Waste-to-Energy: Renewable Energy Instead of Greenhouse Gas Emissions

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Abstract

Global generation of post-recycling municipal solid wastes (MSW) in populated centers amounts to about 1.2 billion tons. Most of this is landfilled, thereby adding to the atmosphere emissions estimated at about 45 million tons of methane, the second most important greenhouse gas. Projected population growth and economic development are expected to double the rate of MSW landfilled by the year 2030.

The only proven alternative to the landfilling of post-recycling MSW is controlled combustion or gasification to recover energy and metals. Worldwide, there are over 600 thermal treatment plants, most of them in E.U., Japan, the U.S., and more recently in China. The most efficient waste-to-energy (WTE) facilities recover as much as 1000 kWh of electricity and district heating per ton of MSW processed. However, in total less than 200 million tons of MSW are subjected to thermal treatment. At the current rate of growth of the global WTE industry, estimated at only four million tons of new capacity per year, methane emissions from landfills will continue to be a significant source of greenhouse gases (GHG) as far out as 2030.

Despite the several advantages of WTE over landfilling (energy and metal recovery, GHG reduction, and, most importantly from the viewpoint of sustainable development, land conservation), its wider application has been impeded by a) well meaning environmental groups that are not aware that modern WTE facilities bear no resemblance to the polluting incinerators of the past, and b) short term economics that do not take into account the environmental and land conservation advantages of WTE. Nevertheless, as major urban centers, like New York City, have run out of landfill space, the combined costs of long distance transport and landfilling municipal solid wastes have increased to the point that waste-to-energy is much preferable to landfilling, both economically and environmentally.

Introduction

In the 20th century engineers designed powerful technologies that met the needs of society: Housing, transportation, food, clothing, and entertainment. However, economic development was accompanied by an enormous increase in the consumption and depletion of the Earth's resources: Minerals, fossil fuels, and ecosystems. Global warming and loss of biodiversity have already signaled that economic development has resulted in major environmental problems that society has to solve in the 21st century. This dire need has resulted in the development of the new "science" of Industrial Ecology that can be defined as "re-thinking and re-designing industrial activities with full knowledge of their environmental impacts". One important issue in industrial ecology is the development of sustainable ways for dealing with the billions of tons of "waste solids" generated by humanity. The global generation of post-recycling municipal solid wastes

(MSW) in urban centers is estimated to 1.2 billion tons (Table 1) of which nearly one billion tons are landfilled (Table 1) and the rest are combusted with energy recovery.

Table 1.Estimated Global Generation of Post-recycling Municipal Solid Wastes

• U.S.A.	260 million tons/year
• European Union	250
• China	200
• Japan	65
•India	50
• All other	375
TOTAL:	1200 million tons/year

Role of Methane in Observed Climate Change

Global mean annual temperature is predicted to increase by several degrees by the end of the 21st century, if greenhouse-gas emissions continue unabated. Hansen et al. (2006) concluded that additional warming of more than 1°C relative to 2000 will produce "highly disruptive" impacts; this represents a total warming of 2˚C relative to pre-industrial climate. Several years earlier, Hansen et al. (2000) argued that the rapid warming observed in recent decades was driven primarily by non-CO_2 greenhouse gases and that a climate target of 1˚C warming in the 21st century, considered to be below the dangerous level, could be achieved by controlling both CO2 and non-CO_2 emissions, such as methane and black-carbon aerosols. Addressing only the CO_2 emissions would require stabilizing atmospheric CO_2 at 450 ppm, not far above the current level of about 380 ppm. Controlling both CO_2 and non-CO2 greenhouse gases (GHG), would allow CO_2 concentrations to stabilize at a higher level (550 ppm), thus affording a better chance of success.

Methane Emission From Municipal Solid Wastes (MSW)

Methane is generated in landfills by the anaerobic biodegradation of organic matter (food and yard wastes, paper, wood, organic textiles, and leather). From the ultimate (atomic) analysis of the components of waste and the atomic weights of the respective elements, it is possible to derive the composite molecular formula. Excluding minor elements and inorganic materials. the average molecular structure of the biomass in MSW can be approximated by the molecular composition $C_6H_{10}O_4$ (Themelis, 2002). It is interesting that this composition corresponds to the structural formula of at least ten organic compounds including ethyl butanedioic acid, succinic acid, adipic acid, and ethylene glycol diacetate (HSC Chemistry, 2006). The maximum amount of methane generated during anaerobic decomposition can be determined from the structural formula presented above::

