear, waste collection vehicles, and compactors. In the last ten years—and increasingly in the past three to four—unmanned aerial vehicles (UAVs), more commonly called drones, can be counted among these common sights. Use of drones is beneficial for a variety of reasons; not only do drones provide efficient, cost-effective collection of high-quality data, but they also provide a safer way to access and collect data from dangerous or difficult-to-access areas. Because of the benefits offered by using drones in waste management, applications have expanded far beyond topographic landfill mapping to include lesser-known uses, such as methane detection and combating waste crime.

2.6.1 Example Applications of Drones in Waste Management

2.6.1.1 Topographic Mapping and Volumetrics

Drone-based surveys can be completed, data processing and all, in a fraction of the time required for a traditional land-based survey. Collected data is used to generate high-resolution orthomosaic images, three-dimensional point clouds, and digital elevation models. Once the three-dimensional model is complete, it can be used to calculate metrics such as remaining airspace, stockpile volumes, slope, and—paired with scale house data—compaction rate. Dozens, if not hundreds of landfills including Paducah Site Landfill, Nortes III Landfill, and many others are using drones to reduce costs as well as improve data collection efficiency and quality.

2.6.1.2 Methane Detection and Surface Emissions Monitoring

While the traditional methods for monitoring surface emissions on landfills are physically demanding, time consuming, and pose a variety of health and safety risks, drone-based methods offer solutions that are efficient, comprehensive, effective, and safe. Companies like Firmatek, SCS Engineers, Tetra Tech, and SnifferRobotics use technologies such as Tunable Diode Laser Absorption Spectroscopy (TDLAS) and the patented SnifferDRONE for aerial methane leak detection. While the U.S. Environmental Protection Agency (U.S. EPA) is still weighing TDLAS technology and the resulting reports for regulatory Surface Emissions Monitoring requirements, Sniffer Robotics was granted approval of a new test method, Other Test Method (OTM)-51, as an alternative to the surface emissions monitoring procedures set forth in Federal landfill regulations. The U.S. EPA's letter to Sniffer Robotics stated that the "UAS-based alternative method yields results that are typically no less stringent and often more conservative when compared to those of existing SEM compliance procedures and is thus adequate to determine compliance with the operational limit." Landfills such as Frank R. Bowerman Landfill in Irvine, CA, a municipal sanitary landfill in Lawrence, KS, and others are using drone-based methane detection methods.

2.6.1.3 Hydrogen Sulfide Monitoring

As one of the key attractions of drones is the ability gather data remotely, particularly where health and safety is concerned, drone-based hydrogen sulfide(H2S) detection is a logical application. Foul smelling and toxic, H2S is not only dangerous to human health beyond certain amounts but is also the culprit behind many odor complaints. In 2023, a team of Brazilian researchers published an article in Analytical Chemistry detailing a “lab-on-a-drone” they created that can sample H2S gas while in the air, analyze collected data, and report results in real-time. Testing was carried out at a wastewater treatment plant; the drone sampled the air at various altitudes and the Bluetooth-enabled detection system transmitted results to the team in real-time. Researchers agree this novel approach to air quality monitoring holds promise for future applications.

SnifferRobotics has taken a different approach to drone-based H2S detection. Using industry studies that correlate the probability that H2S and other malodorous gases may be emitting from the same source as methane, they developed a method using the previously discussed SnifferDRONE to identify low-level methane leak sources over the surface of the landfill. Once these locations are identified, field technicians are deployed to each leak source and manually measure concentrations of other gases. Their studies demonstrate a high correlation of identifying odorous gas emissions sources using low-level methane as a tracer gas.

2.6.2 Waste Crime

Beyond the mere presence of a drone buzzing overhead acting as a deterrent, these versatile machines can be used to combat waste crime in a variety of ways. Drones can be used to monitor locations rife with frequent littering, capture high resolution drone imagery to identify illegal waste sites, document piles of waste stored behind buildings or trees, and collect incriminating data from hostile sites. Drone-mounted thermal cameras have been used to detect heat emitting from illegally dumped waste or even illegally discharged substances into bodies of water back to the point of origin. Evidence collected via drone in these cases has been used in court cases to prosecute those responsible. Cities like Dublin, Ireland, and many others across the United Kingdom are using drones to combat illegal dumping.

2.6.3 Site Inspections

Characterized by their dynamic nature, the presence of heavy machinery, uneven terrain, and other environmental challenges, landfills present a variety of potentially dangerous conditions. Drones provide a means by which to conduct a remote site inspection by quickly capturing high-resolution aerial data. These images can be used to identify potential safety concerns, plan a physical site visit, or investigate operational issues.

2.6.4 Emergency Debris Monitoring

The ability to deploy rapidly and access dangerous areas inaccessible to ground crews make drones an invaluable tool to monitor debris flows remotely in the wake of natural disasters by capturing high-resolution imagery of ravaged areas. These detailed images of affected areas can be used to decipher erosion patterns, changes in topography, and take precise measurements of debris flow deposits. The North Carolina Department of Transportation’s Division of Aviation deployed drones to survey bridges, roads, and other infrastructure during Hurricane Milton in October 2024, flying hundreds of missions within the space of a week. Collected data were used to determine water flow, areas impacted by flooding, and to improve river forecasting models that local, state and federal officials rely on. Similarly, Censys Technologies Corporation used drones to fly over South Daytona's neighborhoods to collect data for post-storm assessments following both hurricanes Helen and Milton. These collected data are not only being used to provide post-storm mapping responses, but also to mitigate future flooding and storm damage.

2.7 AUTONOMOUS LANDFILL MONITORING (GAS, TEMPERATURES, AND LIQUIDS)

2.7.1 Automatic Wellheads

Landfill gas technicians are traditionally responsible for visiting gas extraction wells strategically placed throughout the landfill, using a gas analyzer to ascertain gas composition, and making manual adjustments based on their findings. Automated wellheads have introduced new possibilities. Utilizing sensors permanently installed at the wellhead, automated wellheads measure gas composition and transmit collected data in real-time (Kesari, 2024). In the case of LoCI Controls, one of the companies that sells automatic landfill gas wellheads, automation is used to make small, incremental value adjustments every few hours based on recent measurements. According to LoCI, their automated gas-collection system can increase gas collection by 10% or more (Messics et al., 2018). Hamm Sanitary Landfill in Lawrence, Kansas, has increased methane capture by 32% using LoCI's system (LoCI Controls, n.d.-a). Similarly. The Aria Energy Project in Oklahoma City, Oklahoma, has increased gas flow and plant uptime by more than 30% through installing 50 of LoCI's Controllers (LoCI Controls, n.d.-b). Other sites have opted to use LoCI's sensors on the main legs of their header system to help identify where to start looking for air leaks or dips in incoming gas quality to their gas plants rather than invest in wellheads sitewide.

While automatic wellheads are an exciting and developing area within the landfill industry, there are several critical things to keep in mind when contemplating automatic wellheads:

1. Landfill gas is explosive. Unfortunately, the landfill industry experiences flash fires from landfill gas every year. Engineers must consider this hazard and designate the electrical area hazard classification for the landfill gas wellheads. If they are considering placing electrical equipment into this area, they must make sure that the equipment is rated by FM UL to meet the electrical hazard classification of that area.
2. Class 1, Division 1, Group D is the electrical hazard classification for an area with explosive methane gas concentrations. Class 1, Division 2, Group D is the electrical hazard classification for an area where explosive methane gas concentrations can exist when there is a problem.
3. The performance statements provided to the landfill industry by automatic wellhead companies are based on limited information (e.g., a limited several-month period instead of a several-year period). A comprehensive study of the impact of landfill gas wellheads on landfills is desired and needed for the landfill industry to accurately identify the benefits of this technology.
4. A wellhead is only as good as the vacuum to pull the landfill gas out of the well. If your blower/flare station is not operating well or applying sufficient vacuum (or too much vacuum) your well will not operate correctly, regardless of whether it is manual or automatic. Implementing a flare station Remote Monitoring and Control (RMC) system is a very effective way of improving the operation of your entire landfill gas

well field. The leading provider of flare station RMC systems is SCS RMC. They have implemented several in Florida and dozens across North America.

2.7.2 Landfill Temperature Monitoring

Elevated temperature landfills are an existing and growing area of concern within the landfill industry. One way to help limit the damage from an elevated temperature event at a landfill is to proactively monitor landfill temperatures. Landfills on the East Coast and West Coast have SCS Remote Monitoring and Control (SCS RMC) systems that monitor their landfill gas wellheads and downhole temperatures using Industrial Internet of Things devices. These devices monitor the temperature and report it to a cloud-based dashboard that allows users to see the current and historical temperatures, analyze the data, and receive automatic reports and alarms on the data. These systems have been invaluable to the site operators, engineers, and regulators in analyzing and tracking elevated temperature events within landfills. When used proactively, they can alert you when you have a small problem, and you can act on it to keep the problem isolated and not allow it to spread.

2.7.3 Landfill Liquids Remote Monitoring and Control

Another widespread area of concern within the landfill industry is dealing with the liquids that are present in every landfill. One very successful method for helping to deal with landfill liquids is to utilize a Landfill Remote Monitoring and Control (RMC) system. SCS Engineers has implemented dozens of RMC systems for liquids monitoring and control across North America, including several in the state of Florida. These systems perform several essential functions including but not limited to:

1. **Automatic collection of data** – no person is required to collect data such as liquid levels, runtimes, flows, etc. It's all done automatically. Your people can focus on more important matters and not expose themselves to the health and safety risks that are inherent to landfills.
2. **Cloud-based analysis, reporting, and alarming** – the data is presented in an online dashboard, and users receive automatic reports and alarms based on the data. This allows you to be proactive instead of reactive and keep a small issue as a small issue instead of growing into a large environmental issue.
3. **Interlocking of pumps to the receiving vessels** – pumps are automatically stopped when the location that they are pumping into (e.g., tank, sump, etc.) is full. This minimizes the risk of an overflow and the resulting environmental issues.
4. **Submetering** – RMC systems allow you to know how much liquid each area generates and what the liquid levels look like across your site. This allows you to know where you may have an issue and act on it before it becomes a larger problem.

Together, these RMC systems can help you to:

- Save time
- Save money
- Improve environmental compliance
- Reduce health and safety risk
- Improve quality of life for the facility's neighbors and the workers at the facility

2.7.4 Artificial Intelligence-assisted Autonomous Vehicles at Landfills, Material Recovery Facilities, and Transfer stations

Landfills, material recovery facilities (MRFs), and transfer stations operate as bustling hubs of activity, with a constant flow of people, machinery, and vehicles. The environment always demands heightened situational awareness, as trucks are frequently entering and exiting, drivers are outside their vehicles inspecting waste loads, and front loaders are in continuous motion to manage the movement of waste within the facility.

The complexity of these operations suggests that reducing the human factor could lead to improved coordination, efficiency, and safety at landfills, MRFs, and transfer stations. Automation and technology may offer a path toward a more streamlined and well-orchestrated operational process.

2.7.5 Other Artificial Intelligence-assisted Landfill Applications

Current landfill operations often require collection or transfer vehicle drivers to exit their vehicles to perform tasks, creating a high-risk environment given the numerous activities taking place at the working face. Implementing AI to automate these manual functions presents a significant opportunity to enhance worker safety.

For instance, an AI-assisted device could be used to clean seals at the back of the vehicle, allowing the driver to remain safely in the cab. Additionally, AI could be deployed to monitor and manage fires at landfills, particularly as the frequency of fires linked to lithium batteries continues to rise. These applications of AI have the potential to reduce risks, improve operational efficiency, and ensure safer working conditions for landfill personnel.

2.7.6 AI Monitoring of Cart Images During Dumping /Enforcement App

AI can be used to power smartphone apps that monitor contamination in each waste stream. These apps can be used to increase the efficiency of waste collection in addition to helping identify areas for municipalities and institutions to educate, engage, and correct resident behavior (CSUN Sustainability, 2024). These systems can also be used to identify overflowing bins to assist in streamlining collection efforts. Current use cases primarily exist in the private and institutional sectors. An overview of contamination monitoring app is presented in **Table 4**.

Table 4. Contamination Monitoring Apps

Footprint required	Little to no footprint. All operations can be done through smartphone apps or additional cameras.
Capital expense range	AI powered camera startup City Detect installed cameras on garbage trucks to monitor for litter and illegal dumping at a cost of $48,000 for a pilot to the City of Columbia. A full-scale implementation will cost the city 108,000/year (Leibman, 2024). A widely available, already accepted application is metroKey for anti-contamination.
Details required for consideration and prioritization based on a desktop analysis	Pros: Ability to target generators with highest contamination rates with price increases AMCS offers recording AI service to identify overflowing bins and identify hazardous material (Leibman, 2024) Cost savings from more targeted education initiatives Some systems can also help with code enforcement in other departments (Leibman, 2024) Cons: App-based systems may require additional staffing or training for current staff to monitor bin levels Privacy concerns from residents (Leibman, 2024)
Recovery output (diversion)	Marriott Hotels- used AI Monitoring to reduce food waste by 25% across 53 of its European hotels (George, 2024) Yale University Dining Hall system anticipated to reduce food waste by 30% by next year (Gao, 2024)
Emissions ranges	Marriott Hotels- Estimated mitigation of 486 tons of GHG emissions over course of six-month pilot (George, 2024)
Automation potential, elimination of dangerous repetitive jobs	Some programs can identify dangerous materials in bins and provide alerts to haulers/municipalities to prepare operators to handle hazardous material properly (AMCS)

2.8 AI AND SORTING ADVANCEMENTS INCLUDING ROBOTICS, RECIRCULATION AND SMALL FORMAT RECOVERY

2.8.1 Introduction

Dry solid waste materials which enter waste and recycling streams are constantly evolving, requiring a flexible response to cleaning, sorting and baling through new technologies. For instance, in just the last two decades, packaging has exploded as a percentage of the waste stream and source separated recyclables streams (i.e., dual and single stream). At the same time, the amount of glass, metal and free sheet fiber flowing through these streams has decreased, as a preference for the flexibility of plastics increased. Finally, the movement away from these primary materials to plastics has come with numbing complexities that make recovery harder, including packages and consumer items utilizing materials with new chemistries and formats, i.e., multi-material packaging.

In addition, household and commercial waste collection efficiencies have increasingly optimized the movement of both recyclables and mixed solid waste to either recovery or disposal at lower and lower costs, by maximizing the mass/volume per route trip and reducing the dangers of solid waste collection to truck operators through automation. Collection automation and compaction naturally adds entropy to solid waste from these increasingly complex streams through the relatively new entry of containerized waste system with little-to-no inspection of materials followed by mixing of materials and their increasing densification after collection. Finally, during the same time, processing plant manual sorting of increasingly lighter weight, downgauging, and densified packaging, along with the increase in small format packaging became less accurate, resulting in greater cross contamination of materials. Processing these materials has become a challenge. In fact, during this same 20-year period, the cost of manually sorting recyclable materials in a single stream has more than doubled (for instance, from ~$15-25 per ton at the beginning of this century to more than $35-60 per ton, with some costs twice that range, (i.e., small Single Stream MRF facilities which are still manual). In sum, accurate sorting of the waste and recycling streams decreased as sorting of waste and recyclable stream became more complex.

2.8.2 Artificial Intelligence for Sorting Solid Waste Materials

2.8.2.1 Why AI Has Developed

Manual sorting for recyclables at solid waste facilities is a dangerous and repetitive job with high injury rates and exposures, in an environment that is stressful and loud. These jobs have increasingly lower efficiency and increasingly higher employee turnover rate, along with predictably lower and inaccurate capture rates compared to automated sorting.

Artificial intelligence (AI) use in sorting applications for both sources separated and mixed waste recovery applications has expanded rapidly as these dangerous manual jobs go unfilled. AI-assisted tools combine with mechanical methods of automated sorting (screens, air density separation, magnets and eddy currents) to reduce manual sorting in MRFs by more than two thirds in less than a decade. AI sorting recognition will one day make most sorting in material recovery facilities ("MRFs" or "RMPFs") and front-end mixed waste processing facilities (MWPFs) fully automated. Already there are fully automated MRFs in Europe and Asia under construction (ZenRobotics, 2023).

2.8.2.2 Sorting Machines and AI

AI systems harness the ability of computer programs to perform tasks mimicking, sometimes surpassing, human skills. These systems continually improve upon their already impressive capabilities by adhering to the principles of machine learning, a process by which computers use large and constantly evolving datasets to better anticipate and react to different inputs with more flexibility than conventional programs.

There are two AI sorting machines which dominate recycling sorting and continue to evolve, optical sorters and robots. Both use similar AI-capabilities combined with sensors and imaging technology to sort materials based on a variety of optical properties including color, transparency, reflectivity, and shape. The emergence of image recognition technology (shape/color/size) was first used by AMP Robotics and now is quickly spreading to new optical sorters, which heretofore used near infrared, x-ray, and magnetic image identification. Sensors can also identify smart marks on packages to achieve more efficiency. Each kind of machine automates formerly manual tasks. Optical sorters are

10 times faster than robots, with the ability to separate 600 targeted units per minute compared to the 60 picks/min. capacity of most robots (Barker, 2021).

2.8.2.3 Optical Sorters with AI

Optical sorters have been in use for a longer period and are more widely recognized by MRF operators than AI or robotics. As a result, optical sorters remain the leading and most efficient technology for separating recyclables into distinct, marketable bales. These devices are the most advanced and efficient sorting tools available to MRF operators, capable of targeting nearly 95% of properly prepared materials moving at speeds between 800 and 1,000 feet per minute.

Modern optical sorters have advanced beyond their earlier versions by improving air nozzle placement, widening accelerator conveyors, and incorporating air-assist features that prevent fiber from unintentionally moving until ejected by the operating system. Furthermore, costs for these newer models have started to decline, making them more accessible to operators.

The core technology relies on sensors that detect materials based on light absorption and reflection as they pass along a conveyor line. Data collected by these sensors is processed by computers, which direct air nozzles to sort the material toward the appropriate stream. While optical sorters predate AI, the integration of AI has significantly enhanced their capabilities. Modern AI-powered optical sortation systems combine traditional sorting mechanisms with advanced AI, leveraging higher quality image recognition and cloud storage to improve both individual system performance and overall operational efficiency.

The AI algorithms underpinning these technologies enable them to learn continuously, automatically detecting attributes such as size, shape, chemical composition, and magnetic signatures to distinguish between various materials, including plastics, metals, glass, and fibers. These processes occur at very high speeds, improving sorting accuracy and speed with every pass.

The latest AI systems utilize triangulated detection methods that combine camera image recognition with chemical analysis, allowing for more precise decision-making regarding whether a material should be classified as recyclable or non-recyclable. Furthermore, with all sorts, AI-assisted 3D or camera recognition systems learn from the classification of more material types and their respective characteristics—such as size, color, shape, and depth—resulting in continually improved performance and system-wide efficiency.

2.8.2.4 Robots and AI

Robots have significantly advanced the application of machine learning in recycling and recovery processes. However, their use remains constrained by certain limitations, including inefficiencies in “gripper” performance and the necessity for effective material singulation. Current robotic systems lack the ability to manage the diverse range of three-dimensional objects — of various shapes, sizes, and densities — due to the absence of advanced suction cup or mechanical hand designs. Moreover, their performance tends to decline when dealing with most two-dimensional materials.

