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Waste-to-energy: A review of the status and benefits in USA

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ABSTRACT

The USA has significant experience in the field of municipal solid waste management. The hierarchy of methodologies for dealing with municipal solid wastes consists of recycling and composting, combustion with energy recovery (commonly called waste-to-energy) and landfilling. This paper focuses on waste-to-energy and especially its current status and benefits, with regard to GHG, dioxin and mercury emissions, energy production and land saving, on the basis of experience of operating facilities in USA.

1. Introduction

The most common methods used for MSW are landfilling, composting, recycling, mechanical–biological treatment and waste-to-energy (WTE). The USA follows those methods of MSW management and at present has 88 WTE plants that combust about 26.3 million tonnes of MSW and serve a population of 30 million.

A survey by Columbia University and BioCycle journal (Simmons et al., 2006) showed that the generation of MSW increased at a rate of 2.5% from year 2002 to year 2004. Landfilling accounted for 64% of the MSW generated, followed by recycling (28.5%) and by controlled combustion and generation of electricity (WTE) (7.4%).

Between 1996 and 2007, there were no new WTE facilities in the USA because of environmental and political pressure. The major concern has been the perceived release of hazardous toxic substances into the environment. In the past, the primary focus of environmental groups has been on air emissions, especially of dioxins/furans and heavy metals. However, after the US Environmental Protection Agency (US EPA) implemented the maximum available control technology (MACT) regulations in the 1990s, WTE emissions have been reduced to a point that in 2003 the US EPA named WTE one of the cleanest sources of energy (US Environmental Protection Agency, 2003, www.wte.org/docs/epaletter.pdf). In particular, the implementation of the MACT regulations by the US WTE industry has resulted in reducing mercury and other volatile metal emissions by 99% and dioxin and furan emissions by 99.9%. This work focuses in the current status of waste-to-energy in the USA and especially the environmental benefits that this method offers over landfilling, in terms of greenhouse gas (GHG) emissions, electricity production, land use and cost savings. Another important parameter presented here provides details in public health issues as these can be evaluated from the experience of the operating installations. The experience from the operating WTE power plants shows that the environmental impacts and important parameters regarding public health issues, such us dioxins and mercury emissions, were reduced. Also, the energy produced by this MSW management method enhances the benefits of the method due to the reduction of the demand in fossil fuels. In addition to this the ongoing compatibility, successful results of WTE and recycling are presented.

2. Municipal solid wastes generation and management in the USA

As is true everywhere in the world, the generation of municipal solid wastes (MSW) in the USA has grown steadily. A survey carried out every 2 years by Columbia University and BioCycle journal (Simmons et al., 2006; Themelis and Kaufman, 2004) showed that the generation of MSW increased from 335.80 million tonnes in 2002 to 351.90 million tonnes in 2004, an increment corresponding at a rate of 2.5% per year. Landfilling accounted for 225.53 million tonnes or 64% of the MSW generated, followed by recycling (28.5%), and combustion and generation of electricity (WTE) (7.4%) (cf. Table 1). Most of the recycling is done in coastal states and most of the WTE facilities are on the East coast (Figs. 1 and 2), corresponding to 66% of the total WTE capacity in the USA (Table 2).

Waste-to-energy power plants are in operation in 25 US states. They are fuelled by 26.3 million tonnes of MSW and have a generating capacity of 2700 MW of electricity. They also recover about 0.64 million tonnes of ferrous and non-ferrous metals annually. There are two main categories of WTE plants. In mass-burn plants, the MSW is fed as collected into large furnaces. In refuse-derived

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Table 1
US MSW generation and disposal in 2002 and in 2004 (BioCycle/EEC surveys, 2002, 2004).

	MSW generated	Recycled or composted	Waste-to-energy	Landfilled
2004, million tonnes	351.90	100.10	26.27	225.53
2004 (%)	100	28.5	7.4	64.1
2002, million tonnes	335.80	89.64	25.76	220.40
2002 (%)	100	26.7	7.7	65.6

fuel (RDF) plants, the MSW is first shredded into small pieces and most of the metals are recovered before combustion (cf. Table 3).

