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A review on municipal solid waste-to-energy trends in the USA

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ABSTRACT

This review on current US municipal solid waste-to-energy trends highlighted regional contrasts on technology adoption, unique challenges of each technology, commonly used decision support tools, and major operators. In US only 13% of MSW is used for energy recovery and 53% is landfilled. There are 86 WTE facilities that mostly use Mass-Burn and Refuse-Derived Fuel technologies and are concentrated in densely populated northeast (predominantly in New York) and the State of Florida. For the rest of the country most of the MSW ends up in landfills equipped with gas recovery, which is supplied to homes or used for electricity generation. However, there are many pilot and experimental systems based on advanced gasification and pyrolysis processes, which are viewed as potential technologies to respond to an issue of landfills nearing full capacity in various US states. These systems are viewed as "cleaner" (65% less toxic residue) than established mass burn technologies but not matured to commercialization due technical and cost hurdles. Operation and maintenance costs between $40-$100 per ton of MSW were reported for gasification systems. The heterogeneous nature of MSW, gas cleaning and air pollution controls are the main disadvantages. Key design and decision support tools used by the scientific community and major operators in US include: Techno-economic analysis, Life cycle sustainability assessment, and Reverse logistics modeling. A conclusion drawn from reviewed studies is that adoption of thermal WTE technologies in US could continue to increase, albeit slowly, in coastal and urban areas lacking suitable lands for new landfills.

1. Introduction

Waste-to-energy (WTE) conversion provides an excellent alternative to fossil fuel combustion [1]. The alternative energy source, MSW, burns practically more cleaner than many fossil fuels [2]. Emissions (dioxins, furans, mercury, cadmium, lead, hydrochloric acid, sulfur dioxide, and particulates) from the municipal solid waste-to-energy (MSWTE) facilities in the US were found to be lower than comparable fossil fuel facilities [2]. The source of municipal solid waste (MSW) is the trash collected from household, industrial, commercial, construction, and municipal sources [3]. The acknowledgement of MSWTE as renewable energy generation is promoted by US policy makers in form of tax credits and subsidies to reduce dependency on fossil fuels [4]. The US government also aims to increase the renewable energy generation from its present 12.6% to 25% by the year 2025 [5]. Many WTE reviews have covered the advances in thermochemical and biochemical methods of energy production from solid waste [6–9]. It however appeared to us that there are not many US specific information for waste-to-energy in published journal articles. Although there are many reports from vendors and government agencies, these do not give a current and critical picture of WTE industry in the US. These reports are not well-known platforms to the scientific readers in general, and the data for various US states is very scattered. The WTE practice in US seemed to fall behind many European and Asian countries. Analyzing the recent trends in WTE developments could help in solving the issue of waste management and energy security for the US. State of the art technologies like gasification, pyrolysis, incineration/combustion, and anaerobic digestion with biogas recovery have utilized MSW as feedstock to generate electricity, heat, combined heat and power, and fuels. The byproducts of WTE conversion are also useful in many cases, such as compost (used as

Abbreviations: MSW, municipal solid waste; WTE, waste-to-energy; EfW, energy-from-waste; MSWTE, municipal solid waste-to-energy; MBT, mechanical biological treatment; US-EPA, United States Environmental Protection Agency; RDF, refuse-derived fuel; FBG, fluidized bed gasification; CFB, circular fluidized bed; BFB, bubbling fluidized bed; AD, anaerobic digestion; LCA, life cycle assessment; CFD, computational fluid dynamics; J/g, Joules/gram; MW, megawatt; TEA, techno-economic analysis.

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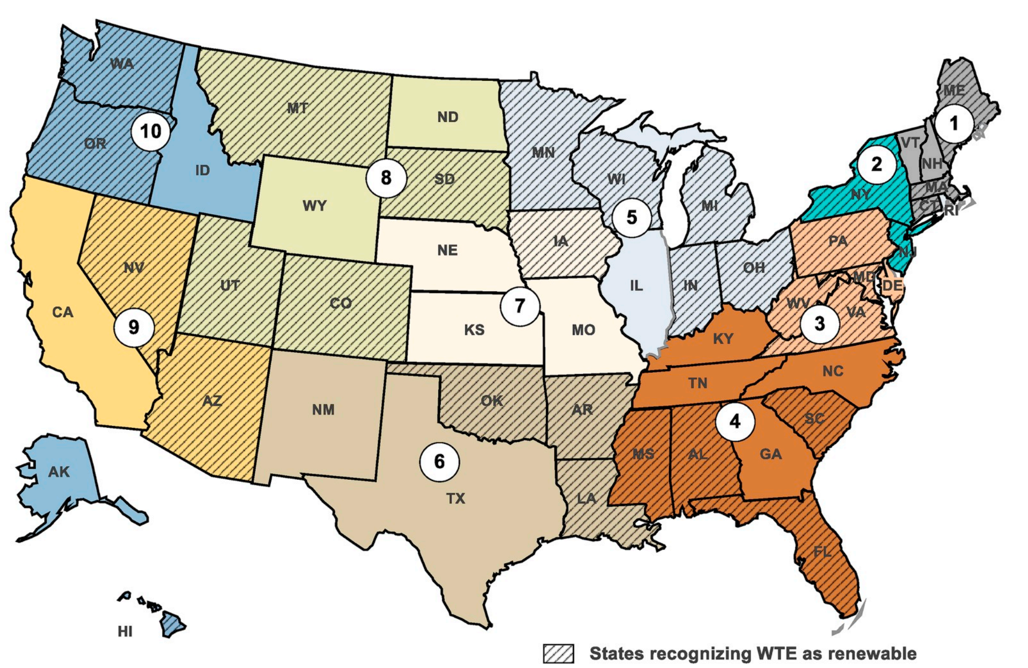
manure), char and slag (for construction material). A review on WTE feasibility for the US will get attention of stakeholders including policy makers, investors, and scientists and can help them select the most sustainable technology. The present review made an attempt to provide a comprehensive overview of the current status and trends in WTE practice and feasibility of various technologies in US.

The thermal and non-thermal WTE technologies, their application based on current US waste streams, as well as their advantages and drawbacks in context of environmental, technical, and cost structure will be discussed in this review. A section on trends, perspectives, policies and practical applications will follow the WTE technology evaluation. Lastly, conclusions of the study will be presented.

Over the past decade countries all over the world have been exploring ways to better use their MSW [10–12]. The increase in MSW can be related to the rapidly growing population and the per capita income. According to the US Census Bureau, the US and the projected world populations were 328, 231, 337 and 7,543, 334, 085, respectively as of January 2019 [13]. The United States Environmental Protection Agency (US-EPA) reported 238.5 million tonnes of MSW generated in 2015, showing a significant increase from the previous ten to twenty years [14]. With the world's biggest economy of 20.4 trillion dollars, the US generates the largest amount of MSW globally but utilizes about 12.8% of it for energy recovery [14–16]. In 2015, out of 238.5 million tonnes of generated MSW, the majority (52.5%) was landfilled, and the remaining was recycled (25.8%), composted (8.9%), and incinerated for energy recovery (12.8%) [14]. Due to greenhouse gas emissions, leachates, and land availability issues in overly populated cities, US states are moving from the traditional landfill practice to WTE as a sustainable alternative [2,17,18]. However, WTE systems are relatively rare due to high capital costs and lack of sufficient local government support. Globally, 765 MSW based WTE plants exist with an annual capacity of 83 million tonnes [19]. The US currently employs 86 of these MSWTE combustion facilities across 25 states [19,20]. A majority of these are mostly located in Florida and Northeastern states like New York that use a mass burn technology to combust MSW without much preprocessing [21–23]. Fig. 1 illustrates MSW disposal in 10 US-EPA regions and the population figure generating this waste [24,25]. Fig. 1 also represents the 34 states in the US which consider the WTE conversion as renewable. The north-east coastal regions (1–4 in Fig. 1) has the highest population density and accounts for the majority of the US WTE practice. In the mid-western regions of the US (5–8 in Fig. 1) landfill is the dominant technology for waste disposal with no to negligible WTE. The west coast regions (9 and 10 in Fig. 1) favor more recycling and composting of their waste than WTE. The coastal regions are more densely populated in comparison to the midwest US regions and therefore have to deal with higher amount of household trash. This clearly reveals that there is a significant challenge in improving the MSWTE generation in the midwest and west coast regions.

