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Comparison of Select Thermochemical Conversion Options for Municipal Solid Waste to Energy

This document provides a comparison of several thermochemical conversion options for municipal solid waste (MSW)—combustion, gasification, and pyrolysis—across various metrics. These options provide alternatives to landfilling and are at various stages of technology development. For example, combustion (incineration) is a well-established, commercially available technology used for waste management in the United States and abroad. Gasification and pyrolysis, although well-known and well-researched technologies, are not as commercially developed. Other options not considered here include anaerobic digestion, composting, and hydrothermal processing of the organic fraction of MSW. Anaerobic digestion and composting of food waste, along with landfill gas capture, are evaluated in a separate document available here: nrel.gov/docs/fy22osti/81024.pdf. All these thermochemical and biological processes are collectively referred to as waste-to-energy (WTE), meaning that the objective of processing the waste stream is to yield an energy product. The following table compares the three thermochemical conversion pathways considered here on the basis of products, number of current projects in the United States, capital and operations and maintenance (O&M) costs, job development potential, emissions, and incentives associated with each pathway, as well as other parameters such as operational considerations, land requirements, and public perception. Informational sources and abbreviations are listed at the end of the document.

	Combustion	Gasification	Pyrolysis
Process	Heating a material at temperatures generally above 800°C in the presence of oxygen or air (full oxidation of the material). MSW combustion technologies include large-scale mass burn facilities (most common), modular systems (small, portable units), and refuse-derived fuel (RDF) systems.	Heating a material at temperatures generally above 800°C in the presence of limited steam, oxygen, or air, enough to create a reducing environment, but not enough for complete combustion (partial oxidation of the material). An alternative to conventional gasification is plasma gasification achieving high process temperature above 3,000°C.	Heating a material to temperatures generally in the range between 500° and 600°C in the absence of oxygen or air such that combustion does not take place (no oxidation of the material). Pyrolysis can be classified as fast or slow process depending on the heating rate, temperature, residence time, and pressure.
Preprocessing Requirements	Some mass burn plants accept unprocessed, mixed MSW and remove inert (noncombustible) materials such as metal and glass after combustion, while other plants sort out recyclable materials and remove inert material prior to combustion. Modular systems burn unprocessed, mixed MSW. RDF facilities require shredding and sorting of the feedstock to remove inert materials.	Sorting of the feedstock to remove inert materials such as metal and glass is required. In addition, shredding, drying, and sizing of the feedstock may be required to suit a particular gasifier design.	Sorting of the feedstock to remove inert materials such as metal and glass is required. In addition, shredding, washing and/or drying, densification, and pre-melt of the feedstock may be required.
Product	The system produces heat and power. Byproducts include bottom ash (chemical constituents such as silica [sand and quartz], calcium, iron oxide, and aluminum oxide), fly ash (fine particles removed from the flue gas), and air pollution control system residues (mixture of fly ash and particulate solids collected from the flue gas treatment equipment—e.g., scrubbers).	The system produces mainly synthesis gas (i.e., syngas, a mixture of carbon monoxide and hydrogen) that can be converted into fuels and chemicals, used to generate electricity or in fuel cells. Byproducts include inorganic solid material (ash/char or slag) and small amounts of condensable heavy organics known as tars.	The system produces bio-oil (an organic liquid that can be combusted in boilers, upgraded to transportation fuels, or used as feedstock for chemicals), char (carbon-rich material that can be used as building material, in road surfacing, etc.), and off-gases that can be combusted directly or reformed to syngas and further converted into fuels and chemicals, used to generate electricity or in fuel cells. Slow heating rates on the order of just a few degrees per minute (slow pyrolysis) produce mostly char with some bio-oil; fast heating rates (flash or fast pyrolysis) of hundreds of degrees per second produce more bio-oil. A byproduct of plastic waste pyrolysis is wax rich in hydrocarbons.
Energy Production	**Fuel:** 36-45 kgoe/ton MSW **Electricity:** 544 kWh/ton MSW	**Fuel:** 36–63 kgoe/ton MSW (conventional gasification) 63–80 kgoe/ton MSW (plasma gasification **Electricity:** 685 kWh/ton MSW (conventional gasification) 816 kWh/ton MSW (plasma gasification)	**Fuel:** 45–50 kgoe/ton MSW **Electricity:** 571 kWh/ton MSW
Operating History	Commercial, 40+ years in the United States and abroad	Limited commercial experience in the United States; decades of experience in Asia and Europe	Limited commercial experience in the United States and abroad