Thermal treatment facilities built in the 21st century have been based mostly on the grate combustion of 'as received' MSW. US facilities follow this type of treatment and on an industrial scale, the dominant WTE technology is grate technology, because of its simplicity and relatively low capital cost. These figures are given also in Table 3 where it is shown that the majority of the facilities (80 of the 87 total) are grate combustion ("mass burned as received" or RDF), while these facilities represent over 80% of the total capacity of WTE in the USA. Three dominant technologies – those developed by Martin, Von Roll, and Keppel-Seghers – are grate technologies. In terms of novel technologies, gasification (JFE), direct smelting (JFE, Nippon Steel), fluidized bed (Ebara) and circulating fluidized bed (Zhejiang University) are in operation around the world, while some of them are under investigation and discussion for possible implementation in the WTE facilities that will be constructed in the USA (Themelis, 2003, 2007).

One of the most successful types of facilities is the RDF-type process of the SEMASS facility in Rochester, Massachusetts, USA, developed by Energy Answers Corp. and now operated by American Ref-Fuel; the facility has a capacity of 0.9 million tonnes/year. This facility was considered to be among the 10 finalists for the Waste-to-Energy Research and Technology Council (WTERT) 2006 Industrial Award; thus to be among the best in the world on the basis of energy recovery in terms of kWh of electricity plus kWh of heat recovered per tonne of MSW, and as the percentage of thermal energy input in the MSW feed, level of emissions achieved, optimal resource recovery and beneficial use of WTE ash, the aesthetic appearance of the facility and the acceptance of the facility by the host community. In SEMASS the MSW is first pre-shredded, ferrous metals are separated magnetically, and combustion is carried out partly by suspension firing and partly on the horizontal moving grate as shown in Fig. 3 (Themelis, 2003, 2007).

3. Benefits from waste-to-energy in the USA

3.1. Energy production and reduction of greenhouse gases using waste-to-energy

According to actual operating data collected by the US WTE industry, on the average, combusting 1 metric tonne of MSW in a modern WTE power plant generates a net of 600 kWh of electricity, thus avoiding mining a 1/4 tonne of high quality US coal or importing one barrel of oil. WTE is the only alternative to landfilling of non-recyclable wastes, where the decomposing trash generates carbon dioxide and methane, a potent greenhouse gas, at least 25% of which escapes to the atmosphere even in the modern sanitary landfills that are provided with a gas collection network and biogas utilization engines or turbines. The non-captured methane that escapes before a landfill is "capped" so that the landfill biogas can be collected, has a greenhouse gas (GHG) potential 21 times that of the same volume of carbon dioxide (IPCC, www.ipcc.ch).

Taking into account the electricity generated and the methane emissions avoided has led several independent studies to conclude that WTE reduces greenhouse gas emissions by an estimated 1 tonne of carbon dioxide per tonne of trash combusted rather than landfilled. Therefore, in addition to the energy benefits, the combustion of MSW in WTE facilities reduces US greenhouse gas

