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ARTICLE

Waste to energy (WTE) in China: from latecomer to front runner

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Abstract
This paper discusses the 2000–2018 evolution of energy and metals recovery from urban wastes in the European Union and China. As a result of the zero-landfilling directive, in twenty years the European Union tripled its recycling rate (11%–30%) and its composting rate (6%–17%), doubled its WTE rate (14%–28%) and more than halved its landfilling (64%–25%). At the beginning of this century, the rapidly growing cities of China were literally surrounded by landfills. Therefore, the national government instituted policies, such as a credit of US$30 per MWh of WTE (waste to energy) electricity that resulted in the construction, by 2020, of 510 WTE plants with an annual WTE capacity of 193 million tons. In comparison, the European Union (EU) WTE capacity is 96 million tons and the USA has remained static at about 27 million tons, i.e., 10% of its post-recycling MSW (municipal solid waste), with the other 90% being landfilled. In the first decade of this century, two WTE technologies, moving grate and circulating fluid bed were developed in China at about the same rate. However, since 2010, the moving grate technology has become dominant and the WTE plants are built functionally and esthetically comparable to and U.S. plants.

Keywords Waste to energy · WTE capacity · Moving grate · Circulating fluid bed · Sustainable waste management

Introduction

Since the beginning of the history, humans have generated solid wastes and disposed them in makeshift waste dumps or set them on fire. After the industrial revolution of the eighteenth century, the amount of goods used and then discarded by people increased so much that it was necessary for cities to build landfills and incinerators for disposing wastes. Starting in the second part of the twentieth century, the traditional management of municipal solid wastes (MSW), by landfilling and incineration, became problematic as the consumption of goods, and the corresponding generation of MSW, increased manifold. In response, the most advanced countries devised means for dealing with solid wastes; they range from reducing waste, by designing products and packaging, to recycling of usable materials, composting of green and food wastes, thermal treatment with energy recovery, commonly called "waste to energy" (WTE), and sanitary landfilling that reduces aqueous and gaseous emissions to the environment [1, 9]. It has been estimated that the recorded post-recycling MSW is over 1.3 billion tons, of which one billion tons are landfilled and 0.3 billion tons are treated by waste to energy processes. This number does not include the millions of tons of wastes discarded at non-regulated dumps or ending up as enormous "garbage patches" in rivers and oceans.

The priority order of waste management methods can be represented graphically by the Hierarchy of Waste Management (Fig. 1). The environmental performance of waste management of a city or country can be rated by comparing their recovery of materials (i.e., recycling and composting) and energy (i.e., WTE) to the amount of MSW landfilled. This comparison can be made by means of another graph, the "ladder of sustainable waste management" that rates nations according to how much they recycle and combust with energy recovery; and how little they are landfilling. Figure 2 shows that several nations have already reached the goal of very little or no landfilling.

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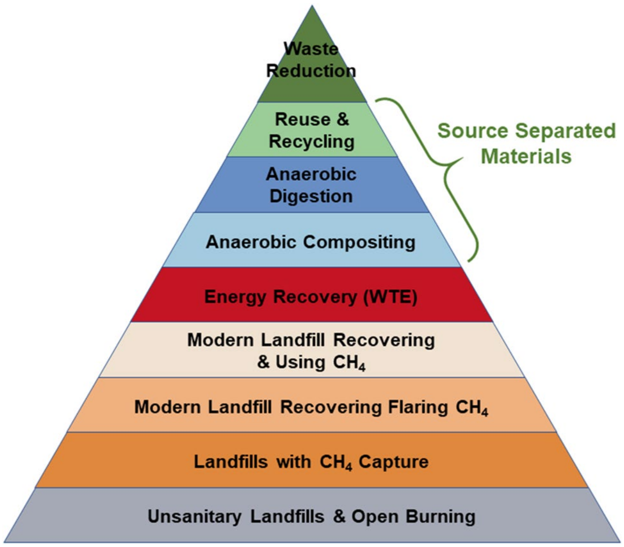


Fig. 1 Hierarchy of waste management. Reprinted from [2] with permission. *WTE* waste to energy

The misconception exists that recycling and WTE compete with each other. However, Fig. 2, which is based on data compiled by many countries/regions, illustrates the general pattern: Cities and countries strive to increase their recycling and composting rates as much as possible. As the recycling rate levels off, the most advanced cities and nations increase their WTE capacity to attain "zero landfilling".