	Combustion	Gasification	Pyrolysis
Number of Projects in the United States and Abroad	United States: 75 commercial facilities: 58 mass burn,13 RDF, and 4 modular. Mass burn systems generally consist of either two or three combustion units ranging in capacity from 50 to 1,000 TPD; therefore, facility capacity ranges from 100 to 3,000 TPD. Modular systems have a capacity between 5 and 120 TPD. Hundreds of plants globally, mostly in Europe and Asia.	United States: 1 commercial facility: Fulcrum's Sierra Biofuels in Reno, Nevada (175,000 TPY, startup 2022). 2 demonstration facilities: ThermoChem Recovery International in Durham, North Carolina (4 TPD, startup 2009), and Sierra Energy at U.S. Army Garrison Fort Hunter Liggett in Monterey County, California (20 TPD, startup 2013). <50 plants in Europe and Asia.	United States: 4 commercial facilities processing plastic waste to fuel and/or chemicals: Agilyx in Tigard, Oregon (10 TPD, startup 2018); Nexus Fuels in Atlanta, Georgia (50 TPD, startup 2018); Brightmark Energy/RES Polyflow in Ashley, Indiana (100,000 TPY, startup 2019); and New Hope Energy in Tyler, Texas (500 TPD, startup 2018). 1 commercial facility processing biosolids to biochar: Rialto Bioenergy, Rialto, California (300 TPD, startup 2020). 1 commercial plant processing MSW to electricity: WTE International in Knoxville, Tennessee (1,000 TPY, startup 2007). Several plants in Europe and Canada.
Plant Life	30–40 years	20–30 years	20 years
Land Area	0.007 acres/ton of MSW processed; typical plants require about 15–20 acres.	3–6 acres for a 200–500-TPD facility	2–5 acres for a 100-TPD facility
Capital Cost	**Modeled cost data (2020 $)** TPY — Million USD 33,000 — 33,000 66,000 — 66,000 99,000 — 99,000 165,000 — 165,000 198,000 — 198,000 330,000 — 330,000 660,000 — 660,000 990,000 — 990,000	**Reported cost data (2020 $)** **Capacity in TPY MSW: million USD** **~20,000 (55 TPD): $14** (gasification to electricity, Philadelphia, Pennsylvania). **93,000: $80** (plasma arc gasification, syngas-only configuration in Iowa; electric power configuration is about $106 million including utility interconnect fee and transmission line extension).* **175,000: $197** (steam-reforming gasification followed by Fischer-Tropsch process to develop syncrude, then upgrade to jet fuel and diesel in Nevada). **330,000: $271** (plasma arc gasification to electricity in an unknown location in the U.S. Gulf Coast).** **700,000: $619** (steam-reforming gasification followed by Fischer-Tropsch process to develop syncrude, then upgrade to jet fuel and diesel in Indiana). ** Original data in 2010 $, adjusted to 2020 $* *** Original data in 2015 $, adjusted to 2020 $*	**Modeled and reported cost data (2020 $)** **Capacity in TPY plastic waste: million USD** **~10,000 (30 TPD): $18** (plastic-to-fuel facility, unspecified location). **~20,000 (60 TPD): $23** (plastic-to-fuel facility, unspecified location). **~30,000 (100 TPD): $31** (plastic-to-fuel facility, unspecified location). **65,000: $32** (plastic-to-fuel facility, Virginia). **100,000: $260** (plastic-to-fuel facility, Indiana). **400,000: $680** (plastic-to-fuel facility, Georgia).