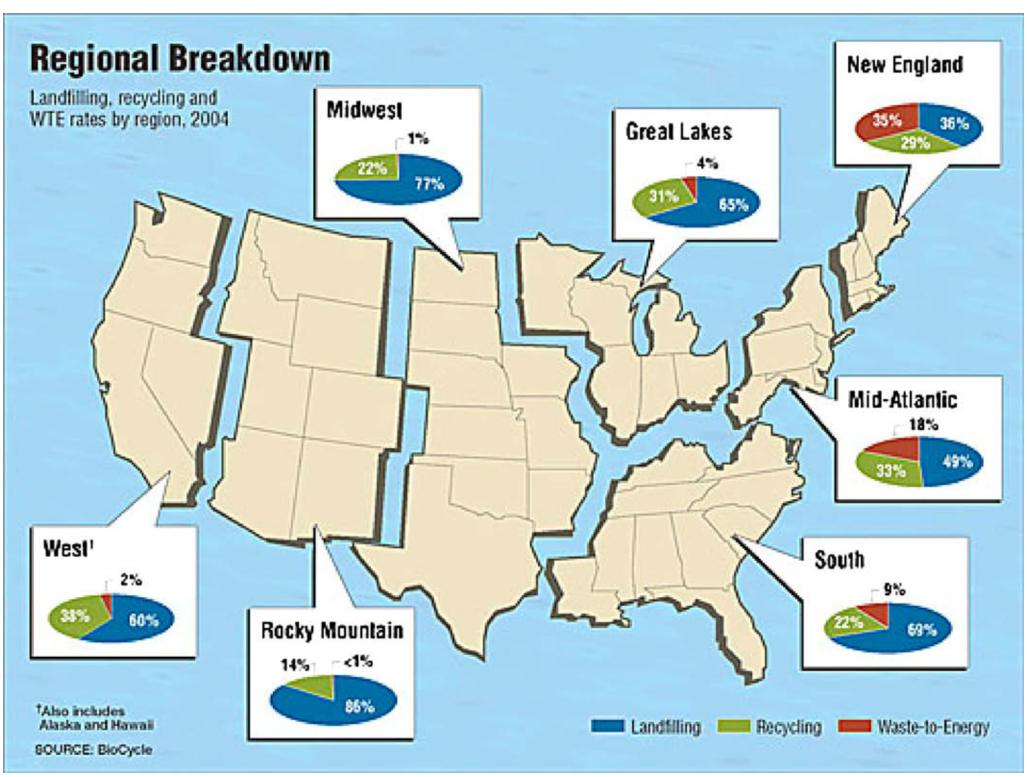

Fig. 1. Breakdown of disposition of MSW by region (Simmons et al., 2006).

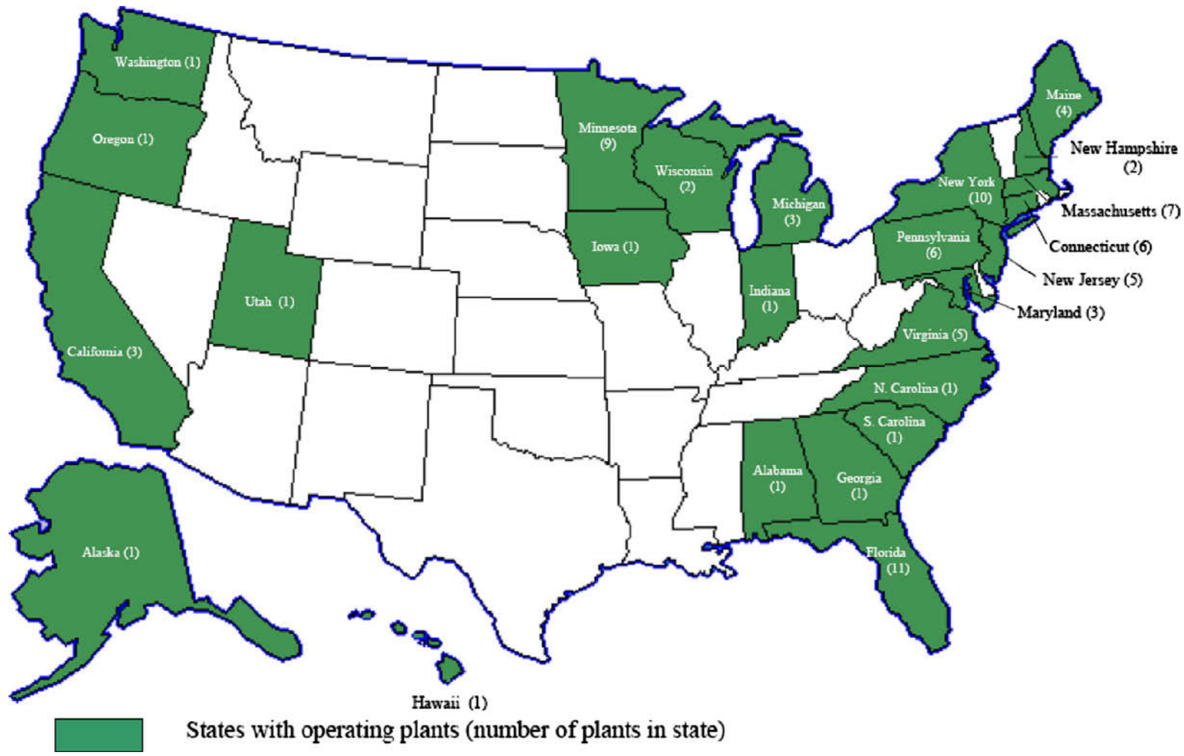

Fig. 2. Operating WTE Plants in USA (Michaels, 2007).

Table 2
Major users of WTE in the USA (Themelis, 2003).