Recovery of materials and energy

The residues of human activities can be transformed into useful resources by means of recycling (materials recovery) or thermal processing (energy and metals recovery). The subject of resource recovery from the discards of society is an essential part of what has been defined by the United Nations as "sustainable development" [3]. As noted earlier, before the second half of the twentieth century, the consumption of materials and energy by humanity was a small fraction of what it is today. An example of the rapid growth in consumption is the use of copper, a metal that has been known since the beginning of history: A 1995 study by one of the authors [4], for the Metallurgical Society of Finland, showed that more copper was consumed between 1945 and 1995 than in the preceding six thousand years. In 2016, this graph was updated by adding the 2015 global consumption of copper (Fig. 3); between 1995 and 2015, copper consumption increased linearly to 23 million tons. If it were not for the increased rate of recycling, humanity would not have enough copper to meet their needs.

A similar trend was followed by all other materials. Technology advances have made possible enormous economic development, which was accompanied by degradation of the global environment and the loss of innumerable species. However, technology has also helped to mitigate the adverse effects of economic development. For example, over one-half of the primary metals and paper fiber consumed in the USA is derived from recycled materials. On the other hand, because of the wide range of plastic compounds and the cost of source separation and sorting, only 10% of the plastic wastes generated are actually recycled in the form of materials.

The physical resources contained in solid wastes can be divided broadly into materials and energy (i.e., electricity and fuels). For example, the millions of tons of non-recycled plastics (NRP), that are currently landfilled, can be used as fuel in WTE power plants, to generate electricity and heat, or in pyrolysis plants, to produce synthetic oil and syngas. Figure 4 divides the Hierarchy of waste management into "recycling" (which includes composting) and "post-recycling" means of waste management.

Landfilling

William Ophuls in "Plato's Revenge" [5] noted that there are similarities between the present age and that of the conquistadores: Scientists and engineers invent ways for producing goods and arms that merchants and soldiers use to dominate markets and nations. A clear example of what has been called "ecological imperialism" is the massive transformation of fields and forests to landfills. In the past, landfills were located in, or near, population centers so that there was a good reason for cities to manage their wastes and try to conserve land. In recent times, cities, like New York, have run out of landfill space and transported their wastes hundreds of kilometers away to mega-landfills. This is made possible by waste transfer stations, diesel trucks, and other equipment; also, by the fact that cities are generally more affluent than the far away communities where the new mega-landfills are located [6]. Currently, if all municipal waste landfills were at one location, they would require a surface area of one hundred square kilometers, each year.

Waste management in various regions of the world

An example of good waste management is the EU and its directive to member nations to phase out landfilling. Figure 5 is based on Eurostat data [7] (August 2017) and shows the progress made, in the period 1995–2015, in reducing the EU landfilling rate to 25% of the total MSW. This was achieved by an increase in recycling plus composting rates to 46% and a WTE rate to 28%. In comparison, the USA,