<table>
<tr><th></th><th>Combustion</th><th>Gasification</th><th>Pyrolysis</th></tr>
<tr><td>O&M Cost</td>
<td>Modeled cost data (2020 $)
<table>
<tr><th>TPD</th><th>Million USD/yr</th><th>USD/ton</th></tr>
<tr><td>50</td><td>$1.84</td><td>$111.68</td></tr>
<tr><td>100</td><td>$2.41</td><td>$73.11</td></tr>
<tr><td>200</td><td>$4.15</td><td>$62.82</td></tr>
<tr><td>300</td><td>$5.57</td><td>$56.24</td></tr>
<tr><td>400</td><td>$6.46</td><td>$48.96</td></tr>
<tr><td>500</td><td>$7.24</td><td>$43.85</td></tr>
<tr><td>600</td><td>$7.92</td><td>$40.00</td></tr>
<tr><td>1,000</td><td>$10.94</td><td>$33.16</td></tr>
<tr><td>2,000</td><td>$16.74</td><td>$25.36</td></tr>
<tr><td>3,000</td><td>$22.20</td><td>$22.42</td></tr>
</table></td>
<td>Reported cost data (2020 $)

Capacity in TPY MSW: million USD/yr

~20,000 (55 TPD): $1.5 (gasification to electricity, Philadelphia, Pennsylvania).

93,000: $10.7 (plasma arc gasification in Iowa).*

330,000: $9.2 (plasma arc gasification to electricity in an unknown location in the U.S. Gulf Coast).**

* Original data in 2010 $, adjusted to 2020 $
** Original data in 2018 $, adjusted to 2020 $</td>
<td>Modeled and reported cost data (2020 $)

Capacity in TPY plastic waste: million USD/yr

~10,000 (30 TPD): $2–$2.9 (plastic-to-fuel facility, unspecified location, cost range depends on whether feedstock is purchased or free).

~20,000 (60 TPD): $3–$4.6 (plastic-to-fuel facility, unspecified location, cost range depends on whether feedstock is purchased or free).

~30,000 (100 TPD): $4–$7 (plastic-to-fuel facility, unspecified location, cost range depends on whether feedstock is purchased or free).</td></tr>
<tr><td>Revenue</td>
<td>Revenue from tipping fees, selling electricity or combined heat and power, and relevant incentives. Additional revenue from selling recovered ferrous and nonferrous metals and rare-earth minerals.</td>
<td>Revenue from tipping fees, selling syngas or its byproducts, and relevant incentives. Additional revenue from selling waste heat or slag byproduct.</td>
<td>Revenue from tipping fees; selling bio-oil, char, and off-gases; and relevant incentives. Additional revenue from selling recovered recyclables (metals and minerals) or brown water.</td></tr>
<tr><td>Operational Considerations</td>
<td>• Low to moderate complexity. Well-established commercial process with little preprocessing or sorting required.
• Energy input is required in the process and can be supplied by its own production.
• High level of training needed for staff to run the system.
• High standards of maintenance and management are required.
• A properly designed and operated system is very safe. Hazard mitigation is more similar to the process industry than the energy industry.
• Medium ability to handle hazardous waste.
• High ability to destroy pathogens, waste pharmaceuticals, and other problematic chemicals.
• Valorization of byproducts can be costly, but disposal may not be an economic or environmentally friendly option (pros and cons of each option need to be weighted in decision-making).</td>
<td>• High complexity. Feedstock requires preprocessing, energy output is highly sensitive to feedstock composition, and there are numerous process flow variations.
• Energy input is required in the process and can be supplied by its own production. Waste heat can be used to dry incoming feedstock.
• High level of training needed for staff to run the system.
• High standards of maintenance and management are required.
• Considered highly safe based on historical process records. Higher safety concerns may exist due to the production of highly flammable gas under high pressure. Hazard mitigation is more similar to the process industry than the energy industry.
• Medium ability to handle hazardous waste.
• High ability to destroy pathogens, waste pharmaceuticals, and other problematic chemicals.
• Valorization of byproducts can be costly, but disposal may not be an economic or environmentally friendly option (pros and cons of each option need to be weighted in decision-making).</td>
<td>• High complexity. Feedstock requires preprocessing, energy output is highly sensitive to feedstock composition, and there are numerous process flow variations.
• Energy input is required in the process and can be supplied by its own production. Waste heat can be used to dry incoming feedstock.
• High level of training needed for staff to run the system.
• High standards of maintenance and management are required.
• A properly designed and operated system is very safe. Safety risks associated with production of medium-flammable potential gas. Hazard mitigation is more similar to the process industry than the energy industry.
• Medium ability to handle hazardous waste.
• Medium ability to destroy pathogens, waste pharmaceuticals, and other problematic chemicals.
• Valorization of byproducts can be costly, but disposal may not be an economic or environmentally friendly option (pros and cons of each option need to be weighted in decision-making).</td></tr>
</table>