State	Number of WTE plants	Capacity (tonnes/day)
Connecticut	6	5896.7
New York	10	10069.8
New Jersey	5	5624.5
Pennsylvania	6	7620.4
Virginia	6	7529.6
Florida	13	17508.9
Total	53	63140.1

Table 3
Operating US waste-to-energy plants.

Technology	Number of plants	Capacity, tonnes/day	Capacity, million tonnes/year
Mass burn	65	64731.3	20.05
Refuse derived fuel (RDF)	15	18161.8	5.71

emissions by about 26 million tonnes of carbon dioxide. In Table 4 the air emissions of WTE and fossil-fuelled power plants are compared.

In addition to methane, landfill gas contains several volatile organic compounds and chlorinated hydrocarbons. Table 5 is based on the landfill gas analysis provided by Tchobanoglous et al. (1993) and the estimated generation of biogas in a typical landfill.

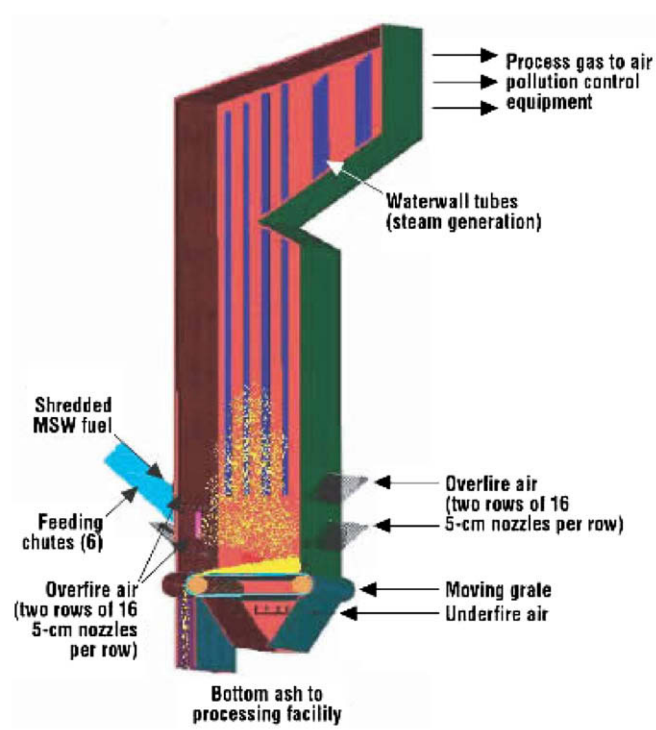

Fig. 3. Schematic diagram of the SEMASS process at Rochester, Massachusetts, USA (Themelis, 2003).

3.2. Source of renewable energy

At this time, the US Department of Energy (US DOE) categorizes WTE as a type of biomass. The term "biomass" means any plant-or animal-derived organic matter available on a renewable basis, including dedicated energy crops and trees, agricultural food and feed crops, agricultural crop wastes and residues, wood wastes and residues, aquatic plants, animal wastes, municipal wastes, and other waste materials (US DOE). Even if one uses a more stringent definition of the term "renewable", one that includes only material from non-fossil sources, about 64% of the US MSW, after material recovery for recycling plus composting, is derived from

Table 4
Waste-to-energy and fossil fuel power plants – comparison of air emissions (O'Brien and Swana, 2006).

Fuel	Air emissions (kg/MW h)		
	Carbon dioxide (CO_2)	Sulphur dioxide (SO_2)	Nitrogen oxides
MSW	379.66	0.36	2.45
Coal	1020.13	5.90	2.72
Oil	758.41	5.44	1.81
Natural gas	514.83	0.04	0.77

Table 5
Gas emissions from landfilling 1 million tonnes of US wastes (100 m^3 of landfill gas/tonne; for regulation landfills: only 25–40% of numbers below).

Compound	Landfill gas concentration, ppmv	Metric tonnes
Methane	500,000,000	35,714
CO_2	490,000,000	96,250
Ammonia	550,000	41.7
Mercaptans/sulfides	500,000	133.9
Toluene	34,907	14.4
Dichloromethane	25,694	9.7
Acetone	6838	1.8
Vinyl acetate	5633	1.6
Tetrachloroethylene	5244	3.9
Vinyl chloride	3508	1.0
Dichloroethane	2801	1.2
Xylenes	2651	1.3
Trichloroethylene	2079	1.2
Styrenes	1517	0.7

Table 6
Concentration of combustible materials in US MSW (US EPA, 1997).