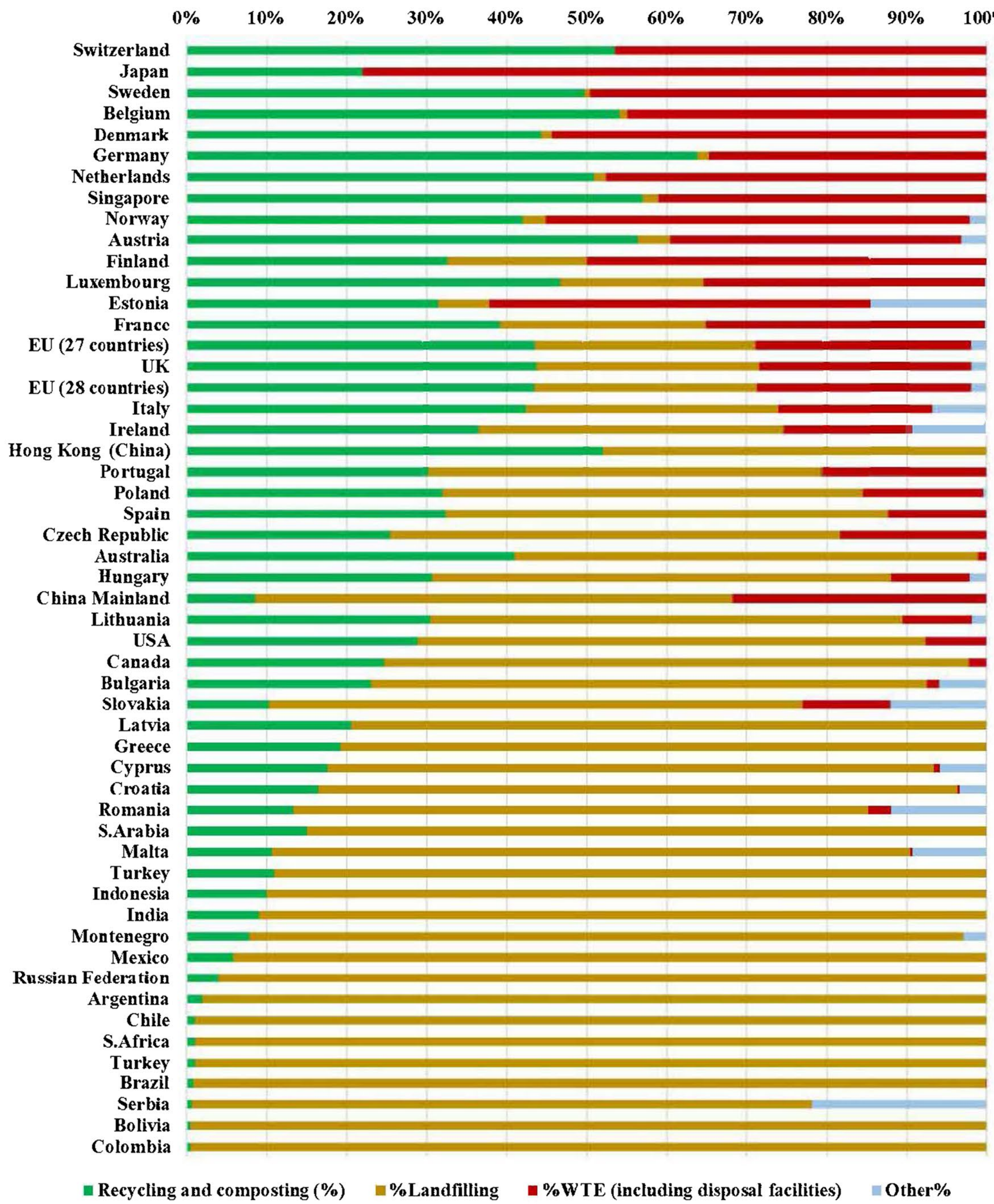


Fig. 2 "Ladder" of sustainable waste management of countries/regions in 2016. Reprinted from [2] with permission

despite its higher economic level, recycles and composts about 30% of the urban waste, combusts another 7% in WTE plants, and landfills 63% [8].