When compared to optical sortation, robotic systems demonstrate a higher missed pick rate — ranging between 20% and 35% — after identifying target materials. Despite these performance challenges, robotic systems can still be advantageous, particularly in smaller, retrofit applications where speed and cost are key considerations. Robots are generally less expensive than traditional optical sorting systems, although the gap is narrowing with the introduction of newer, less costly optical sorters that eliminate the need for high-speed, expensive conveyors.

Robotic systems are especially effective in slower-speed applications with limited non-targeted collateral materials. They are commonly utilized in a presorting capacity within materials recovery facilities (MRFs) to evenly distribute material across the conveyor belt and remove oversized recyclables or contaminants before additional processing. However, robots are not without limitations. Materials that are overly greasy, such as certain plastic films, or challenging items like crumpled aluminum cans, are difficult for robots to grip effectively. Additionally, maintaining these systems is critical, as robots require regular upkeep and gripper replacement to maintain peak performance.

A notable example of successful robotic implementation is the dual-stream MRF in Emmet County, Michigan. The Emmet County Recycling (ECR) MRF underwent a significant retrofit in 2020, involving the addition of a surge bunker and three consecutive robots. This redesigned container line supports a recirculating system that reduces reliance on manual sorters, many of whom previously faced high turnover rates.

The versatility and programmability of the robotic system have enabled ECR to sort a broader range of materials, including end markets that were previously inaccessible. By designating specific surge bunkers for trial bales, ECR can test new material capture rates without disrupting ongoing operations. Notably, they reprogrammed the robots to focus on pill bottles and sleeve-wrapped PET bottles — two material types that align with their end market requirements. This strategic use of robotics has proven both adaptive and cost-effective for rural MRF operations.

2.8.2.5 Recirculation and Redundancy with AI-assisted Optical Sorters and Robots

One of the most promising and transformative trends in AI-assisted sorting is the reintroduction of recirculation into modern MRF (Materials Recovery Facility) sorting systems. Originally, recirculation was employed during the early days of source-separated recycling when efficiencies were achieved by mixing materials for transportation. Circular or recirculating conveying systems allowed recyclable materials multiple opportunities to be sorted into distinct categories, improving overall recovery rates. During this period, human sorters would identify unprocessed materials from the discharge residue line and place them onto circular sorting systems—similar in design to airport luggage turntables—allowing these materials to pass by sorting mechanisms a second time for targeted separation into commodities such as metals, plastics, and glass.

Recently, several MRF equipment manufacturers—including AMP, VanDyk, and Steinert—have reintroduced the concept of recirculation into new and retrofitted MRFs as of 2024. This technology is also being adopted in select MWPFs in Europe and Virginia. The strategy has demonstrated promising results, leading to increases in recovery rates of five to 15% for paper, plastics, and certain metals while simultaneously reducing material loss due to cross-contamination.

In high-speed MRF operations, inefficiencies often occur due to the sheer volume of material moving quickly along conveyor belts. Sorting devices can become overwhelmed, leading to misdirected materials, including non-targeted waste being inadvertently moved with targeted recyclables. These misdirections contribute to a reduction in sorting efficiency, particularly as materials become more complex and less homogeneous.

With AI-assisted recirculation, these inefficiencies can be mitigated by positioning optical sorters or robotic devices at key ejection points, such as the residue line or the final quality control sorting location (e.g., the last sort on the old corrugated cardboard (OCC) line). Previously, this sorting would rely on manual labor, especially during periods of high commodity pricing. Now, AI-enabled technologies can identify up to three missed or mis-sorted items at once, accurately sorting them into designated takeaway conveyors that return them to the initial sorting protocols for targeted recovery. This allows for repeated opportunities to recover these materials even if they are missed multiple times during the sorting process.

This modern, AI-driven reimagining of recirculation offers significant promise, particularly for processing traditional rigid containers such as plastic bottles, jars, and metal cans. By allowing these items additional opportunities for recovery through enhanced recirculation flows, reported recovery capture rates for certain rigid containers have been more than doubled.

Moreover, this approach offers a dual benefit for MRFs that can accommodate the technology at scale. The first advantage is a reduction in disposal costs, as less waste is sent to landfills. The second is increased revenue through the recovery and sale of additional captured recyclables. When combined, these benefits position AI-assisted recirculation as an efficient, cost-effective, and environmentally beneficial innovation in modern recycling operations.

2.8.2.6 Trajectory of AI Driven Innovation

A key aspect of these technological advancements is their adaptability and dynamic capabilities. As waste streams evolve in response to shifting consumption patterns nationwide, machine learning identifies these trends in real time, adjusting sorting strategies to ensure optimal targeting and recovery. Similarly, automation technologies can be reprogrammed to meet changing end-market demands.

The integration of AI into waste and recycling sorting applications was facilitated by the development of robotic systems. However, as limitations such as the maximum number of picks per minute and higher miss rates with robotic sorting became evident, the industry shifted its focus toward AI-driven enhancements in optical sorting technologies. This transition has spurred significant progress, as AI continues to advance the capabilities of sorting systems.

Innovative approaches, such as “nested loops” of optical sorters, now enable systems to dynamically adjust sorting decisions in response to real-time changes in material flow and characteristics. This allows sorting operations to maintain functionality while individual units are taken offline for maintenance, thereby improving overall uptime. Furthermore, “recirculation” technologies continue to enhance these systems by redistributing unsorted material streams, thereby improving the recovery of a greater fraction of recyclables over time.

Additionally, the ability to collect high-quality data on waste streams opens new opportunities for monetization. Brands increasingly value detailed audit trails of their packaging products, while stewardship programs benefit from tracking recovery rates with SKU-level precision.

Although substantial progress has been achieved with advanced optical sorting technologies, several challenges remain. For instance, while optical sorters are highly effective at identifying many types of recyclables, they still face difficulties with thin-walled polyethylene terephthalate (PET) bottles, contaminated items with excessive dirt, and black plastics. Moreover, they struggle to sort items composed of a single base material that are wrapped in a different material, such as shrink-sleeve-labeled PET containers. These limitations highlight opportunities for ongoing research and innovation to further refine the performance and capabilities of optical sorters.

2.9 NEW END MARKET TECHNOLOGIES FOR FLORIDA

2.9.1 Summary

During the planning horizon, it is important to utilize existing and explore emerging end-market technologies for traditional recyclables, particularly given the Authority's geographic distance from domestic end markets and its unique seasonal patterns. The Authority will experience an influx of solid waste during the winter months, when production rates for metals, plastics, glass, and paper tend to be historically low. Additionally, the Authority's reliance on exports will remain vulnerable due to disruptions in these systems over the past decade.

Investigating these new end-market technologies can provide alternative recycling outlets, especially during periods when traditional South Florida end markets are unstable. Furthermore, these innovations could enhance local recycling capacity and foster greater resilience within the regional recycling system. **Table 5** presents an overview of end market technologies and its maturity status

Table 5. End Market Technologies and Maturity Status

END MARKET TECHNOLOGY	INPUT	OUTPUT	STATUS
Small Footprint Fiber Pulping Facilities- wet hydro pulping or dry shredding- can be built locally based on permitting and wastewater treatment availability in much smaller footprint than recycled paper mills.	OCC, Mixed Paper	Wet, dried, or dry Pulp for sale to mills or export to Asian market (surrogate mills for China in Asia big-5 economies)	TFRC, a joint venture between BHS and Cellmark opened an $80M, 200,000 ton-capacity facility in Tidewater, Virginia. Too soon to recommend. Several small dry pulp surrogates for Chinese mill interests have sprung up on the Southeast coast, and some are still in the planning stages. Wet pulp freight may limit viability in low markets. Costs much lower than full papermill. Several start-ups are in development.

END MARKET TECHNOLOGY	INPUT	OUTPUT	STATUS
Chemical Recycling	Polypropylene, polyethylene, other plastic containers	Processes that use high heat, chemicals, or both to break down plastics into their chemical building blocks. Most plastic containers are downcycled and have long freight from So. Florida.	2025 will be a big year for this emerging technology. Too soon to recommend development. Expensive footprint. 11 plants will be on-line by 2026 with a capacity of 500K TPY. Two very small facilities in Florida and Georgia. These could not handle South Fla recyclables. LyondellBasell is building a large facility in Texas.
Glass to Pozzolan Facility for Glass Recycling	Glass bottles	There is only one glass processor in Florida in Sarasota and almost all glass collected in curbside programs goes to landfill cover in south Florida. Unfortunately, almost zero is recycled in the state south of the Palm Beach County line. There has arisen some competition due to the successful substitution of pozzolanic materials for fly ash in the manufacture of cement (Concrete Materials Research - Herbert Wertheim College of Engineering, n.d.; *Pozzotive*, n.d.).	Several operating entities have pozzolanic production operations and there is a need for clean fly ash substitute for cement with production of coal expected to continue to decrease (DeFord, 2016). The region, including surrounding East coast counties, may produce enough recycled bottle glass to make this end market work.

3.0 ADVANCED MIXED WASTE TECHNOLOGIES

3.1 INTRODUCTION

The history of mixed waste processing reflects centuries of urbanization, evolving from simple waste picking to advanced technologies designed to recover valuable materials and reduce landfill use. A short summary of the last 60 years of modern waste management is provided in the Appendix for reference. The evolution of waste management during this period mirrors shifting priorities toward resource recovery and environmental sustainability, focusing on emission reductions, energy savings, and beneficial reuse, rather than the former 'out of site/smell/vectors range, out of mind' of local burning or burying. However, advanced mixed waste technologies still struggle to compete in an economically viable manner with cheaper and more reliable methods like landfilling and traditional waste-to-energy due to the high entropic factors of mixing heterogeneous materials together. In North America, more than 400 such facilities have opened and closed in the past 60 years, resulting in billions of dollars lost — especially outside highly regulated areas like California. Underperforming or failed facilities rates have been unacceptably high and continuous, and, except for special purpose facilities (like those in highly regulated California) no stand-alone mixed waste facility has sustained itself over its predicted lifetime. More than 95% of those in start-up and operation have closed within 10 years.

However, advanced processing technology is improving and there is reason to believe that economic viability and technical feasibility is beginning to overlap. On the West coast, and in Europe, waste technologies have evolved through key developments in municipal solid waste (MSW) recycling, composting, refuse-derived fuel (RDF), and mechanical and thermal treatment methods like mechanical biological treatment (MBT).

Mixed waste processing has progressed from basic disposal methods to increasingly sophisticated technologies aimed at maximizing material recovery and reducing landfill reliance. Initially centered on landfilling and incineration, waste management evolved with rising environmental concerns, spurring innovations in recycling, composting, refuse-derived fuel (RDF), and mechanical biological treatment (MBT). The 1990s established dual stream recycling, which quickly transitioned to single-stream recycling as more equipment capability emerged. On the MSW side, progress toward more advanced RDF production continued, though challenges with contamination remained.

In the 2000s and 2010s, new thermal treatments like gasification and pyrolysis, along with the shift toward a circular economy, created more opportunities for recovery. The adoption of digitally informed sorting, chemical recycling, and carbon capture technologies signals a new era of possibilities. Continued innovation in waste processing holds promise for higher recovery rates, sustainable material reuse, and the development of near-zero-waste systems, paving the way for a more efficient and circular approach to waste management. Today significant opportunities for evolution in recovery depend on exploiting AI driven sorting technologies and new approaches to manage organic streams in a way that limits carbon emissions and controls PFAS contamination.

3.2 THERMAL CONVERSION TECHNOLOGIES

A central challenge with managing MSW is that it is heterogeneous in terms of composition and particle size. Accordingly, any thermal conversion technology must be operationally robust to effectively and efficiently process MSW as it is delivered. Accordingly, the following presents the current state of the industry for thermal conversion technologies. It should be noted that the "commercially proven" are provided for context, while the "emerging" and "developing" technologies are presented to address innovative and future technologies. For each thermal conversion technology, the following data is presented:

- Technology;
- System;
- Status;
- Location;
- Typical Cost or Tipping Fee Range;
- General Description;
- Pros;
- Cons; and
- Processing Capacity.

The thermal conversion technologies were categorized in terms of their stage of development. The following definitions were used to categorize the technologies:

> **Commercially Proven Technology:** *A technology that has been designed, constructed, and operated/implemented in the United States on a commercial scale (not a pilot plant or research facility) for at least one (1) year in a reliable and consistent manner. The technology's capacity is appropriate to manage the quantity of material typically produced, and products of the processing have been effectively marketed. There may be some concerns regarding environmental issues, costs, regulatory issues, land use, etc., associated with such a technology.*
>
> **Emerging Technology:** *A technology that has been designed, constructed, and operated or implemented on a small-scale or pilot-program basis. Technologies may have been operated and shut down, may be currently operating, but experiencing significant reliability problems, or have not been operating in the United States on a commercial basis. There are or may be significant concerns regarding the technical reliability, marketing of products, environmental issues, costs, regulatory issues, land use, etc., associated with the technology.*
>
> **Developing Technology:** *A technology that has been conceptualized, patented, or designed on a small-scale or pilot-program basis. Technologies have not been operated on a pilot or commercial basis. There are or may be significant concerns regarding the technical reliability, marketing of products, environmental issues, costs, regulatory issues, land use, etc., associated with the technology.*

Each thermal conversion technology was evaluated into one of the three stages of development identified above. The solid waste processing technologies are presented below in **Table 6.**

Table 6. Status of Solid Waste Thermal Conversion Technologies

Commercially Proven	Emerging	Developing
Mass Burn Combustion	Gasification	Plasma Arc
Refuse-Derived Fuel Combustion	Pyrolysis	Plasma Arc/Gasification
		Pyrolysis/Gasification

3.2.1 Thermal Conversion Technologies

3.2.1.1 Mass Burn

Mass Burn Combustion, also known as WTE, has a proven operating record using units of varying capacities and configurations up to and exceeding 750 tons per day (tpd) per process train. WTE provides for residual minimization and generates useful byproducts that include:

A. Heat for steam generation, energy recovery, and electric sales;
B. Ash residue that is potentially reusable; and
C. Recovered ferrous and non-ferrous metals.

WTE requires sophisticated air pollution control (APC) equipment to operate within regulatory compliance standards. Physical separation may be used to complement mass burn systems. Potential benefits from the removal of large objects and metals prior to combustion include improved combustion and energy recovery from mass burn systems. Lower operations and maintenance (O&M) costs and higher system reliability. Depending on the level of physical separation, lower air emissions may be realized as well. However, pre-processing will increase operational requirements (e.g., increases in staff, equipment and O&M of the pre-processing system). In addition, should the removed materials not be marketable (if intended), additional system costs will be incurred.

WTE uses oxygen available in combustion air at temperatures approaching 2,200° F. Mass burn plants accept mixed MSW and require little pre-processing (minimally limited to the removal of hazardous wastes and oversized objects). However, large scale physical separation of MSW has been attempted with mixed results as operations have been challenged by operational difficulties, quality of separated materials (i.e., ability to meet market requirements), market conditions, and operating costs.

Combustion byproducts from WTE include heat and ash residue. The heated combustion gases are exhausted to a boiler for heat recovery and electrical generation, with the off-gases treated (cleaned) at atmospheric pressures and subsequently released to the environment. Modern WTE plants are reported to generate 500 to 600 kWh/ton (net of in-house usage).

Ash residue is generally managed as combined fly ash and bottom ash. Combined ash, which consistently meets regulatory standards for non-hazardous waste, may be recycled. Several combustion projects have ash recycling programs. Metals, both ferrous and nonferrous, are typically removed post-combustion from the ash. As the ash reuse market matures and chemical testing continues to demonstrate the non-hazardous nature of the ash, opportunity to further increase the marketability of the combustion system's solid residues exists.

The Solid Waste Authority of Palm Beach County (SWAPB) has worked with the University of Florida (UF) on several projects to develop beneficial reuse methods for ash. There is also collaboration with the Florida Department of Transportation (FDOT) to develop specifications for use of MSW combustion ash in asphalt.

Covanta has also worked on developing a procedure of refining ash into a product that could achieve beneficial use from aggregate producers[1]. Facilities would be able to reduce the ash sent to a landfill for disposal and aggregate producers would reduce costs in mining for virgin sand. In 2014, Pasco County in Florida worked with UF on a Research, Development, and Demonstration Project to construct a test roadway using WTE bottom ash as a road base and aggregate[2]. The ash was cured and reduced to two (2) ash fractions for use in the road construction. Testing for leachability was completed on cured ash and ash products. Structural tests were performed on the mixed concrete. The preliminary results were positive and the County continues work on ash recycling. Lee County also contributes to ash recycling efforts by exploring the placement of ash into a kiln to make cement used for concrete[1].

In the United States, there are reportedly 60 WTE facilities, with a total generating capacity of 2,051 megawatts (MW)[3]. Florida has the largest number of WTE facilities by state, with the most recently constructed facility commissioned in 2015 in Palm Beach County. The facility, Renewable Energy Facility 2, which is shown in Picture 1, has a capacity of 3,000 tpd and reportedly cost more than $600 million to construct[4]. The SWAPB investigated various options for extending the life of their landfill, including a landfill expansion and other conversion technologies, but ultimately decided to pursue the construction of a mass burn facility. Coupled with the design to reduce the volume of

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[1] Can Ash Be Transformed from Waste to Desired Commodity? (waste360.com)
[2] Microsoft PowerPoint - 15_05_01 NAWTEC Presentation (ufl.edu)
[3] https://www.eia.gov/todayinenergy/detail.php?id=55900
[4] https://www.swa.org/Facilities/Facility/Details/Renewable-Energy-Facility-2-11

waste landfilled by more than 90% and metals recovery, the existing landfill has a current life capacity up to 2054 – based on the 2023 Landfill Depletion Model published by the SWAPB[5].

Picture 1. Renewable Energy Facility 2, Palm Beach County, Florida

Scaling up and expansions have been implemented on existing WTE facilities in circumstances where it is more economical to renovate an existing facility rather than close a plant for alternative disposal methods. The Covanta Energy Corp., one of the largest WTE facility operators in the U.S., underwent an expansion of the Niagara Falls facility in New York in 2015[6]. As part of the proposed $30 million expansion project, Covanta also added railroad access to transport the waste via train[7].

Some WTE facilities allocated areas for future expansion during the design and permitting stages of development to allow for facility expansion either when disposal needs increased or when additional funding was available. An example is the WTE facility located in the Pinellas County Solid Waste Disposal Complex, which is shown in **Picture 2**. The facility was initially constructed in 1983 with two (2) boilers and one (1) turbine generator. In 1986, an additional boiler and turbine were added to allow a capacity of 2,700 tpd[8].

Picture 2. Pinellas County WTE Facility by Pinellas County

Similarly, the two (2) WTE facilities constructed in Broward County in the 1990s, were designed to be able to add a fourth boiler in the future, allowing for each plant to process up to 3,000 tpd[9]. The North Broward Resource Recovery Facility closed in 2015, following a Broward commissioners vote to allow Waste Management, the owners at the time, to stop accepting waste for combustion[10]. The tipping floor of the facility is still used as a transfer station; however, most of the facility is closed off.