Biomass combustibles	%	Petrochemical combustibles	%
Paper/cardboard	38.6	Plastics	9.9
Wood	5.3	Rubber	1.5
Cotton/wool	1.9	Fabrics	1.9
Leather	1.5		
Yard trimmings	12.8		
Food wastes	10.1		
Total biomass content	70.2	Total petrochemical content	14.3

renewable sources (Table 6). This fraction of MSW can be used as clean, sustainable and arguably renewable fuel for the production of electricity and steam. The remaining non-renewable portion, however, has to be either separated or accepted as part of the fuel. The BioCycle/Columbia annual survey of MSW in the USA reported the generation of about 336 million tonnes of MSW for 2002, of which about 25.8 million tonnes (or 7.7%) were processed for energy recovery in WTE facilities (Simmons et al., 2006).

In 2004, the US WTE facilities generated a net of 13.5×10^9 kWh of electricity, greater than all other renewable sources of energy, with the exception of hydroelectric and geothermal power (Table 7). For comparison, wind power amounted to 5.3×10^9 kWh, 5×10^9 kWh and solar energy to only 0.87×10^9 kWh (Energy Information Administration, 2000).

The combustible materials in MSW consist of 82% biomass (paper, food and yard wastes plus half of rubber, etc.) and 18% petrochemical wastes. Therefore, MSW is a renewable source of energy and it is included by the US DOE in the biomass fuel category of renewable energy sources.

3.3. Recycling and WTE

According to the US EPA, the current municipal recycling rate in the US is 28%. By comparison, 57% of the 98 WTE communities achieved a higher recycling rate of 33%. Ten years ago, WTE communities had an average recycling rate of 21% versus the national rate of 17%. This trend is shown in Table 8 (Kiser, 2003).

Table 7
Generation of renewable energy in the USA in 2002, excluding hydropower (Energy Information Administration, 2002).

Energy source	kWh $\times 10^9$ generated	% of renewable energy
Geothermal	13.52	28.0
Waste-to-energy[a]	13.50	28.0
Landfill gas[a]	6.65	13.8
Wood/biomass	8.37	17.4
Solar thermal	0.87	1.8
Solar photovoltaic	0.01	0.0
Wind	5.3	11.0
Total	48.22	100.0

[a] http://www.eia.doe.gov/cneaf/solar.renewables/page/mswaste/msw.html.

Table 8
WTE community recycling average vs. national rate.

1992 recycling rate		2002 recycling rate	
WTE communities	Total USA	WTE communities	Total USA
21%	17%	33%	28%

Note: Based on responses from 66 WTE communities during 1992, 98 WTE communities during 2002, and national rates determined by US EPA. Sources: Kiser and Zannes, Integrated Waste Services Association; and US EPA.

Among operating US WTE plants, 77% have onsite ferrous metal recovery programs. These facilities recover more than 702,727 tonnes of ferrous annually. Most of these metals are recovered at mass-burn WTE plants, from the bottom ash after combustion. In addition, 43% of the operating facilities recover other materials on-site for recycling (e.g., non-ferrous metals, plastics, glass, white goods and WTE ash that is used for road construction outside landfills); over 776,364 tonnes of these recyclables are recovered annually. Combining all onsite WTE recycling, 82% of the US facilities recycle nearly 1,479,091 tonnes. In fact, all communities with operating WTE plants are linked to offsite recycling programs. The recycling operations associated with these programs may be public or private, residential or commercial. The programs may also operate outside of the community in which the plant is specifically located (Kiser, 2003).

3.4. Saving of land

With proper maintenance, WTE plants can last well over 30 years. Considering that WTE plants do not require more land than the initial requirement, unless they are expanded to process more MSW, WTE plants do not have a continuing cost in land. Furthermore, the required land is significantly smaller than that needed for landfilling the same quantity of MSW, thus the initial capital for land in very small. As an example, with landscaping and auxiliary buildings, a WTE plant processing 1 million tonnes per year requires less then 100,000 m^2 of land. In comparison, the landfilling of 30 million tonnes of MSW (about 8 years of the total generation of MSW in Greece) would require an estimated 3,000,000 m^2. Also, a new plant could be built on the site of the existing WTE plant, thus reducing in this way the capital cost for land in the new facility to zero. On the other hand, the landfill site cannot be used for anything else, ever, and new greenfields must be converted to landfills.