At present, there are over one thousand WTE plants in more than fifty nations around the globe. Some people confuse the modern WTE power plants with the early incinerators of the twentieth century which were major emitters of volatile metals and toxic compounds. This confusion is not helped using the word "incinerators", referring to modern WTE facilities that are amongst the cleanest high temperature processing plants. At this time, it is abundantly clear that there are only two ways of managing post-recycling wastes: Sanitary landfills or WTE power plants. The major obstacle for the universal adoption of WTE is that it requires a much higher capital investment than landfilling. Therefore, the "gate fee" per ton of waste disposed is higher than that

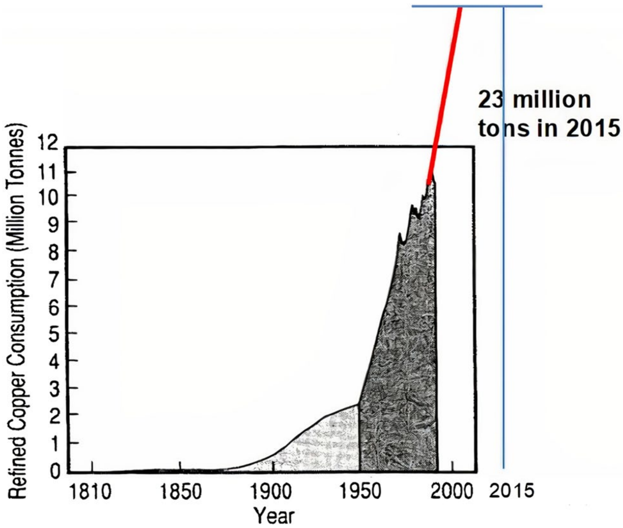


Fig. 3 Copper consumption in period of 1850–2015 (in million tons)

for landfilling; this is because the "external costs" of greenhouse gas emissions and land transformation of landfilling are not included [9].

However, even with the exclusion of the external costs, on a 20-year basis, WTE is economically competitive with sanitary landfilling in cities where the electricity generated by the WTE plant is valued at over $80/MWh. Columbia University carried out the Interamerican Development Bank case studies for implementing WTE in Argentina, Chile, and Mexico [10]. The results showed that, without any government support, WTE plants in these countries would require a gate fee of US$20 higher than that of existing sanitary landfills. Therefore, cities and countries are less likely to build WTE plants, unless the national or regional government has in place policies that encourage public–private-partnerships (PPP) and investments in WTE. The following section shows that China, with a GDP/capita of one fourth that of the USA, has built a WTE capacity six times that of the USA.