A case where closure was more economically preferable than redevelopment was in Connecticut with the 2022 closure of the Materials Innovation and Recycling Authority (MIRA). A combination of low power prices and mechanical breakdowns led to decreased revenue for the plant to the extent that transporting waste outside of the state would be slightly cheaper[11]. After a 2020 proposal for $330

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[5] Landfill-Depletion-Model-PDF (swa.org)

[6] https://www.conteches.com/knowledge-center/case-studies/details/slug/covanta-wte-rail-to-truck-intermodal-facility

[7] Covanta's $30M WTE expansion project approved | Waste Dive

[8] https://pinellas.gov/waste-to-energy-facility/

[9] https://www.broward.org/BrowardNext/Documents/CompPlanDocs/Solid-Waste-Element-Supp-Doc.pdf

[10] https://www.waste360.com/waste-energy/broward-garbage-energy-plant-will-close

[11] Major Hartford trash-burning plant will close within days, MIRA says | Connecticut Public (ctpublic.org)

million in state subsidies was rejected to redevelop the plant, the MIRA announced they would close. Connecticut will continue to transport waste to out-of-state landfills until lawmakers and municipalities determine a long-term solution.

A process flow diagram for mass burn combustion facilities is presented in **Figure 1**, which is followed by **Table 7**, which presents a summary of attributes associated with mass burn combustion.

Figure 1. Process Flow Diagram for Mass Burn Combustion Facilities (typical)

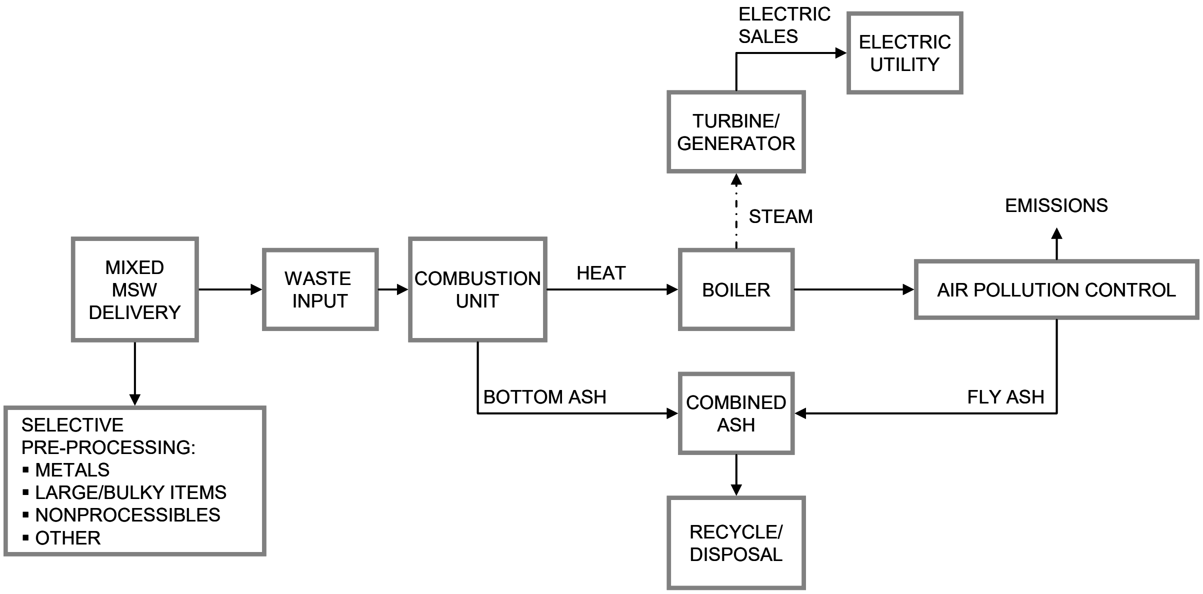

Table 7. Attribute Summary for Mass Burn Combustion Facilities

Status	Commercial
Location(s)	Worldwide
Typical Tipping Fee Range	\$50-\$100+ per ton
Processing Capacity	>600 tpd
Pros	▪ Commercially effective and reliable for more than 30 years in the U.S.; ▪ Large potential processing capacities; ▪ Technology available from many commercially-viable vendors and operators; ▪ Processes mixed MSW; ▪ Combined ash residue is reusable; ▪ Heat generated produces steam and electricity; ▪ Net electric generation ranges from 500 to 600 kWh/ton processed; ▪ Mass and volume reductions typically 90%; and ▪ Proven to meet regulations.

Cons	▪ Some physical separation required; ▪ Materials recovered via physical separation not meeting market requirements could add to costs; ▪ Widespread popular opposition; ▪ High capital costs; and ▪ Some landfilling still required.

3.2.1.2 Refuse Derived Fuel (RDF) Combustion

Refuse Derived Fuel (RDF) facilities include mechanical steps to extensively separate, sort, and/or size waste materials to produce the waste feedstock (e.g., homogenous, densified, etc.) required for the subsequent combustion processing system. RDF is fed directly to a combustion system. The RDF production process, an example shown in **Picture 3**, can vary depending on feedstock materials and desired output. Most common steps used in the RDF production are sorting, shredding, magnetic separation, air classifier, and briquetting.

The combustion of RDF uses oxygen available in combustion air at temperatures approaching to 2,500° F. Combustion of RDF accepts unsorted MSW, with pre-processing to prepare the combustible portion (the RDF). Pre-processing systems are operationally complicated and can be labor and O&M intensive. Additionally, the cost of pre-processing may not be offset by the sales of recovered materials (recyclables), should market availability or dependability not be consistent.

Picture 3. RDF Processing Plant by WiSCON Tech

Combustion byproducts from RDF include heat and ash residue. The heated combustion gases are exhausted to a boiler for heat recovery and electrical generation, with the off-gases treated (cleaned) at atmospheric pressures and subsequently released to the environment. Modern combustion plants are reported to generate 500 to 600 kWh/ton (net of in-house usage).

Ash residue is generally managed as combined fly ash and bottom ash. Combined ash, which consistently meets regulatory standards for non-hazardous waste, may be recycled. Several combustion projects have ash recycling programs. Metals are typically removed post-combustion from the ash. As the ash reuse market matures and chemical testing continues to demonstrate the non-hazardous nature of the ash, opportunity to further increase the marketability of the combustion system's solid residues exists.

Combustion of RDF is similar to mass burn except that due to increased homogeneity of the fuel, the combustion system and the boiler are of simpler design, somewhat mimicking fossil fuel combustion boiler system. The energy efficiency is higher than mass burn system; however, pre-processing energy use and the need for drying can erode this advantage on an overall basis.

The Miami Dade Resource Recovery Facility, which is presented in **Picture 4**, is an RDF plant located in Doral, Florida that began operation in 1982. Over the years there have been many processing and technical difficulties. Most recently in early 2023, the facility experienced a fire that resulted in an unexpected closure that continues today.

Picture 4. Miami Dade Resource Recovery Facility by Miami Today News

Prior to the fire, and consistent with its 2020 Master Plan, Miami-Dade County planned to procure a new mass burn facility with the capacity of 4,000 tpd, with an expected cost between $900 million to $1.5 billion [12]. However, the plans are currently on hold while Miami-Dade County re-evaluates its needs and options. This is, in part, due to opposition to WTE facilities largely stemming from public perception of emissions from WTE facilities and perceived potential harm to human health.

The SWAPB also has an RDF plant, Renewable Energy Facility 1, which began operation in 1989 with a capacity of 2,000 tpd. The plant is able to process up to 3,000 tpd for limited periods. The bottom and fly ash generated during combustion is transported a short distance to the SWA Class I landfill. Although this plant is still in operation, changes in the waste stream and experience with the RDF plant, led SWAPB to choose a mass burn combustion facility for the Renewable Energy Facility 2.

A process flow diagram for RDF combustion facilities is presented in **Figure 2**, which is followed by **Table 8**, which presents a summary of attributes associated with RDF combustion.

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[12] https://www.miamitodaynews.com/2022/04/19/miami-dade-may-move-its-resources-recovery-facility-from-doral/

Figure 2. Process Flow Diagram for RDF Combustion Facilities (typical)

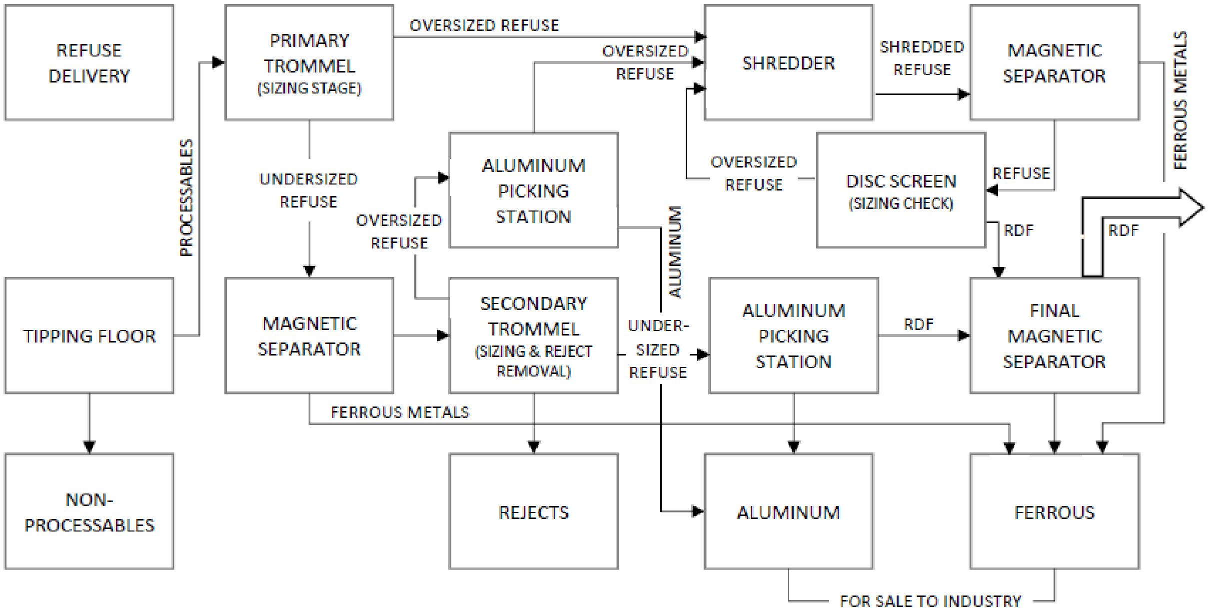

Table 8. Attribute Summary for RDF Combustion Facilities

Status	Commercial
Location(s)	Worldwide
Typical Tipping Fee Range	$70-$120+ per ton
Processing Capacity	>750 tpd
Pros	▪ Commercially effective and reliable; ▪ Large potential processing capacities; ▪ Technology available from many commercially-viable vendors and operators; ▪ Processes mixed MSW; ▪ Better quality of separated materials, increased recyclables; ▪ Lower air emissions than mass burn; ▪ Proven to meet regulations; ▪ Combined ash residue is reusable; ▪ Heat generated produces steam and electricity; ▪ Net electric generation ranges from 500 to 600 kWh/ton processed; ▪ Mass and volume reduction typically 70 % and 90% respectively; and ▪ Energy from RDF recoverable through additional processes, such as combustion or conversion.

Cons	▪ More physical separation and shredding required; ▪ Materials recovered via physical separation not meeting market requirements could add to costs; ▪ Marketability of separated materials uncertain; ▪ Widespread popular opposition; ▪ High capital costs; ▪ High labor cost due to operation of numerous equipment for RDF preparation; ▪ Some landfilling still required; ▪ Physical processing energy consumptive, decreasing net electricity produced and electricity sales revenue; and ▪ Additional facility required to produce RDF.

3.2.1.3 Gasification

Gasification is the partial oxygenation of carbon-based feedstocks to generate syngas. Similar to pyrolysis, except that air or steam is added to promote gasification, forming carbon monoxide, hydrogen, and methane. In a high temperature gasification process, ash is converted to molten slag, which is subsequently quenched. Syngas can be used for power generation or as a feedstock for synthetic fuels or chemicals.

The use of gasification technology began in the 1970s with capacities of less than 10 tpd, of which none are still operating. The use of unprocessed MSW resulted in many mechanical issues with frequent shut downs and scaling up capacities were not successful. Since the 1990s, methods of MSW pretreatment and production of RDF have reduced reactor problems. Fluidized bed reactors have also become more common, which allow for use of relatively lower temperatures (1,300° F to 1,400° F) and use of more readily available construction materials. Despite improvements in the industry, and various vendors operating globally, the use of gasification for MSW has not been demonstrated on a commercial scale outside of Japan, which has the highest landfill tipping fees in the world.

One of the leading waste gasification plant manufacturers are Nippon Steel Engineering, primarily operating in Japan. Reportedly the Shin-Moji Plant in Kitakyushu City, Japan, which is presented in **Picture 5**, has a capacity of up to 30 tons per hour (tph) and has been operating since 2007. In 2009, the Narumi Plant in Nagoya City, Japan began operation for co-gasification of bottom ash and MSW. The most recent waste gasification plant in operation by Nippon Steel is the Kitanagoya Plant commissioned in 2020, which claims to have a capacity up to 28 tph[13]. Nippon Steel operates multiple plants with capacities ranging from 10,000 to 230,000 tons per year (tpy) and have scaled up some of their facilities to increase capacity.

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[13] https://www.hzi-steinmueller.com/wp-content/uploads/downloads/broschure-waste-gasification-en.pdf

Picture 5. Shin Moji Incineration Facility in Kitakyushu by IGES

The Canada based company, Enerkem, has a 25-year agreement with the City of Edmonton in Alberta, Canada to process more than 100,000 tons of waste per year. The Enerkem Alberta Biofuels plant, which is presented in Picture 6, generates 10 million gallons per year of methanol and ethanol. The facility is expected to allow the City of Edmonton to reach a 90% diversion rate of residential waste[14]. The facility processes sorted MSW and biomass. The MSW is sorted by removing carbon-based materials and recyclables, leaving dirty cardboard, plastics, Styrofoam, and anything else besides metal[15]. The sorted MSW is dried and transported to the facility for gasification.

Picture 6. Enerkem Alberta Biofuels Facility by Enerkem

In Florida, a private gasification facility, known as the Indian River BioEnergy Center, was commissioned in Vero Beach with the intent of using yard waste to produce ethanol commercially. The facility was constructed and operated by INOES with funding by the U.S. Department of Energy (DOE) and more than $120 million in taxpayer subsidies[16]. In 2017, the Indian River BioEnergy Center closed, reportedly due to multiple technical problems following years of inconsistent production. In a report published by the U.S. DOE in 2016, problems included greater than predicted moisture in wood feedstock that diluted the syngas and various equipment and power failures.

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[14] https://www.ourenergypolicy.org/wp-content/uploads/2014/07/alternative.pdf

[15] https://edmontonjournal.com/business/local-business/five-minutes-from-trash-to-ethanol-edmontons-long-delayed-enerkem-plant-explained

[16] https://www.tcpalm.com/story/news/2017/01/17/ineos-closes-vero-beach-biofuel-plant/96412616/

A process flow diagram for gasification facilities is presented in **Figure 3**, which is followed by **Table 9**, which presents a summary of attributes associated with gasification thermal conversion.

Figure 3. Process Flow Diagram for Gasification (typical)

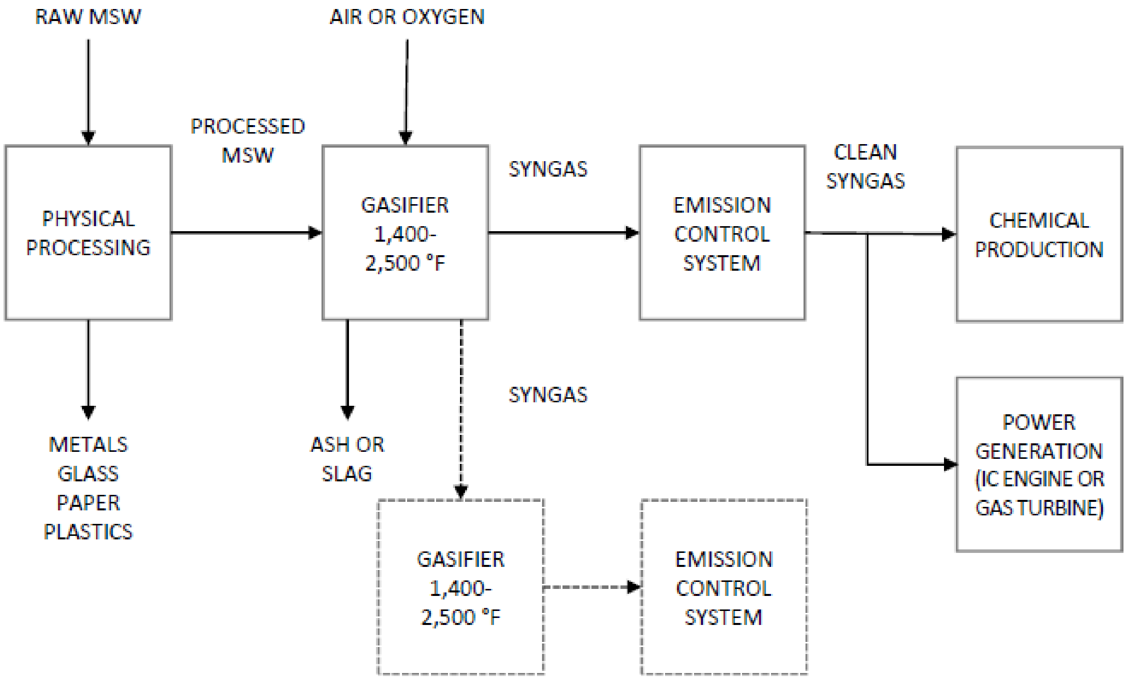

Table 9. Attribute Summary for Gasification

Status	Emerging
Location(s)	Japan and Canada
Typical Tipping Fee Range	Unknown
Processing Capacity	<300 tpd[1]
Pros	▪ Byproducts may have significant reuse potential such as syngas or liquids (light petroleum oils); ▪ High temperature gasification yields residue materials which have significant beneficial reuse; and ▪ Can be combined with other technologies (e.g., pyrolysis, plasma arc) to increase processing capabilities.
Cons	▪ Gasification was attempted during the early 1980s, but failed due to operational difficulties associated with the heterogeneity of MSW feedstocks; ▪ Constant delays in the construction of facilities – Hampden, Maine

	▪ Requires significant pre-processing to remove inorganic materials; ▪ Some landfilling still required; ▪ Syngas byproduct may require steps to remove impurities. These steps produce air emissions and solid residues; ▪ Often includes shredding, screening, air classifiers, drying, and ferrous and non-ferrous metal removal; and ▪ While high temperature gasification has shown technical success, it is very expensive (capital and O&M costs).

[1]Based on Edmonton waste capacity.