Increasing urbanization has led to a rapid growth in MSW in other countries of the world as well, creating urgency in the local governments to properly plan waste valorization. Recently China issued a series of policies to promote WTE practice and diversion from landfills [26–30]. China had 200 waste incineration plants in 2014, and the Chinese government declared that this number would grow to 300 by the end of 2020 [31]. India is the second most populated country in the world with a waste management scenario predominantly based on landfills, but increasing environmental regulations on landfill-based pollution are slowly moving the focus to cost-effective WTE technologies [32–36]. India has only eight operational WTE thermal plants with a total capacity of 94.1 MW, and an additional 50 initiated WTE projects near completion [37]. Energy recovery from MSW is also gaining momentum in the other top ten most populated countries of the world such as Indonesia [38,39], Brazil [40,41], Pakistan [42–44], Nigeria [45], Bangladesh [46,47], and Russia [48,49], as sustainable waste management alternatives. Japan leads the world in recovering energy from waste with almost 78% WTE conversion with the remaining 22% sent to



US Regions	1	2	3	4	5	6	7	8	9	10	Total
WTE (in %)	41	21	17	6	4	0	0	2	2	3	96
Landfill (in %)	24	52	54	73	76	78	76	79	51	53	616
Recycling (in %)	27	23	24	19	15	11	22	9	37	32	219
Composting (in %)	8	4	5	2	5	11	2	10	10	10	67
Population (in millions)	14.8	28.4	30.1	66.4	52.5	42.4	14.1	49.7	49.7	13.5	361.6

Fig. 1. MSW-to-energy landscape of the ten US EPA regions in year 2015 (Adopted from Refs. [24,25]).

recycling and composting [16,50].

In many European countries, WTE facilities are technologically more advanced than in the U.S [50]. Europe has 455 WTE plants in 18 European countries [51]. Denmark, Sweden, Switzerland, and Norway are the top four European countries in WTE sector [50]. In Europe, an estimated 1.3 billion tonnes of waste is generated each year, of which around 241 million tonnes is MSW, and the remaining waste coming from manufacturing, construction, and water treatment sources [52]. The European Union is forcing the closure of all landfills under the Landfill Directive issued in 1999, and mandating that existing landfills meet new, more rigorous leachate and pollution control standards, thus diverting waste from landfill towards recycling and energy recovery [51, 53]. The waste incineration directive in Europe has also set standards to reduce air and groundwater pollution from WTE emissions [52]. Globally, waste disposal option uses proportionally higher amounts of landfills and some incineration with energy recovery [50,54,55]. Urbanization, environmental awareness, regulations, and market forces are influencing the change in this trend.

Besides population growth and amount of MSW generation, per capita income of the countries significantly influences their waste management and WTE practice. Low income (Gross National Income: $1005 and lower) to lower middle income (Gross National Income: $1006 to $3975) countries in Asia (India, Bangladesh, Indonesia, Pakistan, Afghanistan, Thailand, Malaysia, Vietnam, Iran, Nepal), Africa, and South America have little to no source separation of MSW, dump waste in open areas and uncontrolled landfills, and have minimal air and leachate emissions regulations [56]. The majority of MSW from these low income or developing countries is biodegradable organic waste (approx. 64%) which is utilized in few cases for anaerobic digestion and landfill gas recovery [56,57]. Upper middle income (Gross National Income: $3976 to $12275) and high-income population (Gross National Income: $12276 and higher) in developing or developed countries (like Japan, Taiwan, Singapore, South Korea, USA and parts of Europe) practice more source separation, 3Rs-concept of reduce-reuse-recycling (of plastics, metal, and glass); and composting [56]. The higher income countries generate larger quantity of MSW than low and middle income countries, however only about 28% of the waste is biogenic. The non-organic nature of the MSW composition is a major driving factor for implementation of WTE in higher income countries [57].

1.1. Characterization of the US MSW

Characterizing the national MSW waste stream is the first significant step in designing an efficient WTE program. Site specific studies identifying the MSW composition, and analyzing total solids content of the collected waste by sampling, manually sorting or hand-picking, and weighing the individual waste components is the initial step [58]. Elemental evaluation of a MSW stream has revealed C, H_2, O_2, H_2O, and ash to be 17–30, 1.5–3.4, 8–23, 24–34, and 18–43% by weight, respectively, and the average specific heat of combustion as 5–10 MJ/kg [59]. Similar elemental analysis of MSW from the ten regions of the US (Fig. 1) needs to be carried out for exploring their WTE potential and identification of the research gap. Proximate analysis to find the weight percentages of moisture, volatile matter, fixed carbon and ash, and ultimate analysis for weight percentages of chemical elements (carbon, hydrogen, nitrogen, oxygen and sulfur) gives relevant input data in determining the heating values of the solid waste [60]. Additionally, thermal properties and degradation behavior of various MSW components need investigation using thermogravimetric and derivative thermogravimetric analysis to evaluate how different MSW components from residential, industrial, commercial, construction & demolition, and municipal sources can combine to yield high energy [61–63]. The US waste stream is characterized by the US-EPA to contain paper products and cardboard as the most significant percentage (25.9%) followed by food waste (15.1%), yard waste (13.2%), plastics (13.1%), wood (6.2%), rubber and leather (3.2%), textiles (6.1%), metals (9.1%), glass (4.4%), other materials (e.g. electronic-waste 2%) and miscellaneous inorganic wastes (1.5%) [14]. Metal, glass and miscellaneous other inorganic waste components account for the non-combustible portion of the MSW with negligible calorific values. After separation of this non-combustible fraction of MSW and any paper or plastic material that can be recycled, the leftover MSW or "Residual MSW" is more suitable and preferred waste stream for WTE conversion.

2. Current MSWTE situation in the US

WTE or energy from waste (EfW) within the US is a debated topic and speculated as a potential technique to divert waste from existing landfills [64]. Landfill remains the conventional and most economically viable option for the U.S waste stream, due to land availability [2,16, 24]. Although several thermal and non-thermal/biological MSW treatment options are accessible for generating energy in the US there exists a significant gap in employing WTE policy predominantly due to a high cost of construction of new facilities, financial risks, and marginal economic benefits [65]. The deployment of WTE is contingent on several techno-socio-economic impact factors. Technologically, the composition, volume, and energy content (calorific/heating value) of the MSW, thermodynamic and chemical conditions in which the plant operates, as well as the overall efficiency in energy yield are the critical factors. Additionally, incineration ought to be the option for MSW valorization if the average net calorific value of waste is at least 7 MJ/kg, as per energy experts [3,66]. An optimized WTE plant is expected to have a combustible MSW supply of at least 100,000 tonnes per year [3]. This waste supply varies with region, locality, and season. Each waste treating process requires some specific reaction conditions, amount of oxygen-enriched air, moisture content, operating temperature, pressure, pre-treatment steps, gas cleaning, and tar, char or slag control/removal [8,67–70]. Dry MSW is the most suitable feedstock for incineration, gasification and pyrolysis, all of which requires excess to no air/oxygen supply for combustion and operates at high temperatures of 500 to more than 1000 °C [3]. The thermochemical processes generate oxidized or reduced gaseous pollutants like hydrogen sulfide, carbonyl sulfide, SOx, NOx, and solid ash, char or vitrified slag [3]. The wet and biogenic fraction of MSW is more suitable for microbial degradation to produce methane-rich biogas by anaerobic digestion and landfill gas recovery. Further details on these thermochemical and biological technologies are provided in the later sections. Fig. 2 summarizes the WTE technologies available for MSW in the US and a decision-making flowchart. All combustibles with low to high calorific value stand fit for WTE conversion [8]. The non-combustibles like metals and glass are recycled if economical or landfilled [2]. Some of the combustible fraction of MSW such as paper, cardboard, and plastic is also recycled. Calorific value of this residual combustible MSW can be improved with different energy densification steps [71]. Thermal processing is more suitable for dry MSW with little or no moisture content [8]. Non-thermal processing like anaerobic digestion, landfill gas recovery or composting is preferable for high moisture-containing MSW and particularly its biodegradable fraction [72–74]. WTE with biogas/methane recovery from non-thermal treatment should be obtained with a selective collection system for the biodegradable waste or will need advanced pre-treatment for segregating the bio-decomposable portion from the overall waste. Landfilling should be the option for waste disposal only after a significant volume reduction by either WTE conversions or recycling [75]. A critical evaluation of these processes and parameters is required to assemble the decision-making building blocks, attract potential investment opportunities, influence the marketplace, and regulate environmental policies for MSW disposal.