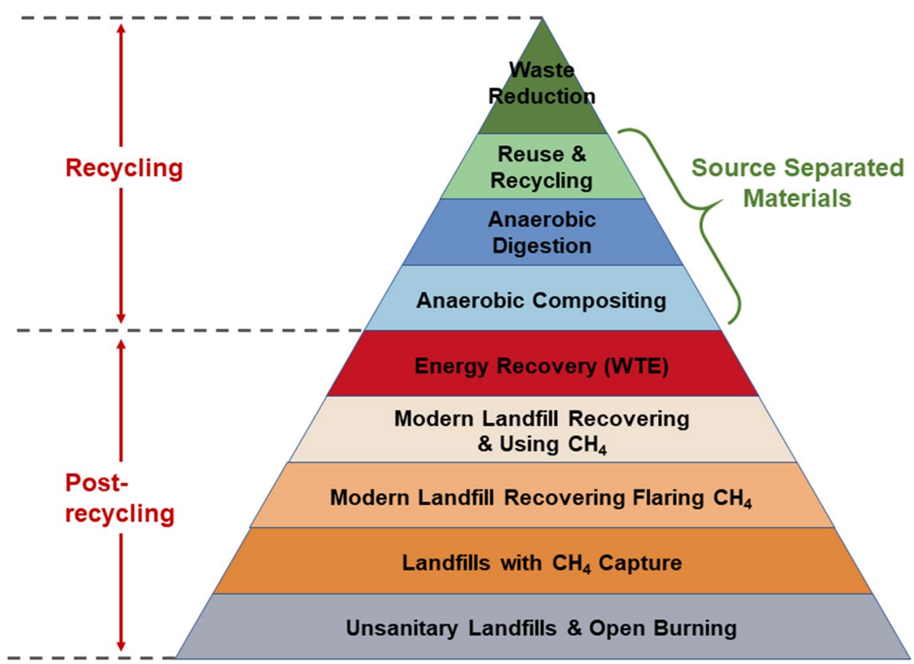
Waste-to-energy in China

At the end of the twentieth century, Beijing and other rapidly growing cities of China were literally surrounded by landfills [11]. Since then, the national government instituted policies, such as a credit of US$30 per MWh of WTE electricity, that have resulted in the construction of 510 WTE plants with an annual WTE capacity of 193 million tons in 2020. In comparison, the WTE capacity in the USA has remained static since 1995 at about 27 million tons, which represents only 10% of its post-recycling MSW; the other 90% is landfilled [12].

These policies have motivated many private and state-owned companies to join the waste-to-energy industry of China. Table 1 is an alphabetic list of the 23 largest WTE companies in China with their total WTE capacity in tons/day.

The tonnage of MSW generated in China and its disposition has been recorded as of 1979 and is shown in Fig. 6. It shows that regulated landfilling started at about 1985 and reached about 50% of the recorded MSW by 2018.

Fig. 4 Recycling and post-recycling means for managing wastes



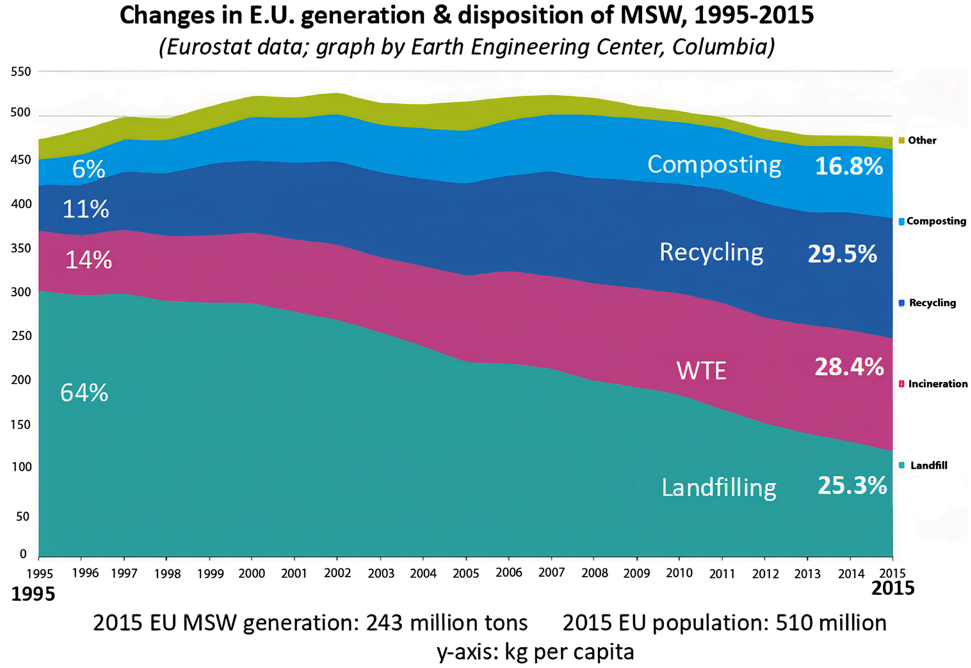


Fig. 5 Gradual phasing out of landfilling in the EU. Reprinted from [7] with permission. *MSW* municipal solid waste