3.2.1.4 Pyrolysis

Pyrolysis is an endothermic process that requires a source of heat to initiate the thermal reaction. These systems typically use drums, kiln structures, or tubes, which are externally heated in an oxygen free system. Pyrolysis systems operate at a range of temperatures between 750° F and 1,650° F depending on the feedstock and desired byproducts. At higher temperatures, syngas is produced and is potentially reusable as a combustion fuel or as a heat source for the pyrolytic process. At lower temperatures, liquids or oils are more readily produced.

Recently in the U.S., efforts are being made to scale pyrolysis by a company based in California[17]. The first project is a facility in Vermont expected to start operations in early 2024. Their focus is currently small- and mid-sized projects with biomass feedstocks.

A process flow diagram for pyrolysis facilities is presented in **Figure 4**, which is followed by **Table 10**, which presents a summary of attributes associated with pyrolysis thermal conversion.

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[17] Clean Energy Technologies, newly public, is working to scale pyrolysis in the United States | Waste Dive

Figure 4. Process Flow Diagram for Pyrolysis (typical)

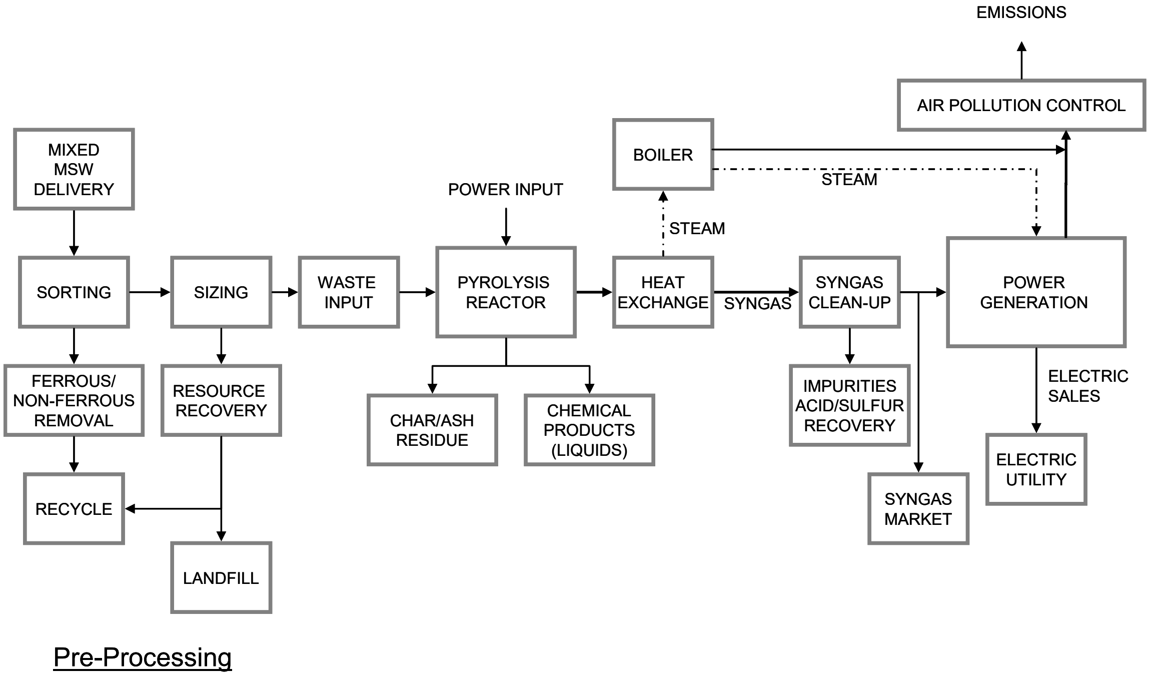


Table 10. Attribute Summary for Pyrolysis

Status	Emerging
Location(s)	Wisconsin, Finland, and Canada
Typical Tipping Fee Range	Unknown
Processing Capacity	<50 tpd
Pros	▪ Byproducts may have significant reuse potential such as syngas or liquids (light petroleum oils); and ▪ Can potentially handle mixed MSW.
Cons	▪ Heterogeneity of MSW feedstock presents problems in desired byproducts; ▪ Requires some pre-processing of MSW feedstock; ▪ The need to remove the char or solid residuals after cooling may interrupt the pyrolytic process and negatively impact operational efficiencies; ▪ Some landfilling still required; if the carbonaceous char is not allowed to be landfilled, char gasification may be required; ▪ Important to render MSW feedstock to a homogenous organic mixture; ▪ Important to remove all inorganic materials (glass or grit) from the feedstock because the inorganic fraction consumes energy; and ▪ Syngas byproduct may require steps to remove impurities. These steps produce air emissions and solid residues

3.2.1.5 Plasma Arc

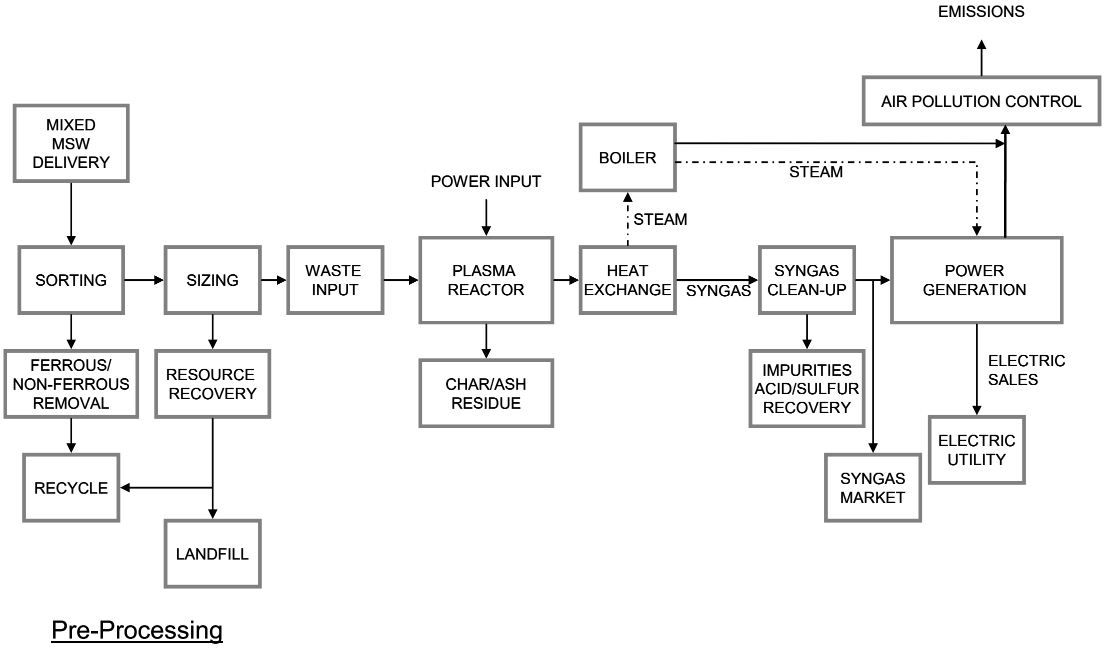
Plasma arc converts select waste streams to slag. The plasma arc system uses electrical current between two electrodes (the arc) to heat a gas (usually air, oxygen, nitrogen, argon, or a combination) to temperatures of tens of thousands of degrees Fahrenheit within the plasma reactor. The heated and ionized plasma gas is then used to treat the feedstock. Coke and lime are often added to the reactor to provide a more reducing atmosphere and to stabilize the slag. Byproducts include syngas and slag.

The use of plasma arc can achieve high levels of material volume reduction, however, achieving the high temperatures for operation require high power needs. The intensive nature of the process also leads to frequent replacement of parts as they are spent and eroded. Operation and maintenance costs can be expensive and the repairs can require specialized experts that may not be readily available, which can potentially cause long shut downs.

Current applications are limited to small-scale plants, some even constructed as transportable systems. The technology in North America is primarily used for small communities or military bases. In Boston, the company Ze-Gen, invested in plasma technologies. However, there was opposition to a proposed plant in Attleboro, Massachusetts, and in 2011, the company stopped its development efforts[18].

A process flow diagram for plasma arc facilities is presented in **Figure 5**, which is followed by **Table 11**, which presents a summary of attributes associated with plasma arc thermal conversion.

Figure 5. Process Flow Diagram for Plasma Arc (typical)



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[18] https://www.thesunchronicle.com/news/ze-gen-drops-plans/article_58a44eec-a6b8-5c0a-a3b6-182079c01a35.html

Table 11. Attribute Summary for Plasma Arc

Status	Developing
Location(s)	Japan and China
Typical Tipping Fee Range	Unknown for MSW
Processing Capacity	Unknown
Pros	▪ Syngas byproduct can be used as a fuel or discharged to a boiler for steam production/energy recovery; and ▪ Vitrified slag byproduct may be reusable depending on market availability
Cons	▪ Use of plasma arc has not been commercially demonstrated for MSW processing; ▪ Some landfilling still required for ash residue; ▪ Market for byproducts unstable or untested; and ▪ High capital and operating costs.

3.2.1.6 Plasma Arc / Gasification

Plasma arc / gasification includes plasma as the initial step with the solid residue discharged to a gasification reactor. The molten residue from the gasification process is typically discharged to a water bath and quenched to form a glassy, slag material. The syngas produced can be used as a heat source to be processed through a boiler for steam generation and electricity production or as a fuel. Plasma arc gasification can treat hazardous and medical wastes as well as MSW. In the process diagram, multiple potential streams of revenue are shown that include tipping fee for waste, sale of syngas, and electricity sale.

The process is able to effectively achieve a high level of destruction and waste reduction; however, there are still residues that would require disposal. Depending on the processing and power generation utilized, the volume of residues can vary. Commercial use is typically limited to feedstock of biomass, hazardous, or medical wastes. The facilities currently in use can process up to 100 tpd.

Large scale commercial plants have not proven to be successful. Although several attempts have been made and were cancelled during the design and permitting phase and /or after experiencing technical issues during the construction phase. In 2016, the construction of two (2) adjacent plasma arc gasification plants in Tees Valley, United Kingdom, was cancelled[19]. Each facility was designed to process 1,000 tpd, and it is estimated that the first facility had cost about $500 million to construct. During the final stages of commissioning the first facility, it was determined that additional design and operational changes would be required prior to commissioning. The company decided not to continue construction due to the estimated additional time and costs.

In Japan, several plasma arc gasification facilities have been constructed and were successful. In 1999, a pilot plant was constructed in Yoshii, Japan, with a capacity of 150 tpd. The plant was decommissioned after the pilot program ended in 2004. In 2002, a plant with the same MSW

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[19] Air Products shuts down Tees Valley development | Resource.co

capacity was constructed in Utashinai City; however, it was closed in 2013. Reportedly the plant was closed due to increases in recycling efforts that reduced the MSW supply to the plant[20].

A process flow diagram for plasma arc/ gasification facilities is presented in **Figure 6**, which is followed by **Table 12**, which presents a summary of attributes associated with plasma arc/ gasification thermal conversion.

Figure 6. Process Flow Diagram for Plasma Arc / Gasification (typical)

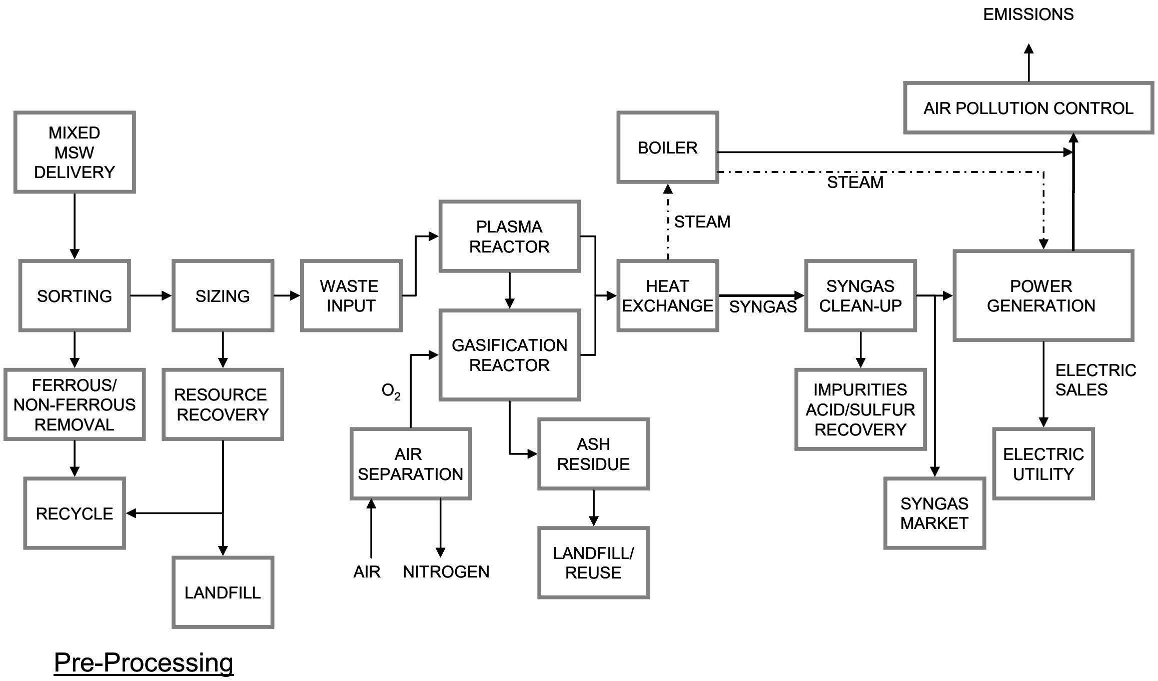

Table 12. Attribute Summary for Plasma Arc / Gasification

Status	Developing
Location(s)	United States, Canada, Japan, Italy, India, China, and Spain
Typical Tipping Fee Range	Unknown for MSW
Processing Capacity	<200 tpd
Pros	▪ The process' thermal efficiency is attractive in continuous feed systems; and ▪ Effectively treats some hazardous and medical wastes as well as mixed MSW.
Cons	▪ Energy consumptive and expensive to operate; ▪ Project economics are largely dependent on the systems revenues to offset operational costs; ▪ Some landfilling still required;

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[20] http://energy.cleartheair.org.hk/?p=1851

	▪ Requires some form of preprocessing; ▪ Technology unproven for processing mixed MSW at this point; ▪ High capital and operating costs; and ▪ Market for byproducts unstable or unknown.

3.2.1.7 Pyrolysis/Gasification

Pyrolysis can be supplemented by gasification to further process and recover energy from the Pyrolysis residues. Pyrolysis is the initial step with the char or solid residue discharged into a gasification reactor. The liquid residue from the gasification process is typically discharged to a water bath and quenched to form a glassy, slag material. The off-gas from this process can be used as a heat source to be processed through a boiler for steam generation and electricity production or as fuel or syngas.

A process flow diagram for pyrolysis / gasification facilities is presented in **Figure 7**, which is followed by **Table 13**, which presents a summary of attributes associated with pyrolysis / gasification thermal conversion.

Figure 7. Process Flow Diagram for Pyrolysis / Gasification (typical)

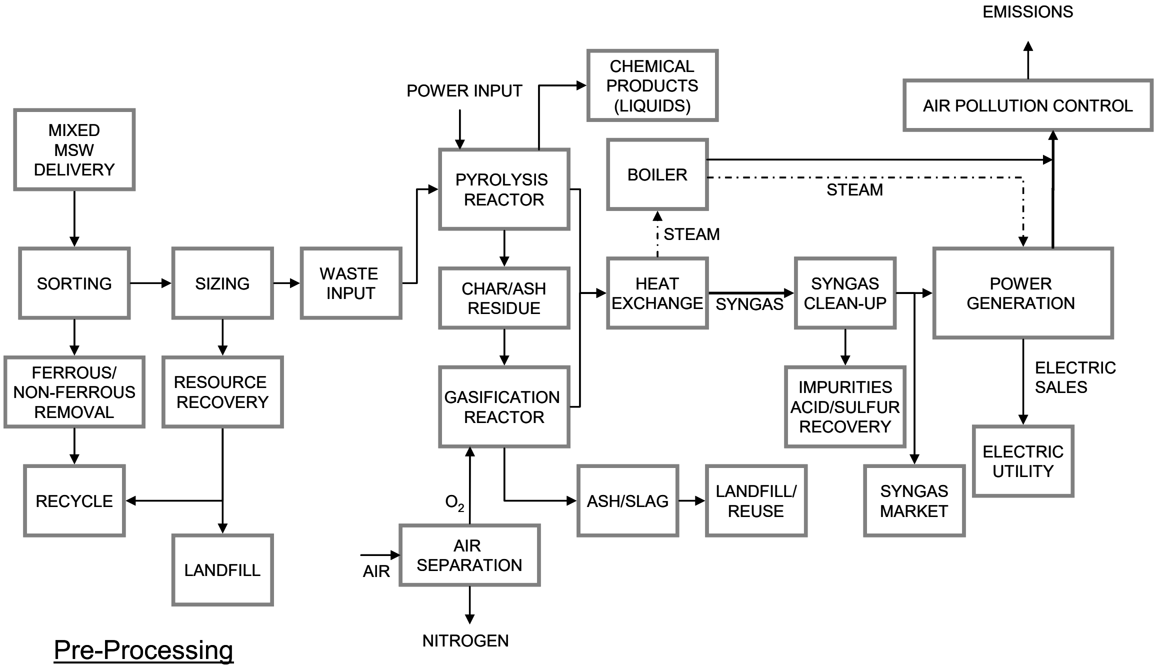


Table 14. Attribute Summary for Pyrolysis / Gasification

Status	Developing
Location(s)	Germany
Typical Tipping Fee Range	\$50 - \$125+
Processing Capacity	~240 tpd
Pros	▪ Byproducts may have significant reuse potential such as syngas or liquids (light petroleum oils).
Cons	▪ Heterogeneity of MSW feedstock presents problems in desired byproducts; ▪ Requires some pre-processing of MSW feedstock; ▪ The need to remove the char or solid residuals after cooling may interrupt the pyrolytic process and negatively impact operational efficiencies; ▪ Some landfilling still required; ▪ Important to render MSW feedstock to a homogenous organic mixture; ▪ Important to remove all inorganic materials (glass or grit) from the feedstock because the inorganic fraction consumes energy; and ▪ Syngas byproduct may require steps to remove impurities. These steps produce air emissions and solid residues.

3.3 COMPOSTING AND DIGESTION-SOURCE SEPARATED ORGANICS

Composting and anaerobic digestion represent two key methods for recycling organic waste, each utilizing distinct processes to manage organic materials and produce valuable end-products.

Composting is a natural, aerobic process that transforms organic matter—such as food scraps, yard waste, and leaves—into a nutrient-rich soil amendment. This process relies on microorganisms to decompose organic materials in the presence of oxygen, resulting in compost. This valuable end-product can be used to enrich soil and support plant growth, reduce waste sent to landfills, and mitigate greenhouse gas emissions by diverting organic waste from landfill disposal.

Anaerobic digestion, in contrast, occurs in an oxygen-free (anaerobic) environment. This process breaks down organic waste into biogas, primarily composed of methane, which can be purified and refined into renewable natural gas. Anaerobic digestion not only offers an alternative energy source but also diverts organic waste from landfills, reducing GHG emissions and contributing to a more sustainable waste management system.