2.1. Thermal treatment options

At present, the US seems to be focusing more on thermal waste-to-

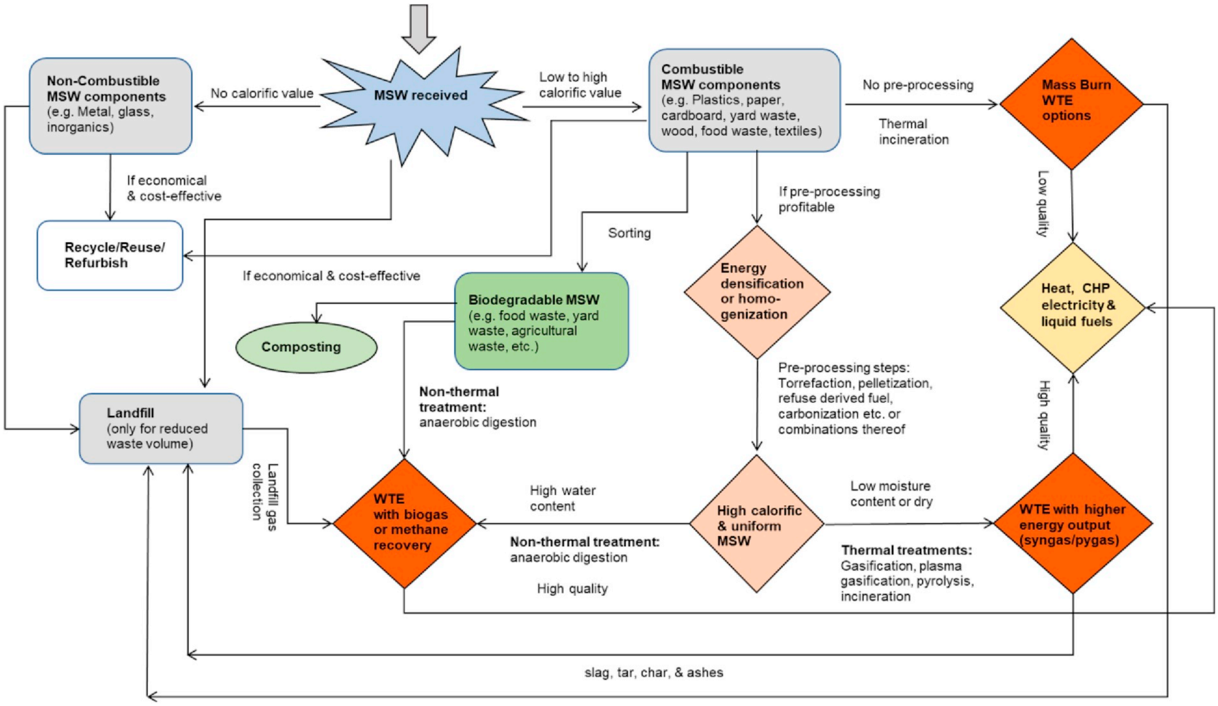


Fig. 2. Decision-making flowchart on available WTE technologies for MSW valorization.

energy options for its MSW management. Lancaster county's MSWTE facility in the state of Pennsylvania, operated by Covanta Holdings Corp., processes 1200 tons of MSW per day, with 99% below air emission limits, setting an exemplary WTE system near the capital region [76]. Florida has the highest capacity in the US to valorize MSW with almost 11 operational thermal WTE plants [77,78]. Covanta Holdings Corp. has around 30 energy from waste (EfW) facilities widespread across the coastal regions of the US which utilize the MSW from the local urban population for generation of power [79]. California has few mass burn facilities of which Southeast Resource Recovery Facility and Stanislaus County Resource recovery facility, both operated by Covanta Holding Corp. together have a WTE capacity of 2180 tons of MSW per day, generating 58.4 MW of electricity [50]. Incineration is the primary thermal conversion method practiced in the US with gasification and pyrolysis as the rest. These thermochemical systems differ widely in their applications, costs, operating parameters, and overall efficiency [23,35,80–85]. All these processes require the MSW to be dry or have little moisture content nevertheless they can handle a wide variety of combustibles [8,83,86].

2.1.1. Incineration or combustion

A majority of the US states classify incinerating MSW as a renewable energy source [50]. It is the most common thermal conversion for carbon containing fuels such as coal, biomass, or MSW [87]. Incinerators have a growing number of concerns and may be unable to cover the operating cost. The tipping fees for incinerating waste is two to three fold more than recycling, composting, or controlled landfilling. Incineration is an exothermic process involving complete oxidation of MSW and generates flue gas, ash, and heat [84,88,89]. Air pollution control systems reduce the half-hour average air emission limit of waste incineration plants below their regulated emission limits; for example for emissions like NOx (400 mg/Nm^3), dioxins and furans (0.1 ng/m^3), sulfur dioxide (200 mg/Nm^3), carbon monoxide (100 mg/Nm^3), HCl (60 mg/Nm^3), HF (4 mg/Nm^3), total organics (20 mg/Nm^3), mercury (0.05 mg/Nm^3), and metals (Cd, Ti, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, and V – 0.05 to 0.5 mg/Nm^3) [90]. A recent analysis of air emission violations found the penalties imposed by the US favor updating emission systems more frequently than the comparable European Union's emission structures [90]. Mass burning is the most common thermal treatment type, where unprocessed or unsorted MSW is burned in large incinerators in the presence of excess air, with a boiler and a generator for producing electricity. The US has 58 mass burn facilities, 4 modular facilities and 13 refuse derived fuel (RDF) based facilities [50]. Most mass-burn facilities have a sloping or movable grate that vibrates to agitate the waste and mix it with air. The other mass burn incineration alternatives are rotary kiln and fluidized bed [67]. Modular systems are small sized and can be easily transported. Modular systems also burn untreated and mixed MSW. The major incineration technologies operational in the US based on the mass burn, RDF, and modular systems are presented in detail in Table 1. Almost all of these technologies receive tonnes of MSW feedstock each day and distribute electricity to the local population.

Advantages: Incinerators take unprocessed or unsorted MSW. These systems not only recovers energy from burning the waste, but also reduces the solid waste volume by almost 90%, and provides a diversion from landfilling [94].

Disadvantages: Mass burn systems require expensive air pollution control systems and can face stringent permit requirement in some US states. Some incinerators require pre-drying of the feedstock if the moisture is too high and the leftover ash contains leachable inorganic pollutants. These pollutants needs proper disposal and are mostly landfilled.

The current trend in incineration and other thermal conversions is to upgrade the MSW feedstock by energy densification pre-treatment steps. The densification systems use pellet miller, tablet press, roller press, extruder, cuber, briquette press, and pressure agglomerator for shearing, mixing, and compacting the waste matter [95]. Incineration of pre-treated and homogenized waste needs additional processing steps; however it improves the net energy gain or energy recovery, and combustion quality of the MSW feedstock. It lowers the waste volume, size, and moisture content considerably and the overall cost for storage and transportation. Incineration of these energy-densified waste offer efficient energy production with reduced emissions. Table 2 illustrates the current energy densification techniques used in waste management.

Table 1
Current operational Mass Burn, Refuse derived fuel (RDF), and Modular Incineration technologies in the US states (Adopted from Ref. [50]).