Table 1 Companies participating in WTE industry of China

Company	Company capacity, tons/day
ANHUI SHENGYUN GROUP (ASEPG)	8000
ANHUI WENERGY ENVIRONMENTAL PROTECTION POWER COMPANY LIMITED	7400
BEIJING ENTERPRISES HOLDINGS ENVIRONMENT TECHNOLOGY CO., LTD.	16,180
CAPITAL ENVIRONMENT HOLDINGS LIMITED	6300
CHINA ENERGY CONSERVATION AND ENVIRONMENTAL PROTECTION GROUP	29,100
CHINA POWER CLEAN ENERGY DEVELOPMENT COMPANY LIMITED	11,875
CHINA TIANYING INC	10,850
CONCH ENTURE	6300
CONVEST ENVIRONMENTAL PROTECTION GROUP COMPANY LIMITED	17,320
DYNAGREEN ENVIRONMENTAL PROTECTION GROUP CO., LTD	26,010
EVERBRIGHT ENVIRONMENT	73,210
GRANDBLUE	15,500
GZ ENVIRONMENTAL PROTECTION INVESTMENT GROUP CO., LTD	15,538
SANFENG ENVIRONMENT	30,100
SE ENVIRONMENT	24,200
SHANGHAI ENVIRONMENT PROTECTION (GROUP) CO., LTD	17,300
SHENGYUAN ENVIRONMENTAL PROTECTION CO., LTD	8400
SUS ENVIRONMENT	22,595
TEDA	6610
TUS-EST	11,100
WANGNENG ENVIRONMENT	15,670
WEIMING ENVIRONMENT	15,700
ZHENENG JINJIANG ENVIRONMENT	29,670
All other WTE plants	141,885
Total WTE capacity, tons/day	566,813
Estimated annual capacity, tons MSW	192.91 millon tons

WTE waste to energy; *MSW* municipal solid waste

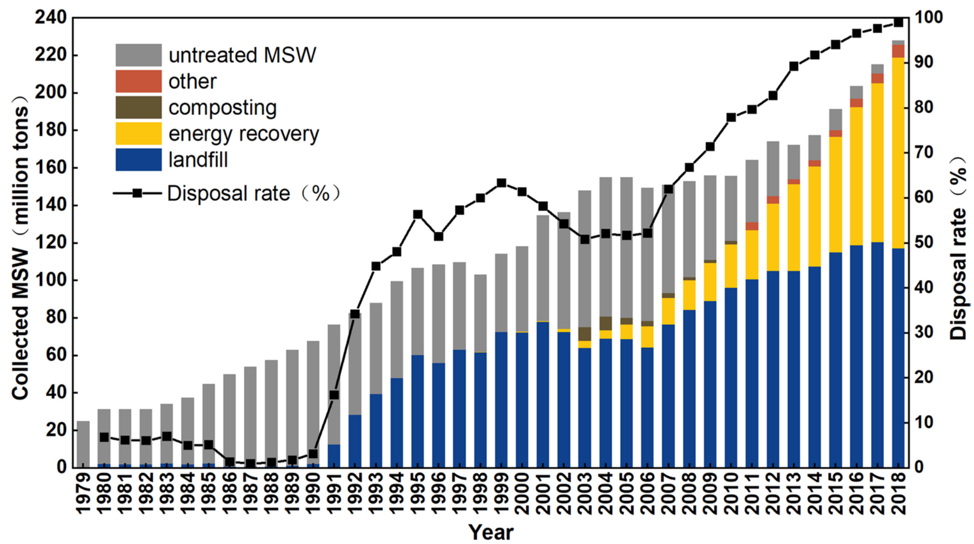


Fig. 6 Recorded generation and disposition of MSW in China, 1980–2018 (Source: Authors)

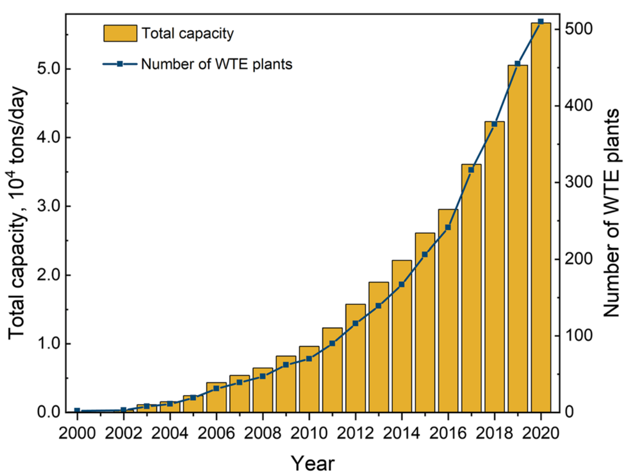


Fig. 7 Growth of WTE industry in China (Source: Authors)