	Combustion	Gasification	Pyrolysis
Materials Recycling and New Materials Production	• Preprocessing systems (RDF) allow for the extraction of metals, glass, and inorganic materials, resulting in the increased recycling and utilization of materials. • Mass burn facilities recover metal, glass, etc. from the ash after combustion, but these materials have lower value than the clean constituents prior to combustion. • In the United States, fly ash is often mixed with bottom ash and is typically used as an alternate daily cover in landfills. • In Europe, fly ash and bottom ash are treated separately, allowing for bottom ash to be used as aggregates. • There are efforts to develop technologies for valorizing fly ash by recovering minerals and salts to support material recycling and reuse.	• Preprocessing systems allow for the extraction of metals, glass, and inorganic materials, resulting in the increased recycling and utilization of materials. • High-temperature gasification and plasma gasification produce vitrified slag as a byproduct that can be used as aggregates (e.g., for making cement, roofing shingles, and as an asphalt filler). • Low-temperature gasification produces ash, which, similarly to bottom ash generated during combustion, could be treated and used as aggregates. • Tars present in the gas product stream from moderate-temperature gasification of MSW could be processed downstream catalytically to form additional syngas.	• Preprocessing systems allow for the extraction of metals, glass, and inorganic materials, resulting in the increased recycling and utilization of materials. • Char produced from pyrolysis of MSW can be used as a building material, for road surfacing, as a potential solid fuel source, and as a soil amendment if not limited by contaminants. • Char produced from pyrolysis of waste tires contains most of the original carbon black added in tire manufacturing, which allows its reuse in various rubber applications. • Wax produced from pyrolysis of plastic waste can be used as a heat source in the system, upgraded in petroleum refineries to chemicals and fuels, added to asphalt as fillers, used as a potential material for thermal energy storage, or used as a solvent for plastic waste in the pretreatment process. • Off-gases produced during pyrolysis can be used to fuel the process and/or dry the feedstock, which offsets the use of fossil fuel.
Incentives	WTE—a broad term including combustion, gasification, and pyrolysis, among other conversion technologies—is viewed as a renewable energy in about 30 states and thus eligible for incentives meant to promote alternative energy production. Financial incentives (e.g., production tax credit, investment tax credit) and regulatory polices (e.g., Renewable Portfolio Standard) are available at the federal, state, local, and utility level. A full list by state can be found at the **Database of State Incentives for Renewables & Efficiency** (dsireusa.org).		
Jobs	140,000-TPY MSW facility creates nearly 700 direct and indirect jobs during construction and about 40 permanent plant operator jobs. 150,000-TPY MSW facility creates about 200 construction jobs and 42 permanent jobs. 990,000-TPY MSW facility supports 150 permanent jobs.	~20,000-TPY (55-TPD) MSW facility creates 13 permanent jobs. 175,000-TPY MSW facility creates 500 construction jobs, 120 permanent jobs, and approximately 1,000 indirect jobs. 700,000-TPY MSW facility creates 900 construction jobs and 160 full-time permanent jobs.	65,000-TPY plastic waste facility creates 52 permanent jobs. 100,000-TPY plastic waste facility creates 80 permanent jobs. 165,000-TPY plastic waste facility creates 150 permanent jobs.
Emissions	Particulate matter: 20 µg/Nm^3 GHG footprint: 1.67 tons CO_2e/ton MSW NO_x: <400 mg/m^3 SO_x: 40 µg/Nm^3	Particulate matter: 12.5–14.1 µg/Nm^3 GHG footprint: 1.3–1.5 tons CO_2e/ton MSW NO_x: <200 mg/m^3 SO_x: 19 µg/Nm^3	Particulate matter: 5.7 µg/Nm^3 GHG footprint: 0.7–1.2 tons CO_2e/ton MSW NO_x: <50 mg/m^3 SO_x: 35 µg/Nm^3
Environmental Justice	About 25% of existing facilities are located in low-income communities. Mass burn and RDF facilities tend to skew toward lower-income communities. It is recommended that new facility locations be evaluated and assessed on a case-by-case basis to address environmental justice concerns.	Existing or planned gasification projects show no trend in surrounding population density or level of income. It is recommended that new facility locations be evaluated and assessed on a case-by-case basis to address environmental justice concerns.	Existing or planned pyrolysis facilities skew toward above the 50th percentile ranking for low-income communities, but no strong trend has emerged. It is recommended that new facility locations be evaluated and assessed on a case-by-case basis to address environmental justice concerns.