4. WTE emissions and public health issues

In the distant past, many US cities had thousands of residential incinerators in the city without any air pollution controls. For example, at one time New York City had an estimated 18,000 residential incinerators and 32 municipal incinerators. The environmental impacts can still be detected in deep lying cores of the Central Park soil. Understandably, this has left a bad image of incineration in New York City that persists to this day. The result is that the City transports most of its MSW to distant landfills in other states. Yet, the adjacent New Jersey and Long Island Sound communities depend largely on WTE and most of the Manhattan MSW is combusted in the Essex County (NJ) WTE facility of Covanta Energy.

At this time, there are over 1500 incinerators of all types in the USA, but only 87 WTE plants. In the past, when the effects of emissions on health and the environment were not well understood, all high temperature processes, including metal smelting, cement production, coal-fired power plants and incinerators, were the sources of enormous emissions to the atmosphere. In particular, incinerators were the major sources of toxic organic compounds (dioxins and furans) and mercury. However, in the last 15 years and at the cost of about 1 billion US dollars, the 87 WTE facilities operating in the USA have implemented air pollution control systems that has led the US EPA to recognize them publicly as a source of power “with less environmental impact than almost any other source of electricity” (US EPA, 2003; Millrath et al., 2004).

In 1995, the US EPA adopted new emissions standards for WTE facilities pursuant to the Clean Air Act. Their MACT regulations dictated that WTE facilities with large units (i.e., >227 tonnes per day) should comply with new Clean Air Act standards by December 19, 2000. Small unit facilities (i.e., 32–227 tonnes per day) represent only 5% of the US WTE capacity and by 2005 also met similar MACT rules. MACT includes dry scrubbers, fabric filter baghouses, activated carbon injection, selective non-catalytic reduction of NO_x and other measures. WTE facilities now represent less than 1% of the US emissions of dioxins and mercury, as discussed below.

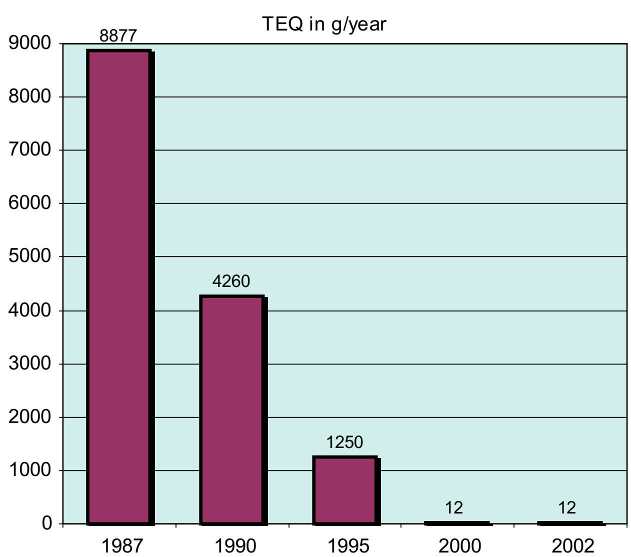

Fig. 4. Reduction of WTE dioxin emissions in the USA (Deriziotis, 2004).

4.1. Decrease in WTE dioxin emissions

The toxic effects of dioxins and furans were not realized, either in the USA or abroad, until the late 1980s. Thanks to the implementation of MACT regulations, the “toxic equivalent” (TEQ) dioxin emissions of US WTE plants have decreased since 1987 by a factor of 1000 to a total of less than 12 g TEQ per year (Figs. 4 and 5). In comparison, the major source of dioxin emissions now, as reported by the US EPA, is backyard trash burning that emits close to 600 g annually (Fig. 5). Table 9 shows the change in major sources of dioxin/furan air emissions in the USA over the years.

4.2. Mercury emissions

The use of mercury in US processes and products reached a high of 2727 tonnes per year in the 1970s. It decreased to less than 364

Table 9
Sources of dioxin/furan air emissions in the USA, in g TEQ (Toxics Release Inventory).