Incineration type	Remarks[a]	Locations	WTE Operators
Mass burn and RDF	Accepts 7.4 million tons of MSW or post-recycled waste each year; generates 5.8 billion kWh of energy each year; generates around 1123 tons of NOx emissions per year; use activated carbon to remove mercury and trace organic compounds; lime treatment to neutralize acidic gases; fabric filter for particulates removal; combustion temperatures exceed 1093.3 °C in boilers	California, Connecticut, Florida, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Virginia, Washington & Pennsylvania	Wheelabrator Technologies [91,92]
Mass burn, RDF and Modular	Accepts 21 million tons of MSW each year; generates 9 million MWh electricity each year; operates 60–90% below the required emission limit; reduced air emissions of NOX, sulfur dioxide and hydrochloric acid	Alabama, California (Modular), Connecticut, Florida, Indiana, Maryland, Michigan, Massachusetts, Hawaii, New Jersey, New York, Oklahoma, Oregon, Virginia & Pennsylvania	Covanta Holding Corporation [16,93]
Mass burn	Accepts 182,500 tons MSW per year; generates 32,850 MWh electricity; provide power to 169,560 people	Florida	Engen LLC.
Mass burn	Accepts 200,750 tons MSW per year; generates 32,193 MWh electricity; provide power to 250,000 people	Maine	Ecomaine
Mass burn	Accepts 91,250 tons MSW per year; generates 10,950 MWh electricity; provide power to 65,000 people	Maine	Mid-Maine Waste Action Corporation
Mass burn	Accepts 73,000–442,380 tons MSW per year; generates 1095–80,373 MWh electricity; provide power to 42,000–1,156,212 people	Minnesota	GRE HERC Services LLC; Olmsted County WTE; Perham Resource Recovery Facility; and Pope/Douglas WTE
Mass burn	Accepts 292,000 tons MSW per year; generates 56,940 MWh electricity; provide power to 426,347 people	Washington	City of Spokane WTE facility
Modular	Accepts 32,850 tons MSW per year; generates 4380 MWh electricity; serves 75,000 people	Wisconsin	Zac Inc.
Modular	Accepts 262,800 tons MSW per year; generates 8760 MWh electricity; provide power to 126,000 people	Minnesota	Polk County
Modular	Accepts 73,000 tons MSW per year; generates 41,610–52,560 MWh electricity	New York	Oswego County Energy recovery facility
RDF	Accepts 1.0 million ton MSW per year; generates 151,110 MWh electricity; provide power to 1,208,813 people	Connecticut	NAES Corporation
RDF	Accepts 146,000–992,800 tons MSW per year; generates 41,600–61,320 MWh electricity; provide power to 250,000–1,280,891 people	Minnesota, Wisconsin	Xcel Energy
RDF	Accepts 63,875 tons MSW per year; generates 35,040 MWh electricity; provide power to 69,898 people	Iowa	Resource Recovery System, City of Ames
RDF	Accepts 262,800 tons of MSW per year; generates 25 MW electricity; provide power to 400,000 people	Maine	ESOCO Orington Inc. or PERC Holdings LLC
RDF	Accepts 365,000 tons MSW per year; generates 54,750 MWh electricity; provide power to 850,000 people	Minnesota	Great River energy

[a] Descriptions are based on company's claims as published in the company website.

2.1.2. Gasification

The growing popularity of MSW gasification in the US is the result of increasing technical, environmental and economic concerns with waste incinerators. Currently, the US has 33 gasification plants running mostly on carbon-based fuels such as coal, petroleum, and gas, with smaller amount of biomass/waste feedstock [111]. There is an increasing demand for developing small-scale and compact MSW gasifiers in towns, cities or on military bases [111]. Gasification plants could be integrated with pre-existing industrial and thermoelectric plants, because of their flexibility and compactness [112]. Table 3 provides details on a few operational gasification technologies in the US based on biomass/waste.

Gasification breaks MSW into a mixture of carbon monoxide, hydrogen, and carbon dioxide by-products, collectively known as syngas (synthetic gas or producer gas) with useable heating value through a sequence of exothermic and endothermic reaction steps [120–123]. The process involves a partial or incomplete oxidation carried out in presence of controlled amounts of oxidants (air, oxygen, or steam) at very high temperatures above 550 °C [124]. The heat content of syngas in commercial scale-ups is also improved by carrying out co-gasification of MSW with coal [125,126]. The heating value of MSW (11,000–12,000 J/g) is low compared to RDF (12,000–16,000 J/g) and coal (21,

Table 2
Energy densification and homogenation techniques for MSW.

Energy densification and homogenation techniques	Remarks
Refuse derived fuel (RDF) [96,97]	RDF systems use shredding or extrusion, magnetic separation, presorting, separating out non-carbonaceous and non-combustible matter in MSW to produce a uniform, combustible, and higher calorific waste for combustion in incinerators.
Torrefaction [98–103]	Torrefaction is another means of producing energy dense biomass with improved grindability, and hydrophobicity. It is considered a mild pyrolytic conversion of biomass into energy dense storable product.
Pelletization [104,105]	Pellets are mostly produced from biomass waste, wood, and waste from agricultural and food industries. The quality and durability of pellets depends on applied pressure, die temperature, particle size of the feed, amount of moisture, operating conditions, and presence of binder such as starch, wood powder, lignosulphate, etc. Waste pellets are mostly utilized for incineration/combustion as the combustion efficiency of pellets is higher than their raw materials.
Combining Pelletization with torrefaction/RDF [106,107]	Modification of carbonized RDF or terrified biomass by thermal pretreatment generates pellets with increased energy density and uniformity in size.
Solid recovered fuel (SRF) [108]	SRFs are produced by shredding and blending a mixture of plastic and paper materials and then compressing it into a solid form; calorific value of SRF is very high; also used for co-firing with coal in cement kilns
Hydrothermal carbonization (HTC) [109,110]	Thermochemical conversion that converts wet biomass into hydrochar of higher heating value without pre-drying; Hydrothermal liquefaction (HTL) and hydrothermal gasification (HTG) are upgraded forms of HTC

000–32,000 J/g) [127]. Plastics and rubber have the maximum heating values in MSW while food waste and yard trimmings have the lowest [127]. Conventional gasification of solid waste takes place in a variety of gasifiers or blast furnaces comprising downdraft and updraft fixed bed, fluidized bed, entrained flow, and twin bed [84,124]. Fixed bed gasification of MSW generates small scale power, less than 1 MW, whereas fluidized bed gasification (FBG) of other feedstock can produce 15–150 MW of power [123,128]. FBG provides great advantages such as uniform temperature distribution, elevated operating temperatures, ease of operation, and easy scale up [84,129]. Dual fluidized bed (DFB) gasifier is another promising technology to produce high-quality syngas [130–132]. The char in DFB gasifiers is converted in the combustor, while in typical FBGs, char conversion is rather limited [133]. The efficiency of biomass gasification is either based on energy (lower heating value, LHV) or exergy (chemical and physical). The efficiency is defined as the ratio between the exergy of the syngas to the exergy of the biomass [133]. Concentrated Solar Power (CSP) can be used to supply the initiation energy required for gasification and improve the target carbon efficiency significantly. For the biomass-to-liquid (BTL) process a carbon efficiency of 60–70% can be reached with the utilization of CSP [134]. Byproducts such as tar and char are primarily eliminated from a gasifier by optimizing the operating parameters such as air or steam to biomass ratio, temperature, pressure, gasifying agents, use of catalysts, and gasifier design [128,135–137]. Almost 100% of tar removal is feasible with catalytic treatments. Nickel catalysts are highly efficient but get deactivated due to deposition of carbon on catalyst surface [135]. Secondary tar removal methods involve physical or mechanical treatment methods outside of the gasifier. Table 4 summarizes current advances in secondary tar removal techniques in the gasification process. Techno-economic concerns in commercializing gasification are to

Table 3
Current operational MSW gasification technologies in the US states.

Gasification Type[a]	Remarks[a]	Location	WTE Operators
Modular Gasification [113,114]	Accepts untreated MSW; no pre-treatment steps needed; accepts loose, bagged, or pelletized waste; accepts 365–730,000 tons MSW per year; operates on different feedstocks like tires, mattresses, furniture, and construction debris; two-stage biomass conversion to electrical energy; first step gasification at 450–550 °C; second step combustion with oxygen at 982–1093 °C; simple design; custom scalability; loads 1102.31 tons MSW per combustion cycle; 95% volume reduction; generates super-rich syngas & ash; minimizes NOx emissions, particulates, and toxic volatile metals; mostly used for waste destruction with capability for power production	Idaho, Alaska	Dynamis 3.0 Thermal Conversion Technology[a]
Gasification in fixed bed gasifier [115,116]	Accepts wide variety of MSW like packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paints, batteries, tires, medical waste, construction & demolition materials and hazardous waste; accepts 4022–36,500 tons MSW per year; feedstock is shredded before feeding; generates energy-dense syngas; ultra-high temperature around 2200 °C; use purified oxygen (contrary to nitrogen-rich ambient air); has zero direct emissions	California, New Jersey	Sierra Energy's FastOx® gasification system[a]
Atmospheric Circular Fluidized Bed gasification [117]	Accepts biomass like wood chips, bark, sawdust, RDF and switchgrass; gasification temperature is 830 °C in one vessel using steam; high throughput system	Ohio, Vermont	The BCL/SilvaGas™ (earlier called BCL/Ferco) technology

(continued on next page)

Table 3 (*continued*)

Gasification Type[a]	Remarks[a]	Location	WTE Operators
Bubbling fluidized bed gasification and combustion [117]	Accepts biomass, RDF and MSW; gasification of feedstock at 800–850 °C	Maryland	MTCI's PulseEnhanced™ steam reforming gasification
Entrained-flow steam gasification [118]	Accepts biomass; no tar formation; modular gasification system	Texas and Louisiana	Brightstar Synfuels Co.
Downdraft moving-bed gasification [118]	Accepts biomass; operates at 982 °C	North Carolina	Thermal Technologies Inc.
Updraft gasification [118]	Accepts biomass, rice husk, switch grass, paper mill sludge, rice straw, bagasse, and poultry litter; generates electricity and heat	Oklahoma and Arkansas	Primenergy Inc.
Air-blown, high pressure gasification [118]	Accepts MSW, RDF, tires, sludges, biomass, etc.; generates power; mass production technology	Texas	Cratech Inc.
Modular gasification [119]	Accepts MSW and biomass; HelioStorm ionic gasification system for small scale energy generation; Hyper-high temperatures of 10,000 °C; integrate WTE with other technologies like solar power, wind power and microgrid energy storage	Virginia	Cogent Energy Systems Inc.