Mulch Colorization Facilities have become relatively common over the last 25 years as composters and producers of soil amendments have successfully implemented value added approaches to increasing their marketplace for recycled organic materials. There are several equipment providers who supplier colorizing equipment that enables hundreds of thousands of additional tons to be marketed. Overall, the 2024 annual sales for mulch were nearly $100 M nationally and its growth is expected to continue for the next twenty years at a rate of 7% or greater annually.

3.4 RECENT TRENDS AND TECHNOLOGICAL ADVANCEMENTS IN ORGANICS MANAGEMENT

Technological innovation is driving advancements in the processing of organic waste, improving efficiency, scalability, and the environmental performance of composting and anaerobic digestion systems. These advances include innovations in feedstock preparation, process optimization, and end-product quality. **Table 14** presents some of the latest technological developments, their timelines, and their applicability to managing source-separated organics. While the option identified in **Table 14** focus on larger scale approaches, the Task 4 White Paper identifies options for backyard composting as well as community-based composting opportunities.

Table 15. Organics Management Technology Overview

TECHNOLOGY	TYPE	DESCRIPTION	TIME TO FINISHED PRODUCT	APPLICABILITY TO SOURCE-SEPARATED ORGANICS
Depackager	Screw Press/ Vortex/Paddles/ Pulper/Hammer/ Screens	Various technologies are used to separate the organic and inorganic fractions of food waste and the associated packaging.	N/A	Front end technology to improve feedstock quality.
Windrowing	Outdoor open air	Organic material is mixed and formed into long rows. Material is periodically turned and mixed.	3-9 months	Commonly used for agricultural and yard waste, best suited for low amounts of food waste (<15%). Simple and lower cost to implement but require more area for piles and labor for turning which is required to maintain sufficiently high temperatures to destroy pathogens. Turning piles can release odors so “best practices” for odor and vector prevention need to be followed.
Aerated Static Pile (ASP) with biofiltration or Covered Aerated Static Piles (CASP)	Outdoor or indoor, System	Organic materials are placed in static piles and. Air is forced (either up or drawn down) through the piles using blowers to maintain microbial activity, reducing the need for turning.	4-6 weeks	ASP allows for faster degradation and requires less area. Popular for food and organic waste processing. Food waste and yard waste are combined with a bulking agent (wood chips) as needed to balance the carbon-to-nitrogen ratio

TECHNOLOGY	TYPE	DESCRIPTION	TIME TO FINISHED PRODUCT	APPLICABILITY TO SOURCE-SEPARATED ORGANICS
		Biofiltration can be provided by a layer of carbonaceous material, such as wood chips or compost, on top of the piles or a semi-permeable fabric cover can be used. Both increase efficiency by trapping heat and moisture and reduce odors and limit attraction of vectors.		(C: N). Follow "best practices" for most efficient breakdown. ASP systems are often used in large-scale and MSW composting applications because of breakdown efficiency with biofiltration or CASP used to limit odor, VOC and other airborne pollutants.
In-Vessel Composting	Outdoor or indoor, System	Organic material is fed into a "vessel", often a barrel, drum or trench, where it is agitated, rotated or otherwise turned until initial decomposition has occurred. Can be batched or continuously fed.	1-3 weeks	Offers a controlled environment, low space, efficient and rapid degradation. A significant curing period is usually required for full organic stabilization. Common in industrial applications, it accommodates animal products. Contamination can be a problem because pre-processing often includes size reduction, thereby creating difficulties for contamination removal.
Anaerobic Digestion (AD)	Outdoor enclosed anaerobic	Organic material is warmed and mixed in a closed, airtight tank. Microorganisms break down or "digest" organic material without the presence of oxygen, producing biogas, a renewable fuel and a nutrient rich effluent (digestate). Biogas can be used to generate electricity, for combined heat and power or increasingly to produce renewable	15-30 days	Historically, AD was reserved for industrial or commercial food waste recovery. These materials allow for proper "feeding" to maintain process stability. However, digestion of household and institutional food waste and residential SSO is gaining popularity. The process requires low solids content (10-14%) sometimes needing additional dilution. Variability of nutrients, energy content, etc. and reliable supply of

TECHNOLOGY	TYPE	DESCRIPTION	TIME TO FINISHED PRODUCT	APPLICABILITY TO SOURCE-SEPARATED ORGANICS
		natural gas. Financial incentives through the Renewable Fuel Standard and California's Low Carbon Fuel Standard (LCFS) are often available to assist in monetizing this recovery approach.		SSO can create instability in the digestion process. Not a solution for high lignin materials (e.g., yard waste) and compostable food service ware can cause issues. Digestate management can be challenging. Recent concerns are being raised over PFAs content that may impact land application.
Co-Digestion at WWTP	At Wastewater Treatment Plant	Organic waste is added to WWTP digesters with excess capacity. Biogas production can be used to power the treatment process, generate heat and electricity or produce renewable natural gas. Liquid digestate can be reintroduced into the digestion process, dewatered, treated for nutrient recovery and discharged. WWTP capital modifications vary from plant to plant depending on tipping and screening infrastructure needs as well as biogas treatment and utilization requirements.	15-30 days	Ideal for high-energy feedstocks such as fats, oils or greases (FOG) with high biomethane potential, where the wastewater sludge can provide buffering to provide steady PH. Low solids industrial food waste is also well suited. Increasingly SSO is also being co-digested. Not a solution for yard waste or large amounts of lignatious compostables.
Biochar	Outdoor or vessel kiln	Biochar is a carbon rich material produced through pyrolysis: where organic material, such as yard waste, food scraps and other organics are inputs. During the high		Carbonaceous materials are particularly well suited for biochar such as yard waste, disaster debris and food scraps. Solid separated digestate from anaerobic digestion can also be used as biochar feedstock.

TECHNOLOGY	TYPE	DESCRIPTION	TIME TO FINISHED PRODUCT	APPLICABILITY TO SOURCE-SEPARATED ORGANICS
		temperatures, low oxygen process, volatile compounds are released leaving behind a stable form of carbon with a porous structure. The sequestration of the carbon stored in the biochar provides a carbon benefit and can be eligible for carbon offset markets. Biochar has many properties that lend themselves to a variety of applications including soil amendment, filtration, PFAS stabilization and construction material substitution.		Biochar is commonly added (5-10% by volume) to compost to increase its value as a soil amendment. There is evidence to suggest that the pyrolysis process mitigates PFAs risk. The potential for biochar applied as ADC to mitigate methane emissions (through oxidation and/or adsorption) is also being investigated.

These technological advances not only improve the operational efficiency of composting and anaerobic digestion facilities and provide additional revenue stream, but they also support climate goals by reducing greenhouse gas emissions, diverting organic waste from landfills, and generating renewable energy sources. Additionally, improved sorting and processing enhance the quality of end-products, meeting the increasing demand for high-value organic products like premium compost and biogas.

These approaches are especially beneficial for source-separated organics, allowing municipalities and private operators to better capture organic waste streams, improve waste diversion rates, and contribute to circular economy goals. As these innovations become more cost-effective and scalable, they will likely become integral to modern organics management systems.

3.5 BIOGAS FROM ANAEROBIC DIGESTION

Renewable natural gas (RNG) produced through Anaerobic Digestion (AD) offers versatile applications across sectors, supported by favorable economics through carbon credits, offsets, and incentive programs. RNG includes the further refinement of biogas generated through the AD process to remove carbon dioxide and contaminants (i.e., siloxane, hydrogen sulfide, etc.) to produce RNG that is equivalent in heating value to natural gas. RNG can also be liquified to produce liquid natural gas (LNG). The growth of RNG in a carbon-conscious market not only mitigates emissions but also contributes to circular economies by repurposing organic waste into valuable energy resources (Zaghdoudi, 2021). Use pathways for RNG include the following (US EPA, 2024):

- **Electricity off-site**- Early utilization of biogas in the US included a significant portion of electricity generation and grid interconnection, supporting renewable portfolio standards (RPS) and grid decarbonization goals. However, the emergence of more favorable federal and state incentives has ushered a shift to renewable natural gas (RNG).

- **Transportation Fuel** – RNG can be used as fuel, as compressed natural gas (CNG) or liquified natural gas (LNG) in vehicles particularly in heavy-duty applications where electrification is challenging, such as long-haul trucks and buses. RNG utilization helps entities (both public and private) comply with low-carbon fuel standards and GHG reduction targets and reduce tailpipe emissions. Big fleet operators (important to the waste and recycling sector) are adopting RNG. RNG exported to the pipeline can also be utilized for the vehicle fuel market or it can be utilized locally which avoids the need to meet natural gas pipeline specifications (meeting vehicle fuel specifications are often less stringent).

- **Pipeline Injection** - RNG can also be injected into existing natural gas pipelines or dedicated RNG pipelines, helping meet energy demands with renewable energy. The RNG must meet the specifications of the receiving gas utility and can be received at the point of injection by a custom pipeline (virtual pipeline), truck or pipeline extension. Pipeline injections reduce carbon intensity of existing gas supplies, enabling some entities to meet their Renewable Portfolio Standards. Under the Renewable Fuel Standard (RFS) program, upgraded RNG produced from MSW or SSO that is injected into the pipeline can generate D3 Renewable Identification Number (RIN) that can be traded-. Every equivalent gallon of renewable fuels is assigned a RIN at its point of generation or origination. These RINs function similar to the way that renewable energy credits work in the generation and trading of renewable electricity. RINs can be traded between parties, bought as attached RINs to fuel purchased, and/or bought unattached on the open market.

- **Onsite Power and Heat Generation**- Using AD biogas or RNG for in-house electricity requirements or thermal demands enables another pathway to capture value capture. Electricity produced through onsite generation or combined heat and power RNG can directly replace fossil-derived natural gas in WWTP or industrial processes requiring high thermal energy, such as cement, steel production, and chemical manufacturing. Heavy industry is incentivized to switch to low-carbon fuels, and RNG adoption can be supported by subsidies and carbon credits.

3.6 BACK-END RESIDUAL PROCESSING OF SEPARATED ORGANICS FOR BENEFICIAL REUSE (FUEL, SOIL HEALTH, LANDFILL COVER)

Products derived from source-separated composting (aerobic digestion) typically target high-value markets that prioritize superior soil fertility enhancement. Soil markets value compost for its ability to provide essential nutrients, improve water-holding capacity, and promote soil health. Finished materials produced from clean, high-quality, largely uncontaminated feedstocks are especially valuable. While most composting facilities utilize back-end screening devices to remove contaminants and oversized materials, the most important efforts to maintain material cleanliness occur at the point of generation. Users of the system are responsible for removing contaminants—such as plastic bags, paper, and rigid plastics—before they enter the composting mass.

Finished compost products derived from this process are often used as growing media for a variety of applications, including lawns, shrubs, flowers, vegetable gardens, truck farms, and indoor plants. When contamination levels are too high for these uses, it typically indicates a need for improved system user education to ensure proper separation of contaminants at the outset.

The effluent from anaerobic digestion is often separated into digestate solids (about 10%) and liquid digestate (90%). Additional stabilization processes are necessary for the separated digestate solids. Composting is the most common and effective method for achieving this type of stabilization. Liquid digestate, is nutrient rich, containing nitrogen, phosphorus, and potassium and can be used as an organic liquid fertilizer. Land applications of digestate has been a widely practiced method in certain regions for many years. It can also be processed for nutrient recovery to produce concentrated fertilizer products that can be sold.

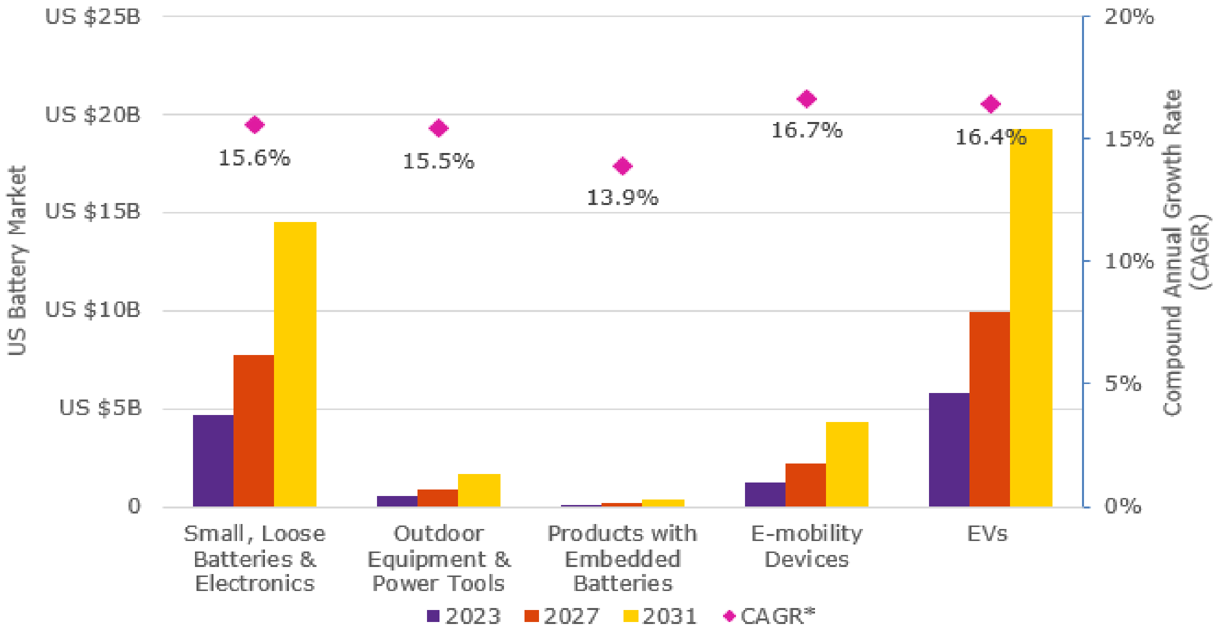
Alternative methods of beneficial reuse — such as utilizing solid digestate as fuel, applying it as landfill cover—are generally considered less advantageous. These methods are typically less economically viable and do not capture the nutrient value contained in the digestate. Thus, the focus remains on utilizing stabilized compost and digestate for their ability to improve soil health, support agricultural productivity, and enhance sustainable resource recovery.

3.7 REDUCING OR IDENTIFYING NEW AND EMERGING BENEFICIAL REUSE OPPORTUNITIES FOR PROCESS RESIDUE

3.7.1 New and Emerging Battery Management Practices and E-Waste Recovery

The rapid growth in battery sales across all sectors reflects the increasing demand driven by technological advancements, consumer preferences, and shifting regulatory and policy requirements. Market analysts project that all battery types addressed in this roadmap will experience an average annual growth rate exceeding 15% over the next seven years, underscoring the ongoing expansion of the production market, technological advancements, consumer demands, and regulatory and policy requirements (Data Bridge Market Research, 2022). **Figure 8** presents the projected marketplace trajectory by battery type.

Figure 8. Marketplace by Battery Type (Data Bridge Market Research, 2022)



** The Compound Annual Growth Rate (CAGR) shown reflects the average projected growth rate from 2023 to 2031, as calculated by Data Bridge Market Research. This figure is based on current market values and future market forecasts.*

The rapid growth in battery sales across all sectors reflects the increasing demand driven by technological advancements, consumer preferences, and shifting regulatory and policy requirements. Market analysts project that all battery types addressed in this roadmap will experience an average annual growth rate exceeding 15% over the next seven years, underscoring the ongoing expansion of the production market and innovation in battery technologies (Data Bridge Market Research, 2022).

However, improper handling and disposal of batteries—regardless of type—pose significant environmental and safety risks. Each year, approximately 5,000 fires are reported at Material Recovery Facilities (MRFs) due to mishandled lithium-ion batteries. These incidents result in worker injuries, facility shutdowns, damage to recycling equipment, increased insurance premiums (with rates rising by as much as 5,000%), and financial losses (NWRA, 2024). Such statistics highlight the critical need for improved battery management practices and the implementation of comprehensive recycling strategies.

To address these challenges, recycling systems must focus on proactive solutions, including the development of new and emerging battery management and e-waste recovery technologies. Innovations such as advanced sorting mechanisms, AI-driven identification tools, and improved collection infrastructure can enhance the recovery rates of lithium-ion and other battery types while minimizing safety risks. Additionally, expanded awareness and education programs targeting consumers and MRF operators are essential for ensuring proper recycling and handling of used batteries.

E-waste recovery represents another critical opportunity. As the volume of discarded electronic devices continues to rise—spanning smartphones, laptops, electric vehicles, and other battery-dependent technologies—systems that incorporate effective recycling methods for e-waste can reduce landfill burdens and recover valuable resources. Emerging battery recycling technologies, such as hydrometallurgical and direct recycling methods, are being deployed to improve recovery rates for critical metals, including lithium, cobalt, and nickel, which are essential for battery manufacturing.

Furthermore, regulatory efforts, including extended producer responsibility (EPR) programs and policies designed to incentivize battery recycling, are creating pathways for systemic change. These strategies can align financial responsibility with battery manufacturers and encourage innovative design improvements, such as the development of modular battery designs and improved product longevity.

Ultimately, while improperly managed batteries and e-waste pose environmental and operational risks, the expansion of technological advancements and strategic recycling opportunities can turn these challenges into avenues for resource recovery and innovation. Coordinated efforts across policy, technological development, and public awareness will be essential for improving both battery management practices and e-waste recovery systems.

3.7.2 Textile Recovery Optimization

In the area of textile recovery, the application of technology is one of the components needed to bridge the sorting-for-recycling infrastructure gap. It is worth highlighting that the textile sorting and grading industry is largely exported and the Authority's location in Southern Florida, with its proximity to ports, is especially well suited to building textile sorting capacity. The region plays a significant role in the secondhand textiles trade due to its strategic geographic location as a gateway to Latin America and the Caribbean, robust shipping infrastructure, and established aggregation and brokerage market for secondhand textiles.

Sorting technology solutions range from handheld and table-top Near-Infrared (NIR) devices to industrial scale sorting lines using hyperspectral imaging, artificial intelligence (AI), image recognition, and machine learning to make the sorting process quick, efficient, and accurate to meet end market requirements for recycling. The aim of these technologies is to sort non-reusable textiles by fiber type for recycling end markets. Technology tailored for reuse sorting is nascent but expected to develop quickly. Projects like Fashion for Good's Rewear Project tests automated sorting technologies using machine learning and artificial intelligence (AI) to identify color, style, garment type, and quality to enable more efficient sorting for reuse. Established equipment manufacturers and technology companies currently exploring automated sorting for textile recycling include Tomra Textiles, Valvan Baling Systems, Pellenc, PicVisa, Andritz, and Trinimax. Furthermore, there are many new startups, such as Matoha, Sortile, Refiberd, circular.fashion, and HKRITA Sorting that are testing means to identify specific fiber types, detect color, remove disruptors (metal detection), and reduce textile sizes.

Digital product passports and digital IDs are another area of innovation and interest in the textile reuse and recycling sector and their use is soon to be required in new products in the EU. However, questions remain about how widely brands will adopt digital IDs, the variety of hardware solutions that will be deployed, which information will be housed in the passport, and how the industry will integrate digital readers in the sorting process.