$$C_6H_{10}O_4 + 1.5H_2O = 3.25CH_4 + 2.75CO_2$$

According to this chemical equation, the biogas generated in a landfill should consist of ~54% methane and 46% carbon dioxide. Matthews and Themelis (2007) assumed a 50-50 CH_4 to CO_2 ratio and 50% bioreaction of the biomass in landfilled MSW (Table 1) and determined the yield of methane from one ton of landfilled MSW for a range of potential biomass contents (30%, 40%, 50%, and 60%) with the balance consisting of moisture, petrochemicals, and inorganic materials such as metals and glass. On the basis of these assumptions, Table 1 shows that 0.05-0.1 ton CH_4 is emitted per ton of landfilled MSW for these biomass classes. For subsequent calculations, these authors assumed 30% biomass in the average global MSW and a corresponding methane yield of 0.05 t CH_4 per ton of MSW landfilled. For the nearly one billion tons of MSW landfilled, the annual generation of methane is 50 million tons. However, some of the modern landfills are equipped for capturing some of the generated methane, as discussed in the following section. Therefore, the fugitive emissions of methane in landfill gas have been estimated at 45 million tons, that is 4% of the anthropogenic GHG emissions. This contribution is expected to increase because the Matthews and Themelis study (2007) estimated that the global rate of MSW generation will double by the year 2030 based on projected population growth and energy use per capita.

Table 2. Waste characteristics and yield of CH_4 and CO_2 per landfilled ton of dry MSW

fraction dry biomass in MSW	0.3	0.4	0.5	0.6
fraction C in biomass	0.148	0.197	0.247	0.296
t C/t MSW	0.148	0.197	0.247	0.296
t C reacted at 0.5 bioreaction	0.074	0.099	0.123	0.148
t C reacted to CH_4	0.0375	0.05	0.062	0.075
t CH_4 generated	0.05	0.067	0.083	0.1
t CO_2 eq. As CH_4 in biogas	1.046	1.394	1.743	2.092
t C reacted to CO_2	0.0375	0.049	0.061	0.073

Capture of Landfill Gas

The EPA Landfill Methane Outreach Project (LMOP, 2006) reported that in 2005 there were 400 LFG collection projects in the U.S. generating 9 billion kWh of electricity plus 74 billion standard cubic feet of biogas. On the basis of these numbers and assuming 35% thermal efficiency for conversion of biogas energy to electricity, we estimated that 2.6 Tg CH_4 was captured and utilized in the U.S. in 2005. LMOP did not provide an estimate of the LFG that is captured and then flared.

Globally, less than 1000 landfills in the world capture biogas (Themelis and Ulloa, 2006). Matthews and Themelis estimated that 4.7 Tg of CH_4 was captured in 2000 (Themelis and Ulloa, 2006) that is 12% of the estimated CH_4 generation in 2000. Furthermore, it was assumed that this 12% capture rate remains constant for 2000-2030. Thus, methane capture increases by 120%, from 4.7 Tg CH_4 in 2000 to 10.3 Tg in 2030 (Fig. 2).

Thermal Treatment of MSW: The Only Alternative to Landfilling

The only alternative to landfilling for treating the post-recycling MSW is by controlled combustion or other thermal treatment to recover energy, metals, and an ash residue that is suitable for road building and other construction purposes. These technologies are generally known as waste-to-energy (WTE) and treat an estimated 170 million tons of MSW annually, i.e., less than 20% of the amount that is buried in landfills. **The Conventional WTE Process**

The conventional WTE combustion process is very much like the stoker burners in many coal- and wood-fired boilers. Waste is continuously fed onto a moving grate in a furnace where high temperatures are maintained. Air is added to the combustion chamber to ensure turbulence and the complete combustion of the components to their stable and natural molecular forms of carbon dioxide and water vapor
The hot combustion gases released during the WTE process are directed through boilers to generate superheated steam that drives turbine generators that produce electricity. Exhausted steam can also be used efficiently for district heating and for industrial processing if those choices are available.

The existing WTE facilities are based mostly on the grate combustion of as-received municipal solid wastes. Worldwide, there are over 650 thermal treatment plants, most of them in E.U., Japan, the U.S., and China. The most efficient waste-to-energy (WTE) facilities are in Denmark, the Netherlands (e.g., AEB Amsterdam), Sweden (Malmo) and Italy (Brescia). They are equipped for co-generation of electricity and heat and recover over 1000 kWh of electricity and district heating per ton of MSW processed.

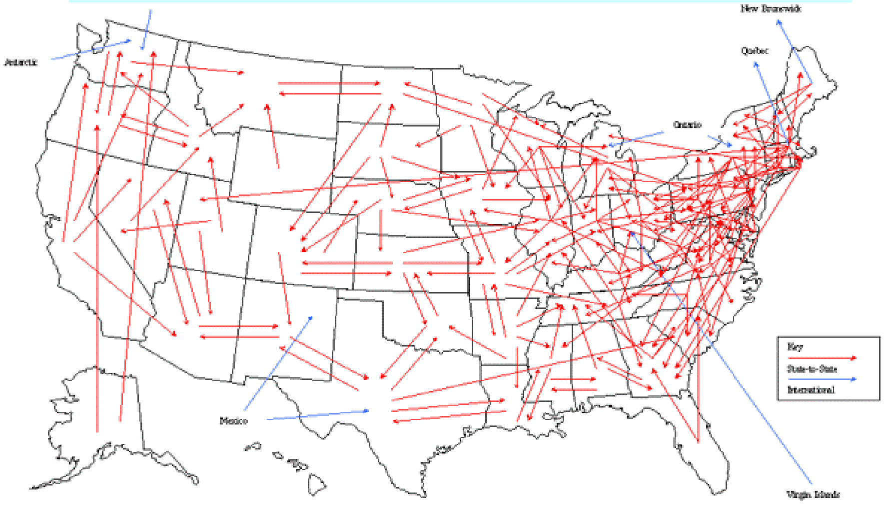
A Columbia University survey of the traditional grate technologies and also of the novel thermal treatment methods, developed mostly in Japan and China, has shown that in the period 2000-2007 there was consistent growth in global capacity of nearly four million tons per year. Although this growth is impressive, the recent study by GISS-NASA and the Earth Engineering Center of Columbia University has shown that it will not be enough to curb landfill methane emissions in the next twenty five years. The reason is that the projected rate of global landfilling, due to increased population and economic development, is by far greater. The only way to reduce landfill greenhouse gases (GHG) substantially between now and 2030 is by attaining a 7.5% growth in thermal treatment capacity, on a global scale, i.e. by as much as 12 million tons per year (Figure 1).