[a] Descriptions are based on company's claims as published in the company website.

meet projected energy production, revenue generation, emission targets, and reduce operation and maintenance costs. Secondary tar removing methods provides economically viable and simple solutions for improving the gasification process.

Advantages: Gasification is a cleaner thermochemical option than incineration [114,115]. The reaction conditions inside a gasifier is reductive which prevents formation of dioxins, furans, and NOx and also improves the quality of solid byproducts like prevents oxidation of metals, and generates inert and vitrified ash [141]. Syngas after proper cleaning and scrubbing generates superior quality fuels and cleaner energy [141]. Clean syngas can be converted by Fischer-Tropsch synthesis to liquid fuels for use in internal combustion engines [142].

Disadvantages: Requires a series of syngas pre-treatment and cleaning that adds challenge and cost [112,124,143,144]. Gasification of waste using catalysts improves the yield and purity of syngas; nevertheless this increase the production cost [145–147]. Gasification is more suited for homogeneous wastes (such as wood chips, waste tires, paper and cardboard, and plastics); the heterogeneous nature of MSW makes gasification and syngas cleaning more challenging. To increase the heating value, gasification may require preprocessing of waste by shredding and densification using steps like RDF, torrefaction, and pelletization [99]. Though gasification is a well-established technology it needs to deal with tar, char, and particulates in the syngas [135,148–150]. Tar can condense at low temperatures and clog the downstream pipes and equipment [137]. Companies have not yet overcome these challenges, hence not many large-scale stand-alone waste gasification plants can be found in the US or the world.

Table 4
Current advancements in secondary tar removal techniques in gasification.

Tar removal techniques	Advantages
Nickel/coalchar and Ni/woodchar catalyst [138]	• Removes 97% of tar in syngas; cost-effective; catalyst gets deactivated later (tar conversion/reforming with catalysts)
Bio-oil scrubber and char-bed filter [139]	• Overall 98% of tar is removed of which 81.5% is removed by char-bed filter; cost-effective; use gasification byproducts for tar removal (tar removal by gas washing and adsorption)
Passing over hot char particles [140]	• Removes 75% of tar at 800 °C (by adsorption)

2.1.3. Plasma assisted gasification

There is an increasing interest in plasma-assisted gasification of MSW in the US [151,152]. Plasma gasification can use a range of waste types including MSW, tires, and hazardous waste [121,153,154]. This technology uses an AC or DC plasma torch as a heat source to pyrolyze solid waste components into syngas [153]. The heat energy is generated by a plasma torch which passes an electric current through a gas, usually air or oxygen used for oxidation [155,156]. Fluidized bed plasma gasification in solid waste is an emerging and promising technology which should enhance performance of gasification [157].

Advantages: It is efficient and a cleaner WTE technology. The plasma stimulates greater syngas yields than regular gasifiers. It operates at very high temperatures, often greater than 5000 °C, and the inorganic waste components are removed as inert vitrified slag, with minimal toxic element leachability [151,158]. The amount of toxic materials in the product syngas is much lower than incineration and conventional gasification techniques. Additionally, plasma gasification exhibits much lower slag leachate toxicity than incinerator ash in landfills [159].

Disadvantages: Although this technology was recognized in some metals and chemical industries, its use in solid waste is relatively recent [160]. No commercial MSW plasma gasification technology is known to be operational in the US so far, most of these systems are currently still in demonstration or experimental validation stage for industrial and pilot scale use [59,154,161,162]. PyroGenesis Canada Inc. installed and operated the first commercial plasma gasification system at the US Air Force base for processing MSW, hazardous, and biomedical waste and generated electricity from the syngas [163]. Currently this facility is not in regular operation [164]. US military bases are therefore exploring the feasibility of the available WTE techniques for waste management solutions at their installations [5]. A few projects in the developmental stage include InEnTec Chemical LLC, Geoplasma Inc., Green Power Systems LLC, and GasPlasma technologies [165–167].

2.1.4. Pyrolysis

Pyrolysis is another attractive substitute to MSW incineration in the US. The rapid development of pyrolysis technology commonly called plastics-to-oil could contribute USD billions to the US economy [168]. RES Polyflow based in Ohio is an industry leader converting plastics and mixed polymers pyrolytically to fuels without significant sorting or cleaning [169,170]. Pyrolysis thermally degrades the polymers and plastics containing large chain hydrocarbons in the absence of external air or oxygen supply producing a mixture of combustible gas, liquid bio-oil, tar, and char at high temperatures of 300–600 °C [112]. Catalysts, if used in pyrolysis, improve the product yield and reduce the energy need for the process. Various catalysts range from nickel and ruthenium built catalysts, zeolites, and dolomite [171,172]. Pyrolysis has also gained significant attention owing to high liquid yield under high heating rates, a reaction temperature of 425–600 °C and short residence time of vapor in the reactor [63]. Pyrolytic heating can be accomplished by conventional or by microwave means [173–176].

MSW is an efficient feedstock for pyrolysis, and the process can be commercialized to obtain high grade fuel [117,177,178]. A co-pyrolysis of different components of MSW observed that synergistic interactions of various MSW components, especially plastics, produce fuels with high heating values comparable to conventional fossil fuels [63]. Most of the industrial MSW pyrolysis facilities are integrated with gasification or combustion processes [179]. The reported pyrolysis reactors include fixed-bed, rotary kiln, fluidized-bed, and tubular reactors, but only rotary kiln and tubular reactors are applied to scale-up facilities [180–182]. The output from commercial pyrolysis systems is mainly power or heat; bio-oil, reformed syngas, and char. The char from the pyrolysis of MSW is of high calorific value and thus a potential solid fuel source.

Advantages: The feedstock is heated directly by conventional or by microwave means and there is no need for feedstock shredding. The pyrolysis process can be used for large scale commercialization due to its low-cost production and flexibility. Natural catalysts like char, zeolites, and dolomites are readily available and increase the efficiency in pyrolysis [63].

Disadvantages: Physical separation of the incombustibles (metal and glass) beforehand, avoids the adverse effects during pyrolysis. Requirement of catalysts increases costs and some natural or synthetic catalysts have some limitations due to the structure, physical and chemical properties. For example, impurities and contaminants in the heterogeneous MSW can deactivate the catalysts in the feedstock. Synthetic catalysts like nickel and ruthenium are high cost and get deactivated at a much faster rate than the natural catalysts [63]. Temperature is kept relatively high to maintain catalysts in optimum particle size range and in the activated form. The char produced from pyrolysis could be contaminated with heavy metals and organic pollutants. MSW pyrolysis pygas could be contaminated with undesirable gases such as HCl, H_2S, SO_2, and NH_3. Pyrolysis facilities employ emission control devices, to measure and improve the quality of the gas, liquid and char products to make MSW pyrolysis a more environmentally beneficial process [178].

2.2. Non-thermal treatment options

Landfilling and anaerobic digestion with methane gas recovery are the most commonly used non-thermal methods of WTE generation in the US [183]. The process is more efficient for wet and decomposable wastes like food waste, wood, agricultural residues, and sewage sludge and utilizes microorganisms to carry out the degradation of organic matter [8].