Automated sorting technology is being piloted in select US-based textile sorting facilities. Receptivity to this technology may increase with the passage of textile EPR laws like the one passed in 2024 in California. However, capital cost and unit economics remain a hurdle.

Assuming most of Broward's textile waste is from the post-consumer segment of the supply chain, most of what is collected would be for domestic resale and/or exported. To date, textile recyclers require controlled feedstock streams like post-industrial offcuts with known compositions to hone their technologies rather than post-consumer materials, that are much more varied and complex. This is expected to continue given chemical recyclers are mostly still at lab scale and focused on testing, proving, and developing their technical capabilities.

3.8 ADVANCED RECOVERY SYSTEMS FOR GASSES, ASH OUTPUT, BIOLOGICAL DIGESTION, ETC.

3.8.1 Advanced Recovery Systems for Gasses

This section on advanced recovery systems for gasses is focused on recovery of GHG, otherwise known as carbon capture. The U.S. EPA determined that WTE facilities inherently reduce GHG emissions due to their diversion of methane-generating waste from landfills and offset fossil fuel usage due to the energy produced (Kaplan et al., 2009). In addition, further GHG reductions may be realized depending on the distance to landfills and the reduction in waste transport-related GHG generation using fossil fuels. However, since WTE facilities do still emit carbon dioxide, further advanced recovery systems for carbon capture are being developed, pilot-tested, and advanced for potential full-scale operation, similar to the trends in the fossil fuel power generation facilities industry.

The following represent two methodologies for advanced recovery of gasses (carbon capture):

- Post-combustion carbon capture from flue gas.
- Direct air carbon capture for use as an offset.

3.8.1.1 Post-Combustion Carbon Capture from Flue Gas

The first methodology involves removing and sequestering flue gas CO_2 at the WTE facility directly from the flue gas stream prior to emission to the atmosphere. This is typically done by intercepting or performing a slipstream and sectioning off a portion of the flue gas prior to the stack. The flue gas is run across a series of chemicals to remove GHG from the gasses prior to reintroduction back to the stack for emissions. The most common removal technology involves amine stripping to remove the GHG from the gas stream. Additional steps are needed to remove the GHG from the amine stream so that the GHG can be re-used at an available market or sequestered.

The following represents some existing or planned post-combustion carbon capture technologies projects that remove CO_2 from the flue gas of a WTE facility:

- AVR WTE Facility (Duiven, Netherlands) - The Duiven facility CO_2 capture plant commenced operation in August 2019 with the first commercial supply of CO_2 to partner Air Liquide (SWANA ARF, 2023).
- Twence Holding Plant (Netherlands) - In 2014, Twence began operating the world's first system to capture CO_2 from a waste-to-energy plant. In 2022, Twence began building a modular carbon capture plant to clean flue gases at its Hengelo WTE Facility (SWANA ARF, 2023).
- Filbornaverket, a waste-fired combined heat and power (CHP) plant (Helsinborg, Sweden)

- The Öresundskraft AB's Innozhero carbon capture and storage (CCS) project in Helsinborg, Sweden, will receive 54 million euro in funding from the European Union (EU) with plans to be operational by 2026 (Sherrard, 2024).
- Herambiente Ferrara WTE Plant in Italy – Saipem's Bluenzyme technology will be used at this facility for carbon capture as a first of its kind in Italy for a WTE facility (SAIPEM, 2024).
- Klemstrud WTE CHP, Norway - City of Oslo and Fortum Oslo Varme entered into an agreement to ensure full financing of a carbon capture plant at Klemetsrud, which is scheduled for commercial operation in 2026 (Les pressemeldingen på norsk, 2022).
- Reworld Hillsborough, Hillsborough County, FL – The County partnered with a South Korean firm, LowCarbon, in 2024 to conduct a 60-day pilot to capture one (1) ton of CO_2 daily out of the 600 tons emitted daily from the flue gas stream and convert it to calcium carbonate powder, which could then be marketed for construction products. The pilot cost was covered by LowCarbon and was successful. The County, however, has chosen not to continue with further collections due to the $25 million price tag to install a larger unit that could capture somewhere between 100 and 400 tons of CO_2 per day (Prator, 2024).

3.8.1.2 Direct Air Carbon Capture for Use as an Offset

The second methodology involves removing atmospheric CO_2 at a facility directly from the atmosphere via large fans that pull atmospheric air into the process. The atmospheric air is run across a series of chemicals to remove GHG from the air prior to reintroduction back to the atmosphere. The most common removal technology involves amine stripping to remove the GHG from the air. Additional steps are needed to remove the GHG from the amine stream so that the GHG can be re-used at an available market or sequestered.

While there are no direct air capture facilities currently in use with WTE facilities, several direct air capture (DAC) pilot facilities have been demonstrated such as the Carbon Engineering, also called 1PointFive, facility in Vancouver, Canada for CO_2 removal from air. The air-cleaning technology would be housed and powered directly onsite and used to directly offset flue gas GHG emissions in lieu of direct flue gas cleaning, which is considerably more complicated. The calcium carbonate tablets produced in a DAC system such as the Vancouver technology are removed and could either be sold as a revenue stream or directly sequestered if needed to comply with regulations.

Multiple commercial examples of DAC are currently under construction in the U.S. and abroad and the U.S. Department of Energy (DOE) is currently providing funding assistance for several distinct technologies to perform DAC. Two (2) examples of DOE-funded DAC facilities are Project Cypress, a Climeworks Corporation and Heirloom Carbon Technologies project in Louisiana, and the South Texas DAC Hub, a 1PointFive project in Kleberg County, TX. Neither facility is commercial yet, but both vendors have functional pilot-scale DAC facilities in other locations (USDOE, 2023).

Direct air capture facilities have been demonstrated such as in Vancouver, Canada for CO_2 removal from air. The air-cleaning technology would be housed and powered directly onsite and used to directly offset flue gas GHG emissions in lieu of direct flue gas cleaning, which is considerably more complicated. The calcium carbonate tablets produced in a DAC system such as the Vancouver technology are removed and could either be sold as a revenue stream or directly sequestered if needed to comply with regulations.

3.9 STATE-OF-THE-ART ASH MANAGEMENT

Modern WTE facilities employ advanced ash management strategies to enhance environmental sustainability and resource recovery. Ash is a substantial fraction, typically between 15% – 25% by weight of incoming MSW in a WTE setting. Without metals recovery or beneficial ash reuse, this ash is disposed of in landfills typically. Therefore, modern WTE facilities use the following approaches to employ advanced ash management strategies:

Enhanced Metal Recovery - Advanced technologies enable the extraction of both ferrous and non-ferrous metals from bottom ash. Typical modern WTE Facility metal recovery technologies recover 85 to 90% or more of the metals in the ash stream. Some WTE Facilities further process their bottom ash to remove even smaller sized metal particles.

Beneficial Reuse of Bottom Ash - Processed bottom ash can be repurposed as construction aggregate, particularly in road construction. Where allowed, overall waste diversion by processed through a WTE facility with beneficial reuse of bottom ash can approach 94% or more by weight of the incoming waste stream.

Separate Management of Fly Ash - Managing fly ash separately from bottom ash, enables facilities to increase metals recovery and recovered metals sales revenues and supports the beneficial reuse of bottom ash. The remaining fly ash continues to be treated and stabilized with a smaller portion of the bottom ash stream to reduce fly ash hazardous characteristics, facilitating safer disposal.

3.10 ADVANCED MIXED WASTE PROCESSING EVALUATION

Significant advancements in advanced mixed waste processing have emerged over the past 24 months, showcasing promising improvements in addressing the historically low diversion rates associated with traditional mixed waste sorting technologies. Notable developments include the RDS MWPF in Chesapeake, Virginia, and the proof-of-concept plant for Koch Industries' Juno technology in Toledo, Oregon. Additionally, several back-end in-vessel wet and dry digestion facilities, designed to operate post-conventional MWPF sorting for recyclables, are either operational or under construction. These innovations demonstrate enhanced capabilities and potential for optimizing waste diversion and resource recovery processes, marking a substantial step forward in sustainable waste management practices.

However, the failure rate of mixed waste facilities before their planned contract or depreciation periods is still above 80%, and almost none are operating as intended in their design. They are expensive to build and operate and are not yet sustainable in low landfill tip fee, unregulated market environments. In addition, MWPFs are never sustained from commodity sales. In the last 60 years, hundreds of such facilities have been briefly operated then closed. Some do stay in operation because of their flexibility to revert to more source separated recyclables processing or other source separated feedstock (i.e., engineered fuel). In addition, they will proliferate in high tip fee markets, like those in the European Union, that allows the needed processing fee to cover the cost of operations and disposal but are increasingly expensive for every point of diversion they deliver. Other facilities continue to sustain operations in highly regulated environments where diversion of solid waste is mandated for public or private solid waste collectors to provide. For instance, much of the installed operating fleet in North America is in the regulated state of California with a 75% diversion law that is enforced.

The following sections and tables provide a thumbnail description of the state of play of MWPFs and are the result of a high-level survey of a large sample of advanced waste options in North America.

Values for each field were obtained from public research. Each facility is classified as still operating, recently closed or cancelled, or 'in-construction'. Where the availability of data was not available for a certain criterion, either a professional judgement estimate is offered, or the criteria is not inputted.

3.10.1 Advanced Mixed Waste Processing Technologies- Current North American Fleet Description and Metrics

Table 15 presents the functional and operational key metrics that were used to evaluate the advanced mixed waste facilities in North America, which are presented in Table 16.

Table 16. Advanced Mixed Waste Technology Evaluative Criteria

CRITERIA	DEFINITION	EVALUATION APPROACH	SCORING METHOD
Operational Experience/ **Past Performance**	Extent that it has successfully been operated in other markets	Review operation through literature and/or outreach to operators and related jurisdictions.	**Very Low** unproven, demonstrated only at bench scale. **Low** proven at small commercial scale <2 yrs **Medium** proven at small commercial scale >3 yrs **High** proven operations for ≥3 yrs
Economic / Operational Risk	Evidence of failure, default or unintended operational approach	Review literature and/or outreach to operators and related jurisdictions. Score based on professional judgement.	**Low -** Proven operational history with two or more plants at scale in North America. Authority should consider further investigation. **Medium –** Operational history with one plant at scale in North America **Unacceptable -** No commercial history of operations or failed facilities
Diversion	% of MSW diverted from landfill	Review data on diversion % through literature or outreach to operators. Audited performance by third-party.	**Percent Diverted** (MSW Stream) - Needs to be verified by third-party audit
End Use	Qualitative evaluation of Potential for use (follows Waste Hierarchy principles): • Reuse • Mechanical Recycling / Composting • AD	Review data about recovered material end use/markets through literature, outreach to operators and/or internal knowledge. Segregated by material groups (organics, plastics, metals, fiber, other). Assumptions will be required; score will be based on professional judgement.	**Low -** No beneficial reuse documented **Medium -** Beneficial reuse document, but instances of criteria contamination identified **High -** Resulting product useful for combustion or ADC only

	• Chemical Recycling • Mixed Waste composting for mass reduction • Engineered Fuel/WTE • Landfill		

Table 17. Advanced Mixed Waste Technology Evaluation

FACILITY NAME	STATE	STATUS	TECHNOLOGY	TYPE	OPERATIONAL EXPERIENCE/ PAST PERFORMANCE	ECONOMIC/ OPERATIONAL RISK	DIVERSION	END USE
Anaergia/ WM **Sun Valley Recycling Park and Rialto AD**	CA	Operating	Commercial Franchise-front end recycling of rigid containers and some OCC. Organics conditioning and delivery to wet, in-vessel anaerobic digestor & water reclamation	MSW-RNG	**Low** Although it has some continuous operations. Anaergia has had financial difficulties caused by low process fees from low-priced contracts.	**Medium to High** due to continued financial performance	**60-90%** of organics received from Municipal Solid Waste (38% of MSW stream) if digestate is permitted for cover. Even without beneficial re-use of digestate, technology is promising for backend recovery of ~40% of organics in mixed waste.	**Low Risk – Recyclables and RNG** Recover Recyclables (WM markets material). Electricity, natural gas. **Medium Risk - Digestate** Use of digestate for enriched land application highly dependent on emerging PFAS and micro-plastic regulation
Athens Sun Valley	CA	Rumors about adding organics solution to process MWPF, not announced or verified	Front end MWPF	MWPF	**Very Low** Converted to heavy duty commercial Single Stream operations with bag breaker	**Low** Required for commercial franchise and SB 54 compliance. Athens will use new MWPF in-construction to meet commercial	**<20%** before any organics processing (None yet installed)	**Low Risk** Recycled commodities

FACILITY NAME	STATE	STATUS	TECHNOLOGY	TYPE	OPERATIONAL EXPERIENCE/ PAST PERFORMANCE	ECONOMIC/ OPERATIONAL RISK	DIVERSION	END USE
						franchise but processes single stream very successfully		
Medina County	OH	Operating	Front End, simple MWPF for commercial and drop off/ contaminated Single Stream recyclables at transfer station	MWPF	**Medium** - operational for six years	**Medium** - insufficient commercial/industrial material forced contract renegotiation of the contract and the need to supplement flow with single stream. Other Rumpke facilities single stream only	**<10%** Commercial comingled recycling stream. Not recovering from MSW, no organics recovery. Estimated 70% recovery rate (OCC, UBC, Steel Cans, Plastic, Glass)	**Low Risk** Recovered materials go to same end markets as any single stream material
Monterey County (ReGen Monterey)	CA	Operating	Traditional Campus approach for Single Stream recycling, commercial recycling, food and	Waste Campus	**Medium** - operational since 2018 but methods and goals have evolved to outcomes with	**Medium to Low** - Market risk for recyclables	**Diversion %** not reported for former MWPF design which was abandoned Est. for C&D (not including generated fines)- ~20%	**Low Risk** Recycling recovery, C&D (wood, aggregate, metals plastic)

FACILITY NAME	STATE	STATUS	TECHNOLOGY	TYPE	OPERATIONAL EXPERIENCE/ PAST PERFORMANCE	ECONOMIC/ OPERATIONAL RISK	DIVERSION	END USE
			yard waste 80 TPH processing (40 TPH for commercial mixed material)		lower ambitions		>95% of available recyclables	
RDS AMP ONE Portsmouth	VA	Operating	Innovative AI-assisted automated sorting, optical sorters, air devices, recirculation of identified recoverables, including fiber	MWPF	**Low -** Operating for one year on a relatively small scale, but overall approach informed by several years of operation at similar commercial-scale pilot plant in Atlanta	**Too Soon to Tell but promising** - No service disruptions or other issues with operations, operates a similar facility in Virginia	**80%** capture of recyclables. Potential production of biochar can be used for ADC % rigid plastic, 7% film (grade B or olefin for pyrolysis), 40% that is organics, 15% to 25% that is OCC and fiber. Can achieve higher diversion with things like conditioning a refuse derived fuel	**Medium Risk**- recyclables, biochar production and organics from MSW harder to find markets. So far, operation claims good acceptance
RePower South, Berkeley	SC	Operating	MWPF, engineered fuel, single stream capable, similar technology to O MRF	MWPF MRF	**Medium -** has operated for five years	**Medium** – Relies on single stream component, does sell some engineered fuel from MSW. Low landfill tip fee	**<25%** estimated diversion from MSW. **85%** estimated diversion from single stream	**Medium** - Fuel market spotty for MSW-derived output and fuel is a lower quality end-use

FACILITY NAME	STATE	STATUS	TECHNOLOGY	TYPE	OPERATIONAL EXPERIENCE/ PAST PERFORMANCE	ECONOMIC/ OPERATIONAL RISK	DIVERSION	END USE
Georgia-Pacific Juno recycling facility	OR	Operating	Shred Autoclave, fiber recovery, wet, in-vessel, AD, back end MRF, and fuel recovery	MSW-RNG	**Low** - proven at small commercial scale for >three yrs without all components proposed in a larger system	**Medium -** demonstration system operating below designed capacity after 18 month "proof of concept" period	**64%** estimated Recovered / 31% Diverted	**Medium for Fuel and Fiber -** With the scaled-up system they will add more diversion features . Only option backed by large paper company
San Jose Green Waste Recovery	CA	Operating	90TPH Front end processing for recyclables Remove MSW, process/clean organics for shipment to ZWE dry AD, LF composting	MWPF with residue and organic output	**High -** required to meet 75 franchise collection for WC in San Jose	**Low -** funded through franchise collection	**30-60%** estimated diversion with up to 75% advertised, includes large Single Stream facility which sends residuals to GWR.	**Medium -** no reported issues in the literature. Likely fiber going to organics solution
Western Placer County/FCC	CA	Operating Re-Build in Construction	100 TPH retrofit- Front end processing for recyclables Remove MSW mixed organics and clean organics to	MWPF/ Mixed Compost, new SS facility, C&D Campus	**High** continuous operations since 1996. Building automated plant while still operating manual plant.	**Medium Risk**, (for new design) FCC operates similar facilities, mostly in Europe. Has not operated	**60%** recovery rate for MSW claimed. Some assumptions on paper and organics go into this that have not been proven out.	**Very High for Paper & Compost** Total recovery from MSW up from 22% to 60%; new materials-mixed paper to dryers to low grade bales; MWPF compost to landscaping or agro

FACILITY NAME	STATE	STATUS	TECHNOLOGY	TYPE	OPERATIONAL EXPERIENCE/ PAST PERFORMANCE	ECONOMIC/ OPERATIONAL RISK	DIVERSION	END USE
			organics facility aerated in-vessel composting; process		Planning to open J 2025	such a system in the U.S.		(if permitted). Skeptical about very low-grade paper in export market & organic end use
WM "O" MRF	CA	Operating	Front end Mixed Waste, dry in-vessel composting, clean compost facility	MWPF/ Mixed Compost, new single stream facility, C&D Campus	**High** continuous operations since 2019, organics composting facility opened in 2021	**Medium –** Supported by strong regulatory environment where process fee cost is buried in franchise collection fees if system is not properly managed and maintained at a high level	**65%** Diverted - 100 ton/hour Organics Composting Facility: 60 TPH	**Medium –** Recyclables low quality; compost diluted to land application or landfill application
Enerkem Edmonton	Al, CAN	Closed	Shred, Syngas gasification, Fisher-Tropsch hot hydrolysis conversion to methanol	MSW-methanol	**Low -** Never hit projected numbers	**High -** System achieved projected operational and financial targets. Represented as a 25-year investment the facility	No data available	**Low -** 11-years of operation produced 5 million liters of fuel, far less than the projected 36 million liters per year

FACILITY NAME	STATE	STATUS	TECHNOLOGY	TYPE	OPERATIONAL EXPERIENCE/ PAST PERFORMANCE	ECONOMIC/ OPERATIONAL RISK	DIVERSION	END USE
						was shut down after 11-years. Investment cost was never recaptured		
Entsorga West Virginia	WV	Closed	Mechanical biological treatment (MBT)	MBT	**Medium/High -** operational from 2019-2022. Never completed fuel conditioning system	**Unacceptable -** Safety, low tip fees, rodent control, fuel market concerns led to closure, failure to reopen and turbulence in foreign ownership	10-20% at beginning of operations	**High** - Cement kilns- not open year-round, unsuccessful in finding another location for end use material. Fuel use is a lower quality end-market
Fulcrum BioEnergy- Sierra BioFuels- Reno	NV	Closed	Syngas Gasification, Fisher-Tropsch hot hydrolysis to hydrocarbon crude. Fuel conditioning facility never constructed on back end	MSW-Fuel	**Low** - Only ran for two years before shutdown	**Unacceptable -** $500 million failure. Cost overruns, California restrictions on waste-to-fuel for diversion, low output. Many technical	Initial Capacity- Convert 175,000 tons of prepared landfill waste into 11 million gallons of renewable syncrude annually	**High -** Never finished work on conditioning plant for syncrude