Source	Year		
	1987	1995	2002
WTE facilities	8877	1250	12
Coal-fired power plants	51	60	60
Medical waste incineration	2590	488	7
Barrel backyard burning	604	628	628
Total US	13,998	3225	1106

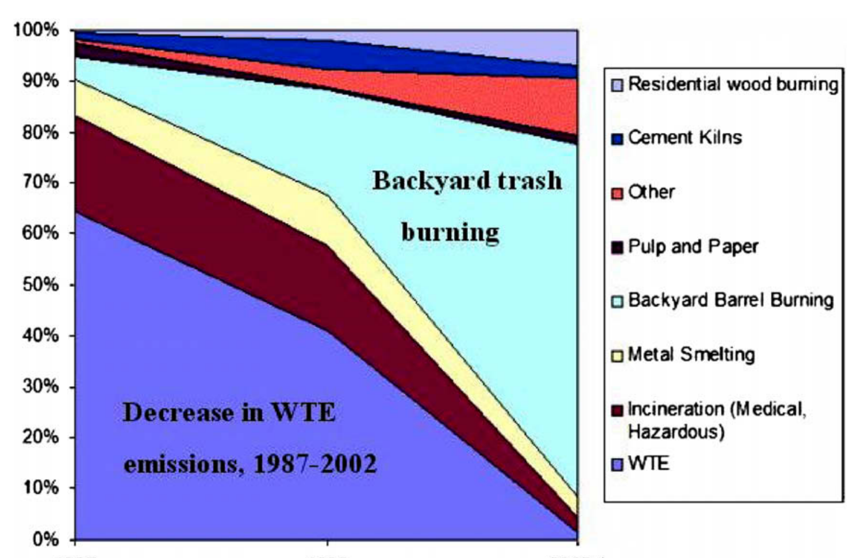

Fig. 5. Dioxin emissions in the USA (Deriziotis, 2004).

tonnes by 2002, due to the phasing out of most applications of this metal, as mandated by the US EPA. For example, mercury activated switches and thermostats have been substituted and the mercury content of fluorescent lamps has been reduced substantially. Also, many communities have put in place strong recycling programs that keep older mercury-containing products out of the MSW sent to WTE facilities. This trend, plus the implementation of the MACT regulations, has decreased the mercury emissions of the WTE facilities from 81 tonnes of mercury in 1989 to less than 1.2 tonnes per year currently (Fig. 6). Now the major sources of mercury in the atmosphere are the coal-fired power plants.

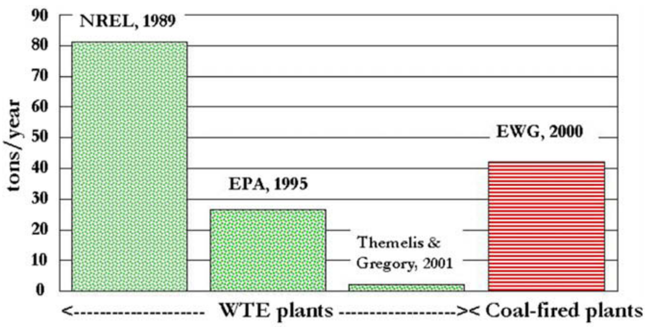

Fig. 6. Reduction of WTE mercury emissions (Themelis and Gregory, 2002).

Table 10
Emissions from US WTE facilities (Stevenson, 2002).

Pollutant	Annual emissions 1990	Annual emissions 2000	Reduction (%)
Dioxins/furans, g TEQ*	4260 g	12 g	99.7
Mercury	41.1 tonnes	2.0 tonnes	95.1
Cadmium	4.32 tonnes	0.3 tonnes	93.0
Lead	47.4 tonnes	4.33 tonnes	90.9
Hydrochloric acid	42,636 tonnes	2429 tonnes	94.3
Sulfur dioxide	27,909 tonnes	3705 tonnes	86.7
Particulate matter	6300 tonnes	643 tonnes	89.8

* Toxic equivalent (sum of substance amounts multiplied by toxicity equivalency

Table 11
Average Emissions of 87 US WTE facilities (Lauber et al., 2006).