2.2.1. Landfilling

Landfill with methane gas recovery is still the dominant solid waste disposal technology in North America [2]. Landfills are gradually becoming full near major cities and reaching their max capacity. For example the Miramar landfill in San Diego, California is the only regional active dumping site occupying 607 ha of land [184]. This landfill will reach its maximum capacity by 2022. Efforts are being made to increase the lifespan of this landfill to 2030 using a new trash compaction method and applying regulations, incentives and fee hikes to raise the recycling rates [184]. Fortistar Methane Group LLC invested in utilizing Miramar Landfill's biogas for generating 51,224 MWh net power for the local communities [185]. Landfilling is often more economical than burning waste in incinerators [186–188]. Traditional landfilling involved dumping MSW into pits and then burying it to decompose naturally over years. The US-EPA regulations on landfills, based on the Resource Conservation and Recovery Act of 1976, made construction and operation of most local dumps illegal [189]. The requirements for current operating landfills are to minimize odor, eliminate any seepages of leachate, and lessen greenhouse gas emissions by burning them off.

Today's controlled and sanitary landfills are technologically more advanced with leachate and landfill gas (LFG) management [7]. Landfill managers are employing new efficient solutions, such as aeration of landfill to accelerate MSW stabilization and controlling methane and nitrous oxide emissions [190]. Landfills use liners to prevent leachates entering the underground water. New liner materials like nanosilica and clay of low hydraulic conductivity and high mechanical strength are efficient for this purpose [191–193]. A study proposed an efficient collection and transportation system for supplying MSW that includes transfer stations, where MSW is treated mechanically, shredded and compacted. The study applied a Multi Criteria Decision Making method ELECTRE III and recommended that a centralized WTE facility with an adjacent landfill is the economic option for MSW disposal [194]. Current technological advancements in leachate treatment and landfilling sustainability are described in details in Table 5.

Advantages: Most US landfills recover landfill gas (methane) to generate heat and electricity for local homes [200]. In US states with available land, landfilling is often more economical than incinerating waste [187,188]. Landills are potential future reservoirs for resource extraction [166,201].

Disadvantages: Landfills require large and isolated lands. Near densely populated areas in US, many landfills have already closed, and availability of any new sites is getting limited and could involve prohibitively long transportation distances. The tipping fees for landfilling is higher in some US states than for incineration [202]. The decomposing waste emits methane which is a more potent greenhouse gas than carbon dioxide [190]. Furthermore, landfills also produce biogenic carbon dioxide, non-methane volatile organic compounds, as well as smaller amounts of nitrogen oxides and carbon monoxide. Additionally, ground water contamination by hazardous leachate, as well as health concerns caused by malodor and gases, make landfills undesirable [191, 192].

2.2.2. Anaerobic digestion

Anaerobic digestion (AD) or bio-methanation in the US regions currently needs exploring for large scale energy generation. The US has over 2100 biogas production facilities of which 247 are for AD on farms, and 38 are standalone operations utilizing the biomass from local waste

Table 5
Recent technological advances in landfilling of waste.

Technological advancements in Landfill	Remarks
Conversion of landfill waste to activated carbons using microwave irradiation and chemical activation steps [195]	• Activated carbons are of high utility in many technological areas, helps in revenue generation, reduce waste volume and increase landfill capacity
Combined treatment of landfill leachate with sequential persulfate and Fenton oxidation [196]	• Decolorization and demineralization is effective in treating highly colored effluents
Treatment of landfill leachate employing Fenton oxidation with air stripping, and enhanced coagulation [197]	• Air stripping removed 51.50% of chemical oxygen demand (COD), 74.60% of biochemical oxygen demand (BOD), and 97.60% of ammoniacal nitrogen • Fenton oxidation removed 67.70% of COD, 92.30% of BOD, and 14.90% of Hg • Coagulant removed 55.98% of COD and 77.68% of Hg • Overall leachate removed 90.80% of COD, 98.0% of BOD, 97.60% of ammoniacal nitrogen, and 82.68% of Hg
Fenton oxidation with electrochemical oxidation (electroFenton process) [198]	• Removes 92% COD and 93% color using aluminum electrodes
Landfill leachate removal using hybrid H_2O_2 oxidation and adsorption in an activated carbon bed [199]	• Removed 97.3% COD by the hybrid treatment by H_2O_2-granular activated carbon

generators [203]. Remaining AD units are at water resource recovery facilities [204]. Table 6 describes the few current operational standalone AD technologies in the US.

The feasibility of AD is already accepted for small scale use on farms and local organic waste; however, development is still ongoing for MSW feedstock for pilot scale use [205–207]. AD is compatible with only the source-separated organic matter of MSW [8,208,209]. The process involves microbial decomposition of organic matter in the absence of air but in the presence of high moisture to recover biogas and enriched compost [8,210]. Produced biogas primarily contains methane, along with carbon dioxide, and trace impurities. It can be upgraded to pure methane (higher calorific value) by the removal of carbon dioxide, water, and other trace elements. Anaerobic digesters operate at different temperature ranges such as 30–37 °C for mesophilic and 50–60 °C for thermophilic [204]. Thermophilic digesters are more expensive and difficult to operate but needs less time to process feedstocks. Mesophillic digesters are more flexible in operation and maintenance, but deactivate less pathogens [204]. In spite of having many industrial methods of AD, there is still room for further improvements, both in the process and in the pre- and post-treatment steps [205,218–220]. A two-phase AD (TPAD) displays superior methane production rates than single phase AD [221–223]. An economic feasibility study of a pilot scale TPAD of MSW blend observed the effects of digestion temperature, fuel content of digester feed, loading rate, RDF particle size and pretreatment with a cellulase or diluted NaOH or lime on the digester performance [224].

Dry fermentation is emerging as an alternative solution where water is not needed. The feasibility of dry fermentation of MSW has been investigated by several research groups [218–220]. The rate of bio-gasification of dry-solid feed is always slow. The gasification process can be accelerated in dry-solids fermentation by slightly increasing the moisture content of the MSW bed later to allow filtration and recirculation of bed leachate. AD needs continuous monitoring and progressive automatic control [221]. The profitability of this technology should be suitably analyzed prior to building a WTE plant.

Advantages: Biogas may be used as cooking gas, household heating fuel, power fuel cells, or combusted for generating electricity [222,223]. The compost or digestate is used in agriculture and soil amendments [224].

Table 6
Examples of few current operational stand alone anaerobic digestion technologies in the US states.

Standalone Anaerobic Digesters	Location	Remarks[a]
RefCom (refuse converted to methane) [211]	Florida	• Accepts MSW; high-rate digestion process; single-stage, low-solids, complete-mix reactor with mechanical mixing and no Heating; process 33,000 tons per year; density separation in a hydrocyclone; faced problems due to clogging
Fluence Corporation [212]	New York	• Accepts MSW; continuous stirred tank reactor; Reduction of greenhouse-gas emissions
PlanET Biogas Technology [213]	New York	• Accepts MSW and wide range of organic waste like manure, crop residues, food waste, or animal by-products; generates biogas or biomethane
Kompogas® Plants [214–216]	California	• Accepts degradable portion of MSW; process up to 36,500 US tons of waste per year; digestion at 55 °C; generates high-grade fertilizer; horizontal plug-flow digester
Michigan State University's anaerobic digester [217]	Michigan	• Digest food waste and dairy manure; process 17,000 tons of organic waste each year; generates electricity from biogas for 10 buildings on campus

[a] Descriptions are based on company's claims as published in the company website.

Disadvantages: AD faces challenges related to low biodegradability of some wastes like lignocellulosic biomass, accumulation of solids, blender malfunction, slow digestion rate, incomplete degradation of large particles, and digester shut downs [225–230]. These lead to poor methane yields, low energy production, high maintenance, and operating costs, and eventually high methane price. Moreover, sometimes the addition of an external water source is needed to produce diluted slurry in large and expensive digestion tanks. The digestate needs significant processing before its use in agriculture [224]. Digesters require heating in cold climates [231]. Digesters also face difficulty in construction and prevention of gas leakage [231]. Moreover AD reduces the volume of waste by about 50% and needs costly biogas cleanup [232].