FACILITY NAME	STATE	STATUS	TECHNOLOGY	TYPE	OPERATIONAL EXPERIENCE/ PAST PERFORMANCE	ECONOMIC/ OPERATIONAL RISK	DIVERSION	END USE
						issues. Only accepted Reno MSW and process residuals were directed to WM (project investor) landfill		
Fulcrum BioEnergy	IN	Cancelled	Gasification-planned 2nd Fulcrum plant	MSW-Fuel	**Very Low** - project in Nevada failed, this project has been cancelled	**Unacceptable** - Project in Nevada failed, this project has been cancelled	No data available	Up to 33 million gallons of jet fuel and processes up to 530,000 tons per year of prepared feedstock
Repower South Montgomery	AL	Closed	Conventional MWPF with RDF component	MWPF	**Low -** Two operators out of business in less than three years	**High -** conventional MWPF play not supported by regulatory structure or market tip fees. $37M project funded by public bonds in poor municipality	**<10%** estimated	**High -** poor quality paper and recyclable output. No data on fuel component promised by Repower

FACILITY NAME	STATE	STATUS	TECHNOLOGY	TYPE	OPERATIONAL EXPERIENCE/ PAST PERFORMANCE	ECONOMIC/ OPERATIONAL RISK	DIVERSION	END USE
BHS- Lane County	OR	In Construction	Front end Mixed Waste Dry AD	MSW-RNG	NA/New Construction, scheduled to open July 2026	**Medium** - equipment systems in O-MRF and RePower South	**Medium** Targeting 160,000 TPY, 45-55% Diversion (including organics)	**Medium** - Will produce marketable recycling commodities and biogas for transportation, will be used in Lane County bus fleet
Athens Irwindale MRF	CA	In Construction	MWPF and AD	MSW/ Commercial MSW	NA/New Construction	**Low -** Cost recovery secured by long-term commercial franchise and residential contract processing payments	**Medium to High** Advertised at up to 85% of potential recyclables (RRS est. of $33 diversion of inbound)	**Medium -** plastics, metal and fiber and fiber, as well as biogas for energy generation

It should be noted that there are some other facilities not utilized for this white paper because the technology was redundant, low diversion, expensive, or has been closed recently, for instance, the MWPFs in southeast Massachusetts and Central Virginia, which have either closed or no longer processing mixed waste. The sampling is representative, however, of commercial scale options in the market.

3.10.1.1 Recommended Operating and In-Construction Advanced Mixed Waste Facility Approaches (see Task 4 Scenarios), Summary Costs, and Technical Requirements

Over the past decade, one of the most significant revelations has been the inability to scale waste-to-alcohol-based hydrocarbon solutions—such as syncrude, char, methanol/ethanol, and jet fuel—within the low tipping fee and low regulatory environment of the North American market. Despite more than a billion dollars invested in new facilities, many projects have either failed to reach completion or operated at recovery rates and output volumes far below expectations that caused their failure. While there are examples of these technologies operating in regions like Japan and the European Union, their success is largely dependent on processing highly stratified waste streams, stringent regulations, and the support of high landfill tipping fees that make such processes economically viable. Without similar incentives or supportive policies, these technologies remain commercially unfeasible in North America.

Technologies like gasification, pyrolysis, and hot hydrolysis refining of organics into sugars have proven to be extremely high-risk investments and are not currently recommended for Authority adoption.

The following is a list of recommended approach - proof points for advanced waste processing facilities in operation or under construction today for the technologies presented in Task 4 scenarios. Though many of the technologies are centuries old, they have recently been improving at a rapid rate because of advances in AI-assisted sorting methods and advanced conditioning and air systems for digestion, odor control, scrubbing and beneficial gas capture and are a part of the below facilities based on the research conducted and the criteria and metrics outlined in Table 7. These facilities, or the equipment they utilize, have demonstrated acceptable production histories with manageable risks and other favorable attributes. They have been vetted for estimated costs, outputs, and siting requirements where publicly available documentation permits. However, because to the private nature and consequent confidentiality posture of many of these operations, some criteria evaluation and economic estimates remain incomplete.

Especially important for both task 4 scenarios “D – High Diversion Wet/Dry MSW collection, Single Stream, and Co-Collection of Food + Yard Waste” and “E - High Diversion - Mixed Waste Technologies and Fiber Capture”, the proof points in the market now better identify the appropriate sorting technology to better extract recyclables on the front and to process organics on the back end within the following scenarios.

1. For Scenario D, instead of requiring the separation of organics through front-end screening and conditioning processes such as bag breaking, shredding, sizing, compressing, moving slurry to a wet anaerobic digestion facility, and caking the organic solids fraction, organics processing could be designed to operate independently of the front-end system within the Wet Dry scenario option.

2. For Scenario E, with the same front-end sorting and conditioning and back end organic core technologies would still be applicable across either high diversion scenario, with one notable exception: the Juno technology. In this approach, fibers are extracted prior to organics conditioning and anaerobic digestion, enabling paper recovery within the slurry created during processing. This technology is optimized for mixed municipal solid waste (MSW) collection scenarios, making it less effective in source-separated wet/dry systems.

The following recommendations are based on a summary of relevant data for preferred processing facilities for further research regarding acceptable technologies, required facility footprints, estimated capital expenditures (Capex), operational expenses (Opex), and, where available, anticipated revenue streams. While these details offer directional guidance, they should not be used for capital budgeting purposes. Further work is required to fully assess local conditions, costs, and additional site-specific factors, typically undertaken during the conceptual and preliminary engineering phases. Cost estimates presented in this document are highly preliminary (+/- 25%).

Finally, identifying the best processing system direction for the Authority requires consideration of the two stages of an MSW recovery system, 1) Upstream physical sorting for available recyclables and 2) downstream organic recovery.

1. **Physical Sortation Stage** – MSW sorting using innovative approaches such as AI-assisted scanning and image, gas signature, and/or x-ray recognition and data storage and coordinated optical air jet or robotic sorting provides capture rates that represent an improved state-of-the-art for the removal of high value commodities. The additions of practical recirculation and redundancy in automated capture systems for the most valuable available commodities, have further enriched the stream as it uses the automated sorting devices. As a result, the vendor-supported sorting solutions provided below (e.g., AMP One, BHS, Machinex, Stadler, VDRS) each can be predictably deployed to enhance diversion, yielding a flow of both valuable commodities and the conditioning of the organic fraction for use in the Organics Recovery Stage.

   Recovered commodity risks include incoming waste characterization, individual commodity recovery rates, and commodity marketplace value. The appropriate choice of equipment systems can dramatically impact the recovery rates and ultimate marketplace value, while incoming waste characterizations tend to be less tractable. That said, new approaches developed at both longstanding integrated equipment system providers (e.g., BHS, Machinex, Stadler, VDRS) are now better positioned to guarantee and fulfill much higher recovery rates and flexibility in the face of incoming material changes. New entrants to the integrated system provider marketplace like AMP are also demonstrating dramatically higher recovery rates and new approaches to system development overall. Together, the available system approaches will provide the Authority with a variety of viable suppliers.

   There have been many attempts to recover the paper fraction in mixed waste processing and 99% of them have been unsuccessful past the scalping of large pieces of unbleached OCC. Recently, a failed MWPF in Maine planned to have an intermediary step of pulling out wet fiber for capture. In the meantime, the Juno technology plant developed by GP Inc., a major producer of pulp and paper, has operated commercially for over three years in Oregon and further investigation of its fiber recovery is recommended before Organics recovery.

2. **Organics Recovery Stage** – There are numerous organics recovery technologies considered in the preceding sections. However, many of these approaches, especially those focused on high temperature conversion, although viable in a laboratory or in small-scale commercial settings, have proven to be infeasible both technically and economically.

   Digestion technologies remain the best approach for organics recovery. Composting, or aerobic digestion is feasible and less expensive than higher tech alternative. However, the recovery profile for composted MSW is poor, because the resulting product is significantly contaminated. Similarly, anaerobic digestion is also proven and has been shown to be a viable operating approach in some markets. The ability to produce renewable natural gas (RNG) as a product that can be used in a variety of end uses has established a better economic profile than simple composting. Post-gas generation steps in digestate management options can take two pathways. First, liquids can be directed to local wastewater treatment facilities, where additional organic removal and effluent treatment occurs through secondary digestion. Second, solid digestate can either be composted (resulting material remains a problem in the marketplace) or directed after dewatering to a WTE facility as fuel. Recent high-profile concerns about PFAS substances contaminating MSW streams and persisting in solid digestate have arisen and are legitimate. The existence of PFAS in the flow further limits viable digestate management pathways.

Though not recommended now, the emergent feature could be the use of solid digestate in the production of biochar. Production of biochar, if proven out, would have the dual benefit of both binding or eliminating PFAS substances and sequestering carbon in both the production and use of the biochar. Although no current commercial scale applications of the biochar production systems are operating, several similar systems have been proposed for large public applications and are currently being seriously considered. This technology and approach to digestate management has been shown to be a justifiably exciting option and will require careful evaluation soon as an approach that could benefit the County significantly.

The next steps should include further investigation through procurement processes to gather more detailed information on each facility's technologies and their applicability to the Authority's specific needs, with the goal of achieving the higher diversion rates.

Table 17 presents the functional and operational key metrics suggested to be applied to each advanced mixed waste facility recommended for further study, which are presented in Table 18.

Table 18. Advanced Mixed Waste Functional and Operational Key Metrics

CRITERIA	DEFINITION	EVALUATION APPROACH	METRIC USED
Climate Benefit	Estimated or reported GHG emissions reduction or other benefit	Modelled emissions reduction from diversion and expected end use using U.S. EPA WARM (version 16). Assumptions on end use will be required, and score will depend on professional judgement	Tons CO_2 equivalent or estimated projection
Est. Capital Cost	Estimated cost to develop the site	Review data on up-front cost (infrastructure + land) through literature and/or outreach to operators and related jurisdictions.	Total Cost/Cost per ton
Est. Operating Cost	Estimated cost to operate the site	Review data on ongoing costs through literature and/or outreach to operators and related jurisdictions.	Cost (Opex plus annualized Capex) If known
Net Economic Benefits	Net economic benefits including Disposal Cost Savings, Tip Fees Generated, Commodity Value,	Qualitatively review data and reported costs-revenues, such as existing tip fees, expected tip fees, expected commodity revenue, which can be reasonably obtain	Qualitative known or estimated economic revenues, tip fees, savings from disposal costs, etc.
Footprint/Siting and Legal Political Risk	Ability to site in Broward County given function of facilities	Available development data and status. Qualitative description and estimated needs	Summary
Proof Point Best Practice	Why it is listed as a recommended facility to study further	Operations records, team visits to each, or understanding of facilities through projects or research	Qualitative identification of features for either front end MWPF sorting, organics processing or both

Table 19. Functional and Operational Key Metrics Applied to Each Advanced Mixed Waste Facility Recommended for Further Study

RECOMMENDED FACILITY NAME	CLIMATE	CAPITAL COST (+.- 20%)	OPERATING COST ROUGH EST. OR REPORTED $/T	AUTOMATION POTENTIAL STAFFING (ROUGH ESTIMATE)	NET ECONOMIC BENEFITS	EST. FOOTPRINT, SITING/ LEGAL/POLITICAL RISK	PROOF POINT BEST PRACTICE
Anaergia/ WM Sun Valley Recycling Park and Rialto AD	Up to 220,000 MT $C0_2$	$185 Million	Sun Valley Recyclables Capture/ organics conditioning/ Orex $150-200 Rialto Anaerobic Digestion, transport and process $100 Total Operating cost not available	25-35 No data available	Diversion of up to +40%- 160,000 tons per year net from the landfill (T&D in Los Angeles ~$85/T No other data available	Sun Valley 10-20 Ac. Zoning, solid waste permit, NIMBY Rialto- 30 Acres Waste Water Permitting, Odor, quality WWT output,	Conditioning of mixed waste organics, wet anaerobic digestion and water treatment plants which high diversion
Athens Irwindale MRF	Up to 190,000 MT $C0_2$	Est. $170M (not including WWTP effluent conditioning)	Est. Inbound MSW $65 (Not including disposal). Wet AD (on-site)	75-90 first shift, 40-75 second shift	$7-12M (rough estimate) commodities and RNG Rev.	15 Acres Already Permitted. Good Politics.	Highly advanced, front-end sorting, conditioning of the organic fraction, anaerobic

RECOMMENDED FACILITY NAME	CLIMATE	CAPITAL COST (+.- 20%)	OPERATING COST ROUGH EST. OR REPORTED $/T	AUTOMATION POTENTIAL STAFFING (ROUGH ESTIMATE)	NET ECONOMIC BENEFITS	EST. FOOTPRINT, SITING/ LEGAL/POLITICAL RISK	PROOF POINT BEST PRACTICE
			$49/T (not including WWTP by others)		Total capture of annual cost of ~$55M Opex plus profit		digestion on the back end
RDS AMP-One Portsmouth	750,000 tpy facility will sequester est. 300,000 MT $C0_2$	$20M bldg., $10M in fixed equip. capital ($300K- 350K ton/hour for 25 ton/hour system)	Est. $/T Range: Inbound MSW: $35-60 per ton, not including disposal costs (residual T&D)	750,000 TPY facility would generate 150 jobs directly indirectly, and induced	No data available	20 acres for 750,000 TPY MSW Facility	Use of recirculation and redundancy, with low-cost optical sorters and other air devices for high capture
Georgia-Pacific Juno recycling facility	High: If running at full capacity (330,000 tons) CO_2e will be reduced by 525,000 tons (1.59 tons CO_2e for every ton of	Very High Cost: $350-$500M $1000-$1500/ton of nameplate capacity Includes: Property, plant, equipment, infrastructure, startup costs,	Assumed medium-high cost. No specific detailed data available but expected higher Opex than simpler systems.	Highly Automated. All systems can be managed from the central control room. No sorters needed beyond pre-sort.	No data available	25 acres	Capture of fiber, anaerobic digestion, and recycling of water before water treatment for organics processing

RECOMMENDED FACILITY NAME	CLIMATE	CAPITAL COST (+.- 20%)	OPERATING COST ROUGH EST. OR REPORTED $/T	AUTOMATION POTENTIAL STAFFING (ROUGH ESTIMATE)	NET ECONOMIC BENEFITS	EST. FOOTPRINT, SITING/ LEGAL/POLITICAL RISK	PROOF POINT BEST PRACTICE
	material processed) compared to landfill	contingency, etc.					
FCC West Placer County **(In construction)**	No data available. Assume to be close to similar recovery to Athens Irwindale (220,000 MT $C0_2$)	High Cost - $141M retrofit, facility stated $100-120M (building already present, all for equipment)	Medium cost: $60-80/ton tip fee	Very automated with Van Dyk system. 14 opticals, 5 robots, screens, & shredders. 20-25 staff per shift, additional significant cost from maintenance, parts and electricity	No data available	320-acre waste management complex. Permits are required for air, water, building, and solid waste. Time consuming. Typical siting challenges	Planned, highly advanced, front-end sorting, conditioning of the organic fraction, aerobic contained composting for organics
WM O MRF	No data available- Mitigation of methane from Landfill	$120 million	No data available	+25 staff per shift	No data available	53-acre campus, including five recycling facilities, mulch colorization plant, clean compost facility, MWPF and planned new MRF	Highly advanced, front-end sorting, conditioning of the organic fraction, manual sorting for capture of mixed fiber on the residue line, aerobic in-vessel

RECOMMENDED FACILITY NAME	CLIMATE	CAPITAL COST (+.- 20%)	OPERATING COST ROUGH EST. OR REPORTED $/T	AUTOMATION POTENTIAL STAFFING (ROUGH ESTIMATE)	NET ECONOMIC BENEFITS	EST. FOOTPRINT, SITING/ LEGAL/POLITICAL RISK	PROOF POINT BEST PRACTICE
							composting for organics
BHS- Lane County	Mitigation of methane from Short Mountain Landfill - the largest source of greenhouse gas (GHG) emissions from County operations. Equivalent reduction of taking 20,000 cars off the road for the next 25 years. Facility claims huge reduction	$150 Million $45 Million would cover Lane County's portion of the project costs. The remaining $105 million will be covered by BHS	Charge county $69/ton, internal cost of disposal $31/ton, but varies based on tonnages	Highly automated - 52 total staff	Revenue sharing exists above a set threshold	Processing and service agreement, permitting and construction in process	Highly advanced, front-end sorting, conditioning of the organic fraction, anaerobic digestion on the back end

4.0 SOLAR PHOTOVOLTAICS ON LANDFILLS

The installation of solar photovoltaic (PV) systems on closed landfills provides an opportunity to repurpose otherwise underutilized land for renewable energy generation. The following sections identify advancements, strategies, and challenges in landfill-based solar PV projects. The discussion includes an overview, system types, and critical considerations such as location, access, foundations and wind, stormwater, security, interconnection, and economics, while emphasizing sustainability and the importance of recycling PV materials.

4.1 OVERVIEW

Closed landfills represent a significant opportunity for renewable energy generation due to their large, open areas and proximity to grid infrastructure. Solar PV installations on these sites align with sustainability goals by repurposing non-productive land while minimizing environmental impacts. Landfill sites, often encumbered by restrictions on traditional redevelopment, provide unique advantages for solar PV projects, such as reduced land acquisition costs and community support for environmentally friendly initiatives.

4.2 SYSTEM TYPES

4.2.1 Fixed Systems

Fixed-tilt solar PV systems are widely used in landfill applications due to their simplicity and reliability. These systems involve panels mounted at a fixed angle to optimize sunlight capture. Fixed systems are typically ballasted to preserve landfill cap integrity and require careful design to address differential settlement and site-specific wind conditions. The durability and lower maintenance requirements of fixed systems make them a popular choice for long-term energy generation projects.

4.2.2 Tracking Systems

A tracking solar system (i.e., single or dual axis) uses mechanisms to continuously adjust the PV panel angle throughout the day to follow the sun's movement, resulting in significantly more energy production from the tracking system, but at a higher initial cost, and with increased maintenance needs compared to the fixed tilt option. It is a great option for limited space where the increased efficiency can provide additional generation. Generally, this is not ideally suited for a landfill application due to the additional racking and foundation requirements.

4.2.3 Closure System Integration

Erosion issues on landfill slopes, exacerbated by weather conditions like rain and wind, necessitate regular upkeep. Conventional closure methods, which use a thick soil layer and vegetative cover, not only take considerable time to install but also demand high maintenance costs. Geomembrane closure turfs consist of a textured geomembrane, an artificial grass turf designed for landfills along with a specified backfill material. This type of closure system allows for the direct attachment of solar panels while virtually eliminating the racking structure required.