	Combustion	Gasification	Pyrolysis
Public Perception	Somewhat negative in the United States due to the following reasons: • Emissions. MSW combustion facilities have not always had air emissions control equipment, and thus gained a reputation as highly polluting. In Europe and Asia, modern plants employ sophisticated air pollution control equipment to ensure that emissions meet standards. In the United States, existing plants have also been upgraded. • Community impact. Many communities do not want the increased traffic, noise, and odor from trucks transporting MSW or to be adjacent to any facility handling MSW ("not in my backyard," or NIMBY concerns). This issue could be mitigated by siting any MSW handling facility in industrial zones, away from residential and commercial areas. • Energy justice. Proponents of the technology argue that these facilities are in a range of socioeconomic locales and note that many were built decades ago when the area surrounding the sites was likely very different from today (e.g., urban sprawl was likely not accounted for). To avoid these issues, it is critical that developers engage communities surrounding proposed facilities and consider the potential burden to vulnerable communities. • Perception that MSW combustion doesn't encourage recycling and waste reduction. Proponents of the technology argue that data from European countries and U.S. counties and municipalities that utilize MSW combustion show positive correlation with increased recycling and reduced amount of landfilled waste. This issue could be avoided by implementing aggressive local programs for source separation and recycling, with only the unrecoverable portion of the waste being combusted. Public perception is more positive in Europe and Asia (e.g., Japan). Properly operated and monitored facilities appear to have public support and are exploring carbon capture and sequestration options. Surveys have revealed that public awareness of MSW combustion is low, but once its role in integrated waste management is explained, the public develops a positive opinion.	• Given the lack of extensive commercial experience, public perception is unknown. • Negative public perception about MSW combustion may transfer to other WTE technologies, including gasification, by association. Conversely, this technology is considered an alternative WTE pathway, which may lead to a positive public perception and acceptance.	• Given the lack of extensive commercial experience, public perception is unknown. • Negative public perception about MSW combustion may transfer to other WTE technologies, including pyrolysis, by association. Conversely, this technology is considered an alternative WTE pathway, which imparts circularity to plastics and may lead to a positive public perception and acceptance.

	Combustion	Gasification	Pyrolysis
Challenges to Further Commercialization	• Public opposition due to negative perception. • High investment and operating costs.	• Techno-economic challenges to meet projected energy production, revenue generation, and emissions targets. • High investment and operating costs	• Techno-economic challenges to meet projected energy production, revenue generation, and emissions targets. • High investment and operating costs.

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Abbreviations

$\mu g/Nm^3$	micrograms per normal cubic meter
CO_2e	carbon dioxide equivalent
EPA	U.S. Environmental Protection Agency
GHG	greenhouse gas
kgoe	kilograms of oil equivalent, a standardized unit equivalent to the approximate amount of energy that can be extracted from 1 kg of crude oil with a net calorific value of 41.9 MJ/kg (Eurostat Glossary)
MSW	municipal solid waste
NO_x	nitrogen oxides
O&M	operations and maintenance
RDF	refuse-derived fuel
SO_x	sulfur oxides
TPD	short tons per day
TPY	short tons per year
WTE	waste-to-energy

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