3. Modeling and simulation in MSWTE evaluation

Optimal design of MSWTE systems entails mathematical modeling and simulation tools. The use of models has become almost inevitable in waste management decision-making. Computer codes and models based to assist incinerators/gasifier designs [233,234], for evaluating concentration of air pollutants [235], landfill gas to energy system [236], life cycle assessment of environmental impacts of MSW incineration [237], and efficiency of syngas generation [238], are all found in the literature. When properly executed, these models can accurately portray problems such as short-circuited flows, dead zones, recirculation zones, and other conditions that can significantly affect the performance of the WTE system. Models were also used to predict the calorific value of MSW components [239,240]. Available models range from relatively simple to complex systems [241,242]. Models on cost analysis of MSW management helped to estimate both economic and environmental costs [243]. The capacitated vehicle routing problem model was developed for waste collection and route optimization [244]. Over the last decade modeling has evolved as a useful technique in solid waste management systems [245,246]. Integrated models of biomass gasification with solid oxide fuel cells (SOFCs) showed efficiency in predicting the performance of energy recovery contained in the syngas [247]. Modeling of fluidized bed gasifiers is considered challenging owing to multiple mathematical complexities in hydrodynamics of fluidization and phase rules [248–250]. Accurate forecasting of MSW generation is essential for the design and operation of an efficient MSWTE system. Application of machine learning algorithms, specifically decision trees and neural networks have been successfully used to develop models of MSW generation with good prediction performance [251]. The WTE decision-making process can benefit from the modeling and simulation tools for optimizing the technical parameters and cost factors using a techno-economic approach.

3.1. Techno-economic analysis (TEA)

The technical and economic feasibility of any new WTE technology depends on an in-depth understanding of the process steps, chemical and physical parameters, as well as operational, maintenance, and capital costs. Simulations stand as useful tools in carrying out TEA of MSWTE systems [252]. Advanced Simulator for Process Engineering (Aspen) Plus is a problem-oriented input program based on mass and energy balances that has been used for optimizing the WTE process steps and calculating the costs [253]. The Aspen Plus software accounts for solids in addition to vapor and liquid streams. The composition and yield of the gasification products are modeled by considering thermodynamic equilibrium or Gibbs free energy minimization. Aspen Plus simulator is equipped with large data containing various stream properties required to model the material streams in a gasification plant wherein in-house data can be added to update the process. FORTRAN subroutines are developed, wherever more refined calculations are needed [133,254]. Aspen Plus models assess the mass and energy flows and incorporate principal conversion reactions and operating parameters of the reactor

[80,133,255–262]. Several TEA models of biomass WTE based on Aspen Plus are known in the literature [263–265]. Table 7 presents descriptions on some of the studies reviewed, modeling scheme and major remarks.

3.2. Life-cycle assessment

In the last decade, life cycle assessment (LCA) models have been extensively used to evaluate the environmental impacts from solid waste management systems, including incineration, gasification, pyrolysis, and anaerobic digestion (AD) and landfill with energy recovery [245,246,271]. In LCA all material and energy inputs or resources, and outputs (emissions to air, water, land and useful products like heat and power) are identified and quantified [272–275]. Without sufficient understanding of assumptions an LCA model can significantly affect the conclusions of studies, and lead to discrepancies in impacts and potentially lead to contradictory results [276].

The LCA modeling of solid waste is data intensive, and the quality of data governs the impact and validity of the model's output [277–279]. The data source and completeness influence the output of WTE process analysis. The generic LCA models of WTE are mostly constructed using popular tools such as SimaPro [280,281], GaBi [280,282–284], Umberto [285–287], and EASEWASTE [280,288–291] software packages. Most of these tools host the Ecoinvent, a database containing more than 2500 processes [292]. OpenLCA is an open source generic LCA software widely used for life cycle assessment [293].

These tools determine mass and energy flows and contain modules to include different waste treatment processes [294,295]. For WTE, the inputs and outputs of biomass and energy are used to estimate cost of energy around processes, raw materials, pumps, pipes, transportation, and construction of the processing plants. Emissions from processes are also accounted for [296,297].

The technical literature referring to the LCA of MSWTE methodologies for a few studies is illustrated in Table 8.

Table 7
Recent Techno-Economic Analysis models using Aspen Plus simulator.

Models of WTE technology	Remarks
Model for fluidized bed and entrained flow gasification of biomass (2018) [266]	• The thermal efficiency of entrained flow is 11% higher than fluidized bed (45%) • The minimum H_2 selling price for fluidized bed process is \$0.3 per kg H_2 lower than the entrained flow • To make the least hydrogen selling price of biomass-based plants equivalent to comparable natural gas-based plants a biomass price of \$100 per tonne, either a \$115/tonne liquefied CO_2 or a minimum of \$5/GJ natural gas price is required • Sensitivity analysis evaluates the impact of feedstock cost on the minimum hydrogen selling cost
Model for fluidized bed gasification of biomass (2018) [267]	• Comparative TEA of different technological alternatives in Biomass Integrated Gasification Combined Cycle (BIGCC) power system with CO_2 emission control • Sensitivity analysis assess the impacts of availability factor, capital cost, and operational and maintenance cost on the power systems • Monte Carlo shows the uncertainty in simulation in different operational periods. It shows a 86% confidence interval based for less than 4 cents/kWh electricity distribution cost • Technical assumptions: Equivalence ratio-0.27, gasification temperature - 810 °C, pressure - 1 atm, and carbon conversion ratio - 90.5% • Biomass price lower than \$10 per ton air gasification without CO_2 capture and storage (CCS) is comparable to commercial electricity generation technologies, but with CO_2 removal is \$90 per ton then using CCS technology reduce cost of power plant
Model for integrated anaerobic digestion with torrefaction of biomass (2018) [268]	• Selling price of torrefied biomass pellets reduced from 199 euros/ton for standalone torrefaction to 185 euros/ton for the integrated process • Feedstock price and total investment are sensitive input parameters • The integrated process has better economic and technical feasibility
Model for entrained flow gasification of biomass (2018) [269]	• 1 kg dry biomass yield 18.5 mol of methanol • Steam and CO_2 use in gasification gives high yield
Model for fluidized bed fast pyrolysis of biomass (2018) [270]	• Optimal temperature between 400 and 450 °C, the flow rate of 45 L/min and 21.3 g of biomass feeding per injection gives maximum bio-oil yield • \$0.55/liter bio-oil selling price is profitable for plant size of 1000 tonnes/day

3.3. Reverse logistics modeling

An important step in the conceptual development of any WTE project is the design of logistics, collection area determination and capacity proposal. This is often covered by so-called "reverse logistics" modeling [308,309]. Reverse logistics process as stated by American Reverse Logistics Executive Council is "the refurbishing, reclaiming, reusing or recycling materials or finished products and related information back to its origin for recapturing the asset value or for proper disposal" [310]. The increase in packaging materials caused a waste disposal and environmental concern and many countries are developing policies geared towards reverse logistics to recuperate materials for recycling and reuse [311]. Significant cost savings and optimization of the WTE process steps can be achieved by analyzing the parameters such as collection site/districting/zoning, collection patterns, cost of waste collection (equipment and manpower), location of transfer stations, processing facilities, and landfills, shipping of waste flow, and ratio of recycling to WTE alternatives [309]. Stochastic parameters such as generation of waste and time to transport the waste as well as socio-political influences needs to be accounted for in future reverse logistics analysis of WTE projects [309].

4. Trends and perspectives

4.1. Techno-economic comparative assessment of the WTE studied

The capital cost of thermal technologies (Mass-burn/RDF, gasification, and pyrolysis) is comparatively not much different; it is estimated between 0.15 and 0.4 Millions $ per "Ton-per-Day (TPD)" of waste (300-1000 TPD facility) and \$7,000–11,500 per kW generated (15 MW facility) [312,313]. Major differences occur in operation and maintenance costs (O&M). One source estimates \$8.33 per MWh of energy generated in Mass-burn facilities; about \$20 million annually for a 1000 TPD facility. Costs could also involve contingencies such as fire accidents, breakdowns and air emissions exceedance [314,315]. There are few information sources on O&M costs of gasification and pyrolysis technologies in US since gasification is still on trial phases. Estimates of vendors range between \$40-\$100 per ton [316,317]. Plasma gasification uses electricity which is an expensive energy source in US and gasification systems are prone to corrosion due to high temperature oxidation [318]. Gasification produces 65% less residue than incineration, which could translate into less disposal costs [319]. For these thermal technologies, the net energy, revenues, and operating costs are dependent on composition of the waste stream. While plastics are high calorific waste preferred by thermal systems operators, there is a debate in US that

Table 8
LCA models of MSWTE technologies.