4.3 CONSIDERATIONS

4.3.1 Location

The location of a landfill solar PV project significantly influences its feasibility and performance. Factors such as solar irradiance, proximity to grid infrastructure, and the landfill's size and shape, must be evaluated during the planning phase. It is important to select sites with minimal shading and optimal orientation for maximum energy production. Local climate conditions, including temperature variations and seasonal weather patterns, must also be considered to ensure consistent energy output.

4.3.2 Access

Access to the landfill site is a critical consideration for construction, operations, and maintenance. Roadways and pathways must support the transport of equipment and materials without compromising the landfill cap. Proper access planning ensures safety and efficiency throughout the project lifecycle. Additionally, ensuring year-round accessibility for maintenance and emergency response crews is essential, particularly in regions with harsh winters or frequent storms.

4.3.3 Foundations and Wind

Landfill solar PV projects must be designed to withstand site-specific wind conditions. High winds can pose risks to panel stability and mounting systems. Wind load assessments can inform the selection of racking systems and the placement of panels. Enhanced mounting systems with increased ballast weights or aerodynamic designs may be required in areas prone to extreme wind events.

4.3.4 Security

Ensuring the security of the solar PV installation is vital to prevent theft, vandalism, and unauthorized access. Fencing, surveillance cameras, and lighting are common security measures recommended for any solar installation. Secure access points and regular monitoring enhance the overall safety of the site. Advanced technologies such as motion detectors and remote security monitoring systems can provide an additional layer of protection, especially for large or remote installations.

4.3.5 Interconnection

Understanding the local energy demand and potential uses for generated power is crucial. Landfill solar PV projects may supply power to municipal facilities, support on-site operations, or feed into the grid. It is critical to evaluate the utility interconnection requirements and grid compatibility during project planning by submitting a preliminary interconnection application to the utility. Emerging technologies such as battery storage systems can enhance the value of landfill solar PV projects by providing backup power during peak demand periods or grid outages.

4.3.6 Economics and Funding

Economic feasibility is a key driver for landfill solar PV projects. Factors such as installation costs, available incentives, energy production potential, and maintenance expenses must be considered. A detailed financial analysis leveraging federal and state incentives to enhance the project viability should be performed. Programs like the Investment Tax Credit (ITC) and renewable energy certificates (RECs) can significantly improve project economics. Additionally, landfill solar projects often qualify for grants or funding aimed at promoting renewable energy development. More recently, community solar PV projects are being promoted and developed by many cities and municipalities to support municipalities broader renewable energy goals. These Environmental Justice (EJ) solar PV projects are being driven to provide access to clean energy and create opportunities for low-income communities.

4.3.7 Decommissioning

When referring to a PV system, decommissioning usually includes removing the PV array, removing the balance-of-system (e.g., other parts of the system, excluding modules, such as wiring, inverters, mounting system), and restoring the land. Decommissioning policies and requirements can vary greatly from state to state, granting certain jurisdictional powers to either state or local governments.

4.4 SUSTAINABILITY AND RECYCLING

4.4.1 Recycling of Solar PV Materials

As solar PV panels approach the end of their lifespan; recycling becomes a critical component of sustainable project planning. It is important to recycle PV materials to recover valuable components such as silicon, glass, and various metals and alloys. Recycling processes not only reduce landfill waste but also support the circular economy by reintroducing materials into the manufacturing cycle. Companies specializing in solar panel recycling are emerging, offering innovative solutions to address the growing volume of retired panels.

4.4.2 Circular Economy Approaches

Incorporating circular economy principles from project inception enhances sustainability. This includes sourcing panels made from recycled materials and establishing partnerships with recycling facilities to manage end-of-life panels effectively. Designing for disassembly and modular construction can further streamline recycling processes, reducing costs and environmental impacts.

4.4.3 Policy and Industry Trends

Growing awareness of solar PV recycling has spurred policy developments and industry collaboration. Some states have implemented mandatory recycling and extended producer responsibility programs for solar panels, while others are developing standards to ensure that materials are responsibly managed. These efforts align with broader renewable energy goals and the push for greater sustainability in the energy sector.

4.5 FUTURE OPPORTUNITIES

Solar PV installations on closed landfills represent a win-win solution for renewable energy development and land reuse. As beneficial land reuse and sustainability continue to evolve, these projects become increasingly viable and impactful. Addressing key considerations such as location, access, foundations, stormwater, security, utility interconnection, and economics ensures project success. The integration of sustainable practices, advanced technologies like battery storage, and stakeholder collaboration will be key to maximizing the potential of landfill-based solar PV systems.

5.0 PER- AND POLYFLUOROALKYL SUBSTANCES CHALLENGES AND OPPORTUNITIES

The emerging and urgent body of literature on PFAS (per- and polyfluoroalkyl substances) and its impact on MSW treatment facilities is an important consideration. While a full analysis of this evolving concern is beyond the scope of this White Paper, this section provides a brief overview of the current situation with an emphasis on the implications and challenges related to the future technologies discussed.

PFAS are prevalent in many consumer products, textiles and food packaging, and can accumulate in soil, water, and organisms. PFAS contamination of organic streams can come from food packaging or the food itself and PFAS may leach into liquid effluent generated during MSW processing.

Composting and anaerobic digestion processes do not inherently remove or destroy PFAS compounds. Thus, if materials entering the facility contain PFAS, they can persist or accumulate during processing.

The focus of PFAS regulation has primarily been on drinking water standards. The recent National Primary Drinking Water Regulation (NPDWR) establishes limits for PFAS in drinking water and requires the Publicly Owned Treatment Works (POTW) to monitor PFAS levels and to conform to the limits within five years (U.S. EPA, 2024a). Thus, liquid effluent discharged to the POTW including liquid digestate from the Anerobic Digestion (AD) process will be subject to PFAS mitigation as part of treatment. It is uncertain whether any testing or limits will be imposed for those discharging to the POTW.

The latest guidance on the destruction and disposal of PFAS is provided in the U.S. EPA's Interim Guidance Update and includes several established technologies along with some novel technologies which show promise for capture and/or destruction (U.S. EPA,2024b). Included in these technologies are the thermal conversion technologies of pyrolysis and gasification. While it remains a subject for further investigation and research, pyrolysis followed directly by combustion of the syngas produced in a thermal oxidizer (after burning) may be an effective form of PFAS destruction (U.S. EPA,2021). This technology is best suited for feedstock with low moisture but concern over PFAS applied to crops or agricultural land as fertilizers have also been raised so PFAS contaminated of the dewatered AD solids may also need to be addressed. However, using pyrolysis to treat the separated digestate solids is encouraging. A benefit of pyrolysis over other potential thermal conversion technologies (e.g., high temperature combustion) is that it results in a valuable co-product, biochar. In addition to its value in sequestering carbon, improving soil health, and accelerating microbial processes (e.g., AD, composting) biochar can play a valuable role in PFAS management. At the most basic level, the end product results in material volume reductions of more than 90% compared to the input solids, making transport and use or disposal more energy efficient and lessening the environmental impacts (e.g., lower landfill leachate PFAS loadings compared to biosolids disposal) (U.S. EPA, 2021). Further, the unique physical properties of biochar, which are similar to those of activated carbon, lend its application to the extraction of pollutants. Studies have shown encouraging results in using biochar as a filter to capture PFAS as well as microplastics and pharmaceuticals and chemicals from personal care products (Keller et al., 2024). Biochar produced in an organics processing facility could be a valuable consideration and option to reduce or eliminate PFAS contamination present in liquid digestate from AD processing or effluent from MSW processing. In addition, contaminated organics entering the composting process is also a concern as the moderate temperatures and microbial activity in compost systems are insufficient to break the strong molecular bonds of PFAS. Adding biochar or materials with similar binding properties to the composting process may reduce the mobility of the PFAS. However, this does not destroy PFAS, and disposal of the PFAS-laden material must be managed carefully. Emerging chemical treatments like advanced oxidation processes or bioremediation are being explored but these are not yet practical for large-scale application in compost systems.

The most effective strategy is to prevent PFAS-containing materials from entering the composting stream. Currently, Florida does not have specific state-level regulations addressing PFAS in food packaging. However, the state is actively involved in broader PFAS management and contamination mitigation efforts (FL DEP,2021). Regular testing of feedstock materials for PFAS, optimizing waste separation (such as screening out coated food packaging) and monitoring PFAS levels in the final compost product can help ensure compliance with safety standards.

The bottom line is that agencies responsible for managing MSW should stay informed on the evolving regulations and technological advancements in PFAS mitigation.

Attachment A

Brief History of U.S. Waste Management Technology and Practices Last Sixty (60)-Years

1960s–1970s: Early Days of Waste Management and Advanced Recovery

1) Waste management centered on landfilling and incineration, with little focus on material recovery. Growing environmental concerns (e.g., non-point source odor, toxic air and water emissions) and shrinking landfill capacity gradually boosted interest in waste recovery.
2) Recycling Initiatives: Re-introduction of WW-II era separation of mixed recyclables focused on source-separated recycling of materials like paper, glass, and metals. Some emphasis on processing mixed waste manually but not widespread, failures abound. Inefficient 5-7 Bin collection vehicles with manual curb sorting from small household storage bins.
3) Controlled Incineration as a Primary Treatment Method: Incineration with minimal pollution control was widely used to reduce waste volume and mass, but the practice led to public outcry due to concerns about air emissions. In addition, the 15 – 45% of ash remaining after combustion required special handling and its own disposal.

1980s: The Emergence of Mixed Waste Processing

1) Rise of technologies that suggested their ability to more effectively recover useful materials from mixed MSW. Many of these innovations were spurred by increasing environmental regulations and a push for higher resource recovery.
2) Dual Stream Materials Recovery Facilities (MRFs) were created to separate recyclables collected curbside, with 2D paper in one stream and 3D containers in another. Trucks were divided into two bins, and densification improved payloads. New materials, like PET bottles, were added, and sorting used mechanical methods like screens, eddy currents, air knives, and magnetic separators, along with manual sorting. Early MRFs were basic, relying heavily on homeowners and businesses to pre-sort materials.
3) Refuse-Derived Fuel (RDF): RDF technology emerged to produce a combustible fuel from the organic fraction of mixed MSW. Mechanical processes shredded the waste and separated inert metals, glass, and non-combustible materials. The resulting RDF could then use in industrial boilers or power plants. In some states, RDF could be “counted” as diversion.
4) Early Composting Technologies: In the 1980s, pilot projects for composting separated green waste and mixed waste began. While composting reduced waste volume, mixed waste compost was often too contaminated and of poor quality to sell. Municipal yard and green waste composting emerged across the U.S., with many areas adding a third green waste collection, even without composting facilities.
5) Waste-to-Energy (WTE) Facilities: WTE facilities using mass burn incineration technology gained acceptance, especially in countries with limited landfilling capacity. RDF manufacture receded because it could not compete with mass burn efficiency. Modern WTE plants first incorporated advanced air pollution control technologies (SO2, particulates, especially heavy metal capture.

1990s: Technological Advancements and Diversification of Waste Treatment

The 1990s marked significant progress in waste processing, with new technologies developed to better manage and recover resources from MSW.

Advances in Mechanical Sorting: In 1998, Single Stream recycling was introduced on the east coast to reduce collection costs through optimum densification of materials. Larger rolling carts (5x) replaced bins, increasing convenience and participation. New technologies, like motor control systems that adjusted to material conditions, closed air density separation, optical sorters, and automated storage, boosted MRF efficiency. Larger facilities used gravity and conveyor-fed baling for automatic densification of materials.

Increased Adoption of Advanced RDF: More sophisticated systems, incorporating better shredding, separation, and drying technologies to produce higher-quality fuel for better markets. Some facilities began co-firing RDF with coal as recognition of the operational difficulties and emissions faced by RDF only facilities. Closure rate of these facilities high despite increased development efforts.

Composting Gains Traction: Source-separated organics composting became more common; many states implemented yard debris landfill bans, leading to the quick expansion of outdoor, windrow composting facilities around the country. Mixed-waste composting continued to struggle with contamination, odor, and other emission issues. Some large facilities spectacularly failed (e.g., Reuter, Baltimore).

Emergence of Mechanical Biological Treatment (MBT): MBT facilities combined mechanical front-end sorting with biological treatment (composting or anaerobic digestion) to handle mixed waste. The goal was to stabilize organic matter and recover recyclables, i.e., Nova Scotia.

2000s: Integration of Thermal Treatment and Increased Focus on Waste-to-Energy

1) The 2000s saw a significant shift toward advanced waste-to-energy, though a quiet and spreading moratorium occurred for large mass burn facilities. Though capacity remained steady during this decade and in Florida, no new facilities were being built anywhere in North America.
2) Advances in Mechanical Sorting: Automated sorting boosted productivity and safety in MRFs, enabling the growth of single-stream collection with larger carts and automated trucks to reduce energy use and costs. Larger single-stream facilities, like the record-setting Elkridge, MD plant, processed more than 25,000 tons per month. Optical sorters replaced more manual stations, allowing continuous operation. Enhanced air classification, centralized HVACs, and new sorting tech improved capture of small materials. Meanwhile, steady demand for mixed paper grew, and advanced shredders and screens better sorted plastics, while optical sorters handled more plastic bottles and food containers in mixed waste facilities.
3) Growth of Mechanical Biological Treatment (MBT): Originating in the late 1970s, MBT combines waste sorting and organic treatment, working best in regions with high landfill fees. In North America, a 1990s-era plant in Nova Scotia still operates.

4) MBT is the combination of two approaches to sorting waste after de-bagging and shredding material to liberate it from plastic bags.
    A. The first step is sorting uncontaminated recyclables, like bottles, cans, boxes, OCC, and scrap metal, using similar technology to mixed waste facilities.
    B. The second step treats the remaining highly organic stream (food, paper, non-rigid plastics) through composting or drying, creating RDF fuel for energy use. Inert materials like glass and rocks are screened out, and the material is often densified into high-BTU pellets for stable, efficient combustion and long-term storage. Pellets allow longer term storage than shredded RDF and have a more consistent burn for boilers.

MBT facilities became widely adopted in Europe, where they were used to comply with landfill diversion targets, enjoyed more fuel end markets, and competed against much higher landfill tip fees (over $150 T average at the time).

5) Emergence of Advanced Mechanical Biological Thermal Treatment (MBTT): During the same time, MBTT incorporated a thermal treatment step to further reduce the volume of waste and produce energy. MBTT aims to recover energy while minimizing the production of emissions. Again, lower landfill tip fees in the U.S., limit the spread of this technology, which has a much higher cost basis. Common MBTT approaches include:
    A. Gasification involves heating organic material at high temperatures (700–1,500°C) with a limited amount of oxygen. This partial combustion produces syngas (a mixture of hydrogen, carbon monoxide, and other gases), which can be used for energy, fuel, or chemical production. Syngas can power turbines, generate electricity, produce hydrogen, or serve as feedstock for synthetic fuels and chemicals.
    b. B. Pyrolysis heats organic material at lower temperatures (400–800°C) in an oxygen-free environment. The absence of oxygen prevents combustion and instead breaks down the material into gases, bio-oil, and solid char. The bio-oil can be refined into fuels, while char is used in agriculture or as a fuel. Pyrolysis is more commonly applied to create biochar and renewable fuel.

Increased Adoption of RDF in Cement Kilns: RDF became a more popular alternative fuel for the cement industry, where it was co-fed with traditional fuels. This market trend grew as applications for RDF stumbled elsewhere.

2010s: Integration of Circular Economy Principles and Advanced Technologies

1. The 2010s marked a shift toward a more circular economy approach, focusing on maximizing material recovery and minimizing residual waste.
2. Waste Characterization Changes: Waste stream evolution led to a concept called “The Evolving Ton” in which dramatic reduction in newsprint, glass, and office paper along with the increase of plastic packaging leads to a less dense and more difficult to separate stream of household and commercial recyclables.

3. Advanced MRFs and Sensor-Based Sorting: In response to the evolving ton and industry desire to recover a more diverse stream of materials, MRFs evolved to include sensor-based sorting technologies like near-infrared (NIR) spectroscopy, robotic sorting, and artificial intelligence (AI) to handle complex streams and improve material purity.
4. Improved Composting and Anaerobic Digestion: Source-separated organics processing matured, while mixed waste composting was largely abandoned in favor of MBT and anaerobic digestion. Anaerobic digestion gained traction as a way to produce biogas from organic waste.
5. Refinement of RDF and Solid Recovered Fuel (SRF): RDF production focused on improving fuel characteristics, and the term SRF (solid recovered fuel) was introduced to designate higher-quality RDF for specific industrial applications.
6. Thermal Treatment Technologies: Pyrolysis, gasification, and plasma arc technologies were explored for their potential to produce synthetic gas (syngas) and reduce waste to inert slag. However, these technologies faced economic and technical challenges in scaling up.

2020s and Beyond: Integration of Digitalization and Circular Economy Models

1. Recent developments reflect a growing emphasis on sustainability, efficiency, and digitalization in waste management.
2. Decline in National Recycling Rate: With recycling rates peaking in the mid-2010s, communities and policymakers are now focusing on boosting recovery through food waste recycling, C&D processing, and MSW sorting. This push aligns with corporate goals for recycled plastic in packaging, which is driving demand for more recycled product.
3. Digital Sorting Technologies: AI and machine learning are increasingly used to optimize sorting and improve recovery rates in MRFs.
4. Chemical/Advanced Recycling: Petrochemical and entrepreneurial efforts to establish cost effective recovery of plastics to fulfill packaging targets focus on pyrolysis approaches to build recycled resin feedstock (especially for food contact applications) streams.
5. Carbon Capture and Circular Economy Integration: Modern MBTT facilities are exploring the use of carbon capture technologies and integrating circular economy models to achieve near-zero waste and carbon neutrality.
6. Increased Emphasis on Organics Recycling: Anaerobic digestion is being coupled with advanced composting techniques to handle a wider range of organic waste, reducing the volume of landfilled materials and producing renewable energy.
7. Biochar production from contaminated organic MSW streams shows opportunity for carbon sequestration and PFAS mitigation.

Attachment B

Additional Resources

COLLECTION SYSTEM TOOLS

Smart Waste Management Apps

Call2Recycle – Collection Partner: https://www.call2recycle.org/collection-partner/

Call2Recycle – Drop-Off Locations: https://www.call2recycle.org/Locator/

Evergreen Disposal – Disposal App for Residents: https://www.evergreengarbage.com/app

The Recycling Partnership – Recycle Check: https://recyclingpartnership.org/recyclecheck/

Earth 911 – iRecycle: https://earth911.com/irecycle/

DRONE TECHNOLOGIES FOR MANAGEMENT OF COLLECTION AND DISPOSAL SYSTEMS

Autonomous Methane and H_2S Monitoring

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STATE OF AUTONOMOUS COLLECTION TECHNOLOGIES

AI-assisted Autonomous Vehicle Garbage Collection

AI-assisted autonomous vehicle garbage collection is now a few years away and will soon be a preferred collection method over the planning horizon and an understanding of the current state of this technology is required now.

AI-assisted Autonomous Vehicles at Landfills, MRFs and Transfer Stations

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Table 18

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