Pollutant	Average emission	US EPA standard	Average emission (% of US EPA standard)	Unit
Dioxin/furan, TEQ basis	0.05	0.26	19.2%	ng/dscm
Particulate matter	4	24	16.7%	mg/dscm
Sulfur dioxide	6	30	20%	ppmv
Nitrogen oxides	170	180	94.4%	ppmv
Hydrogen chloride	10	25	40%	ppmv
Mercury	0.01	0.08	12.5%	mg/dscm
Cadmium	0.001	0.020	5%	mg/dscm
Lead	0.02	0.20	10%	mg/dscm
Carbon monoxide	33	100	33.3%	ppmv

dscm: dry standard cubic meter of stack gas.

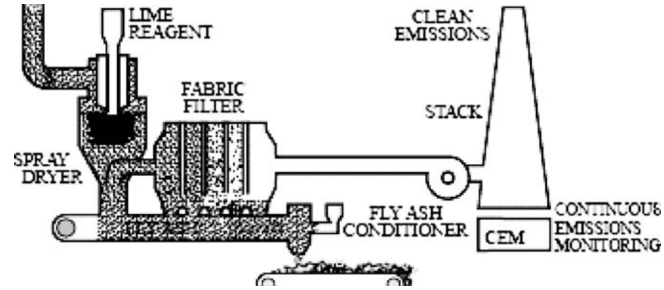

Fig. 7. Air cleaning system of SEMASS WTE facility (Energy Answers Co.).

The only remaining WTE emissions of concern are nitrogen oxides. However, the total WTE emissions of NO_x correspond to only 0.22% of the total US NO_x emissions. For comparison, coal-fired power plants contribute 19.5% of the US NO_x emissions (Albina, 2005). Table 10 presents the reductions in emissions from US WTE facilities between the years 1990 and 2000, while Table 11 presents the average emissions of 87 US WTE facilities, the US EPA standard requirements and the respective percentage considering the US EPA limits.

In addition to the above, data regarding emissions from the 10 finalists (four from the USA and six from the EU) for the Waste-To-Energy Research and Technology Council (WTERT) 2006 Industrial Award are presented in Table 12. The data were provided by operating WTE facilities around the world. The list of finalists included nine stoker grate (mass burn) facilities and one refuse-derived fuel (RDF) plant (SEMASS WTE plant). All 10 finalists had demonstrated high availability and very low emissions; Table 12 compares the emissions of the three top contenders for the award and gives the average emissions of all 10 plants, along with corresponding EU and US environmental standards. Fig. 7 depicts the Air Cleaning System of the SEMASS WTE facility.

5. Conclusions

WTE facilities for MSW management serve about 30 million people in the USA. According to the US experience, the environmental impact of MSW management was reduced (lower GHG emissions, energy production, land savings, materials recovery, etc.). Furthermore, the emissions of toxic and dangerous substances like mercury and dioxins have been significantly reduced, thus protecting public health. Evaluating further these results, it can be seen that the WTE facilities have quite lower emissions compared to electricity production facilities from fossil fuels (except natural gas), reducing further the GHG emissions from landfills while at the same time decreasing the dependency for power production on fossil fuels. In addition, 80% of the combustible bio-

Table 12
Emissions to air from the top three contenders for the WERT 2006 Award (Themelis, 2007).

Emission	WTE-A (mg/Nm^3)	WTE-B (mg/Nm^3)	WTE-C (mg/Nm^3)	Average of 10 finalists (mg/Nm^3)	EU standard (mg/Nm^3)	US EPA standard (mg/Nm^3)
Particulate matter (PM)	0.4	1.8	1	3.1	10	11
Sulphur dioxde (SO2)	6.5	7.5	3	2.96	50	63
Nitrogen oxides (NO_x)	80	11	58	112	200	264
Hydrogen chloride (HCl)	3.5	0.5	0.7	8.5	10	29
Carbon monoxide (CO)	15	7	15	24	50	45
Mercury (Hg)	0.002	0.005	0.002	0.01	0.05	0.06
Total organic carbon (TOC)	0.5	NA	0.9	1.02	10	n/a
Dioxins (TEQ) ng/m^3	0.002	0.002	0.0015	0.02	0.10	0.14

mass included in MSW can be considered as renewable fuel, a fact that is already acknowledged by the US DOE which categorizes MSW as biomass. One more significant parameter that was observed is that the communities that use WTE have a 17.8% higher recycling rate than the US EPA average, which counters the usual argument of environmental groups that building of new WTEs will result in lower recycling rates.

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