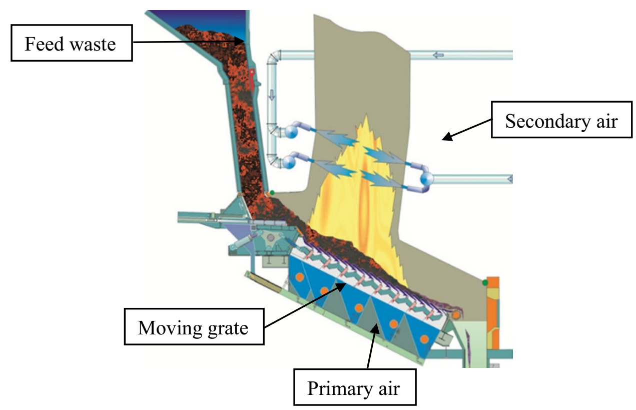


Fig. 8 Schematic diagram of the moving grate furnace. Reprinted from [14] with permission

Combustion with energy recovery started at the beginning of this century and reached about 38% by 2018 [10].

Figure 7 shows the nearly exponential growth of the WTE industry in China between 2000 and 2020, in terms of the number of WTE plants constructed and their cumulative total capacity in tons/day [13].

Two thermal processing technologies [14] are dominant in China. The moving grate (MG) technology (Fig. 8), initially developed by Martin GmbH in Germany, was brought to China by European companies and by now is used in hundreds of plants that use both foreign and home-developed designs and machinery [14]. As shown in Fig. 8, the grating moves slowly in either a forward or backward motion, with primary air injected beneath it. In the water-cooled furnace, secondary air is also supplied to ensure complete combustion.

During the same period, Zhejiang University and some other research institutes developed the WTE circulating fluid bed (CFB; Fig. 9), a technology that had been used globally by the thermoelectric power industry for burning pulverized coal. CFB reactors operate at temperatures between 840 °C and 950 °C [15–17], using a bed of inert material, such as sand or ash, into which shredded MSW fuel is injected from the reactor's side. These reactors have higher fluidization velocities, which are associated with higher fine particle concentrations in the upper part of the reactor. The removal efficiency of fine pollutants in these reactors is up to 99.5% [9, 18, 19].

In the process, fine particles (below the cyclone cutoff diameter) flow through the cyclones and into the back draft of the boiler, while the medium and coarse particles are collected and recycled to the furnace. The cyclone is located adjacent to the fluidized bed, and an external fluidized bed heat exchanger may be utilized to lower the temperature of

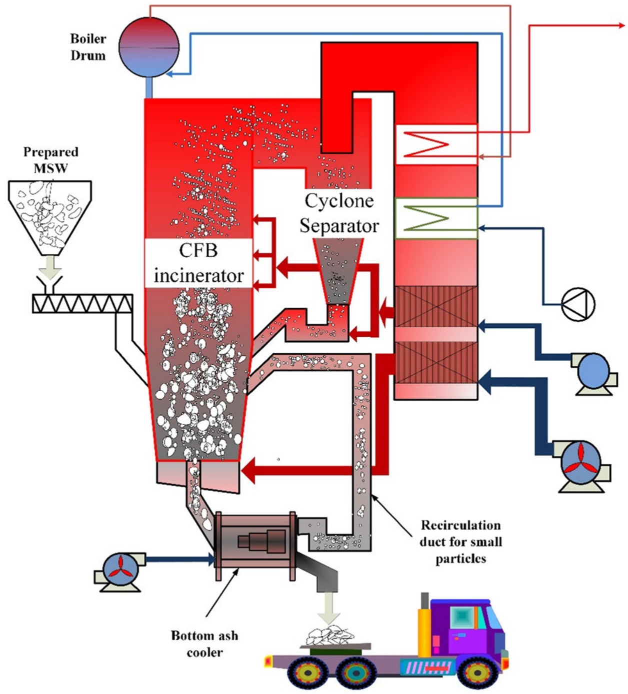


Fig. 9 The CFB (circulating fluidized bed) WTE technology. Reprinted from [14] with permission

the collected particles and allow for particle cycling in the combustion chamber. However, to maintain stable operational conditions, the particle and flue gas rates must be regulated, which is difficult to do with low calorific value MSW.