Models of WTE technology	Remarks
Model for comparison of co-combustion, and anaerobic digestion, with incineration (2011) [298]	• Incineration with energy recovery was preferred over anaerobic digestion • For co-combustion waste composition and flue gas cleaning were essential • Energy production from mixed high calorific waste and source separated organic waste was evaluated
Model for comparing anaerobic digestion, incineration, pyrolysis, and gasification (2019) [299]	• Anaerobic digestion and gasification contributed lower to global warming and acidification than incineration • A strong relation was identified between a country's economy or income and rate of LCA analysis of WtE • North American and EU member countries were evaluated • LCA results varied with waste structural characteristics, calorific value, gas cleaning systems, emission control, WTE technology employed, and uncertainty analysis, amongst other factors • A gap was identified in LCA analysis of polymers and electronics WTE treatment
Model for environmental assessment of grated firing incinerator (GFI) and fluidized bed incinerator (FBI) (2010) [290]	• GFI contributes less to global warming potentials than FBI • Incineration of MSW with lower heating value requires presence of secondary fuel • GFI has higher net power generation than FBI
Model for comparison of climate impacts of landfill and WTE (2010) [300]	• Crossover rate was influenced by composition of waste, heat capture, electricity generation efficiency, scrap metal recovery, greenhouse gas intensity, and LCA time horizon. • Greenhouse gas emissions were observed from both WTE and landfill methane • Neither WTE nor landfill were carbon neutral • Landfill with effective methane capture is better for the climate than burning MSW in WTE
Model for comparison of thermal treatments of waste (2009) [301]	• Thermal treatment and energy generation from waste can be optimized for reducing emission of greenhouse gases
Model for comparison of incineration and anaerobic digestion (2007) [302]	• Anaerobic digestion resulted in higher net energy output compared to incineration • Anaerobic digestion had more potential impact for nutrient enrichment than incineration
Model for MSW landfill gas to energy (2007) [303]	• Evaluating environmental consequences of landfilling • Large centralized landfill and electricity production is preferred over several small, localized landfills • Global warming potential depends on gas collection efficiency
Model for comparison of integrated biomass gasification combined cycle (IBGCC) with similar coal gasification (ICGCC) (2005) [304,305]	• Assessment showed reduction of greenhouse gas emissions and natural resource depletion with use of biomass in gasification • Results were presented according to Eco-Indicator 95 impact assessment methodology
Model for comparing anaerobic digestion and landfilling of food waste (2012) [306]	• Anaerobic digestion of food waste was found preferable compared to landfilling • Environmental impacts decreased with better recovery from waste
Model for comparing landfilling, incineration, recycling, digestion and composting using SimaPro 4.0 (2005) [307]	• Combustible and recyclable or compostable fractions of MSW was considered like food waste, newsprint, cardboards, polyethylene, polypropylene, polystyrene, polyvinyl chloride and polyethylene terephthalate • LCA analysis validated the waste hierarchy, recycling-incineration-landfilling, based on overall energy use, green-house gas emissions, and the total weighted results

plastics and paper should be recycled instead of being burned [317]. All these thermal systems require a water supply, sludge treatment, and chemicals, which is an additional logistical and regulatory burden. In water-stressed regions of the southwest US such as California, the water footprint of thermal systems could be a concern. Thermal combustion and gasification of chlorine-containing materials such as plastics and textiles produces toxic dioxins and furans and these have been touted as an air pollution control challenge of MSWTEs [312,314]. Occasional breach of permitted limits has been reported for existing systems and creates a public relations nightmare for operators. The ability to de-conflict technical, environmental, economic and regulatory aspects for gasification is key for future success. Integrated systems such as a wastewater treatment plant and a waste-to-energy system have been suggested.

4.2. Environmental and policy analysis

Most of commercial WTE were built in 1980s and 1990s, after the passage of the 1978s Public Utility Regulatory Policies Act (PURPA) to promote the energy security and conservation after the oil crisis [320–322]. Tax incentives, funding and the approval process made it possible to build multiple dozens of WTE facilities. Those facilities are now aging and need investments. Some struggled to meet design specifications and were forced to close or operate under capacity. Mass burn incinerators faced opposition from various citizens groups and for 20 years no new large facility was built [87,323–325]. During that period globalization was in full swing and facilitated export of waste to developing countries (mostly in China) and new advanced landfills were built in US [326]. A recent ban of waste import in China and issues with dwindling landfill space near population centers in US have revived interests in WTEs [326]. There are dozens of planned facilities in US, mostly in island US territories such US Virgin Islands, Guam, Puerto Rico, and Hawaii [327]. However, the approval process is an uphill battle because of public opposition, the time it takes for impact assessments and the approval process. In addition, WTE is viewed as a renewable energy only in 34 states and in others it does not get incentives meant to promote the renewable energy [24]. Detractors claim investments in WTE will undermine "reduce and recycle" efforts and reverse gains in air quality improvements. In US the national air quality standards can make it impossible to site WTE in some areas, and face stringent air pollution regulations in others.

Siting WTE in poorer neighborhood has also raised environmental justice protests. The Wheelabrator's and Covanta's Mass burn facilities in Baltimore and Philadelphia are always cited in News Media as example of worst cases of WTE and environmental justice [322,328].

In near future, most states could come up with integrated waste management that include incentives for separation at the source, recycling facilities, advanced WTEs, and more trade in waste management services across state lines.

Policy makers can provide more economic incentives and tax credits to Renewable Obligation Certificates (ROCs) holders for renewable energy practice. Policies should also promote maintaining strict environmental emission level standards by imposing higher taxes on carbon emission outputs [327]. The governing bodies can also make mandatory for WTE investors to evaluate the costs and benefits of their WTE projects through techno-economic analysis; control assets and resources through reverse logistics; and facilitate location of WTE plants near MSW sources or city energy distribution infrastructures [142]. Life cycle analysis is another comprehensive performance evaluation tool which should be mandated in WTE project proposals and reports for identifying key determinants and environmental factors [142]. Social acceptance can be achieved by supplying the renewable electricity production at a lower price than fossil fuel generated electricity.

4.3. Practical implications of this study

Major challenges in developing any WTE technology for commercial use include capital, plant O&M, controlling the air emissions such as dioxins, furans, NOx, SOx, CO, CO_2, acid gases, and other greenhouse gases. Additional concerns are the solid byproducts like fly ash, slag, char, and tar control for proper disposal or further reuse. Syngas, pygas or biogas cleaning before use in electricity generation to meet regulatory standards add to the overall cost burden. Along with technical challenges, socio-economic acceptance of the WTE concept by local communities and WTE investors also needs consideration while evaluating the viability of any WTE technology.

Future technologies may include integrating one or more WTE techniques to give better energy outputs. These could include plasma with fluidized bed gasification, plasma gasification with solid oxide fuel cells for generating electricity, gasification with pyrolysis, or anaerobic digestion with gasification. An ideal MSWTE technology in US would be a cost-effective system that promote recycling, reduces emissions, and address the MSW disposal issue in a sustainable manner.

5. Conclusions

The US generates the largest amount of waste in the world, recycles less (about 25%), and landfills most of the waste (about 53%). The US regions without adequate landfill space are considering various advanced WTE systems. These systems have to overcome pollution, financial, and technical challenges. This review presents various WTE technologies including incineration, gasification, plasma gasification, pyrolysis, and anaerobic digestion with biogas recovery. The technical aspects, advantages, and disadvantages of each technology are highlighted. Existing systems that uses mass-burn technology are aging and most do not perform well in terms of pollution control and financial soundness. High capital cost, operational and maintenance costs, energy consumption, pre-treatment steps, and post-generation fuel cleaning, make these technologies unattractive to investors. Most gasification systems are still at the experimental and trial phases and not much is known about their operational success. Many literature sources show that they produce fewer toxic residues and air emissions than incinerators. But the operation and maintenance costs of gasification systems could be twice or higher due to higher energy consumption, cleaning of syngas, and complexity of the systems. There are many factors that affect WTE systems in US including economic incentives and subsidies from the local governments, amount of tipping fees, revenue from selling energy, public acceptance, and environmental regulations. These parameters are often optimized using life cycle assessments, techno-economic analyses, and reverse-logistics simulations. Trends and perspectives on policies, techno-economic aspects, and practical applications are also discussed in this review. A system that integrates recycling, other infrastructure such as wastewater treatment, minimizes emissions, creates jobs, and is profitable, can be successful in the US.

Disclaimers

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the US Air Force, the US Department of Defense, or the US government.

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