As shown in Fig. 10, until 2010, these two technologies grew at the same rate. Since then, the moving grate capacity in China increased nearly exponentially while the CFB continued growing at the same rate as in earlier years. At present, the MG capacity of China is about four times larger than that of the CFB technology.

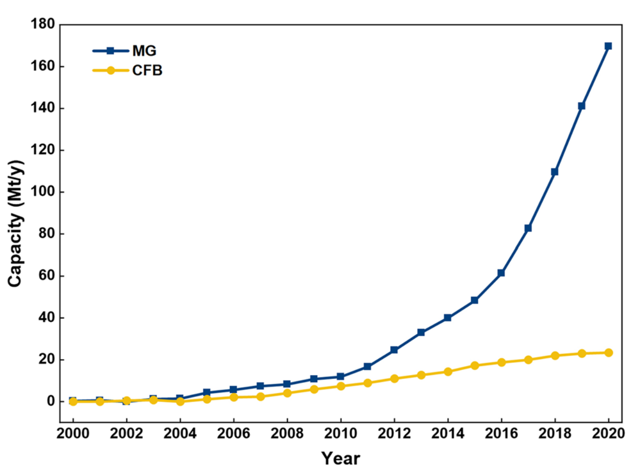


Fig. 10 Historical development of MG (moving grate) and CFB technologies in China

Table 2 Growth of the WTE industry in China in 2020

Item	Data
Number of WTE plants	510
Total WTE capacity	566,813 tons/day
Total tons processed annually	193 million tons
Average plant availability	99%
Average power to grid	0.294 MWh/ton
Total power to grid	56,800,000 MWh/year

Simplicity, reliability, energy efficiency, maintenance costs, regulations, and policy incentives issued by the government at national, provincial, and municipal levels are some of the factors affecting the choice of a given waste treatment technology. In China, over the past decades, the dominance of MG over CFB could be dictated by the following reasons:

(a) the fuel to MG furnaces is as-received MSW, while the MSW to CFB reactors is pre-shredded using high-torque low-speed shredders [14]. In other words, no pre-treatment of the MSW is required before it is combusted using a moving grate, and it can accommodate large quantities and variations of MSW composition and calorific value.
(b) MG allows a sustainable process of MSW and provides a better removal of combustion products [20], and
(c) the in-plant electricity consumption of MG plants is slightly lower than the consumption of CFB plants [14].

Table 2 summarizes the results of this investigation of the waste to energy (WTE) industry and technology in China.

Conclusions

As a result of its zero-landfilling directive, in the last twenty years, the European Union tripled its recycling rate (11%–30%) and its composting rate (6%–17%), doubled its WTE rate (14%–28%) and more than halved its landfilling (64%–25%). The major developments in the global waste to energy have been in China, where the national government has instituted policies resulting in the construction, by 2020, of 510 WTE plants with an annual WTE capacity of 193 million tons. In comparison, the WTE capacity in the USA has remained static at about 27 million tons, which represents 10% of its post-recycling MSW, with the other 90% being landfilled. In the first decade of this century, two WTE technologies, moving grate and circulating fluid bed were implemented in China, at about the same rate. However, since 2010, the moving grate technology has become dominant and the Chinese WTE plants are functionally and esthetically comparable to EU and USA plants. By 2020, the WTE installed capacity of China was greater than that of EU, USA, and Japan combined.

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Declaration

Conflict of interests The authors declare that there are no conflict of interests regarding the publication of this paper.

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