Environmental Benefits of Thermal Treatment of MSW

WTE offers several advantages over landfilling : Energy and metals recovery, GHG reduction estimated conservatively at 1 ton of CO2 per ton of MSW processed by WTE rather than landfilled and, most importantly from the viewpoint of sustainable development, land conservation. It has been estimated that modern landfills require one square meter of overall land surface area for each ten tons of MSW landfilled; accordingly, the one billion tons of MSW that is landfilled currently converts 100 . use one square meter for each WTE also offers short-term economic advantages at major urban centers, such as New York City and Los Angeles, that have run out of landfill space and have to transport their MSW over long distances to distant landfills. This is illustrated in the graph shown in Figure 1 that shows the routes of trucks and trains that transport MSW across state boundaries in the U.S., sometimes in both directions.

Despite its obvious environmental and economic advantages and the full acceptance of WTE by the host communities in thirty five nations, wider development of WTE is being impeded by a) well meaning environmental groups that are not aware that modern WTE facilities bear no resemblance to the polluting incinerators of the past, and b) short term economics that do not take into account the environmental and land conservation advantages of this renewable source of energy. At this point, U.S. is the world’s largest landfiller, followed by China. However, in recent years, China has included WTE in its renewable energy portfolio. This has led to the building of nearly 50 WTE facilities in the last ten years, with hundreds more being planned for its larger cities.

Interstate Transport of Municipal Solid Wastes
(Congressional Research Service)



Interstate Shipment of Municipal Solid Waste in 2002 (CRS, 2002)
Note: Map does not include transactions with the District of Columbia

Figure 1. Interstate transport of MSW in the U.S.A.

Thermal Treatment Technologies

There are ~600 waste-to-energy facilities worldwide, most of them in the EU (~400), Japan (>100) and the U.S. (88). The dominant technology is combustion of as-received fuel (“mass burn”) and generation of steam that is used in steam turbines for electricity generation; in some EU nations turbine exhaust is used for district and industrial heating.

New capacity of WtE facilities for 2000-2007 by the two dominant technologies (Martin and Von Roll Inova) increased by 12.3 and 7.1 Tg, respectively. With additional construction by other technologies such as Mitsubishi Heavy Industries, Japan Steel, JFE, Ebara, Seghers-Koeppel, and the Zhejiang University fluidized bed process, total WtE capacity increased by ~28 Tg, or ~4 Tg MSW per year, between 2000 and 2007.

Matthews and Themelis (2007) constructed several scenarios of waste-to-energy development through 2030. The reference scenario (WtE Ref) assumed that WTE capacity continues to increase by 4 Tg MSW/yr as it did during 2000-2007; for scenarios WtE5 and WtE 7.5, capacity increases by 5% and 7.5%/yr, respectively, between 2010 and 2030. Since permitting and construction of WTE facilities requires 3-5 years, the WtE scenarios do not diverge until after 2010.

Figures 2 and 3 show the impact of multiple scenarios of WTE growth on reducing the flow of MSW to landfills. Post-recycling MSW grows by 120% between 2000 and 2030. WTE scenarios (Fig. 3) indicate the powerful potential impact of increasing WTE capacity on lowering landfilling rates and attendant methane emissions. The most conservative WTE scenario (Ref) diverts 86% more MSW from landfilling in 2030 than in 2000 but, in the same period, landfilled MSW more than doubles. Increasingly aggressive establishment of WTE capacity slows the 2000-2030 growth of landfilled MSW to 84% (WtE5) and to 42% (WtE7.5), relative to 2000: the most optimistic WtE10 scenario produces an absolute decline of 31% in landfilled MSW by 2030, dropping from 781 Tg in 2000 to 535 Tg in 2030. By 2030, the lower growth in landfilled MSW achievable with increased WtE capacity has the potential to reduce the global landfilling rate by a minimum of 13% (Ref) to a maximum of 73% (WtE10) relative to a recycle-only strategy in that year.

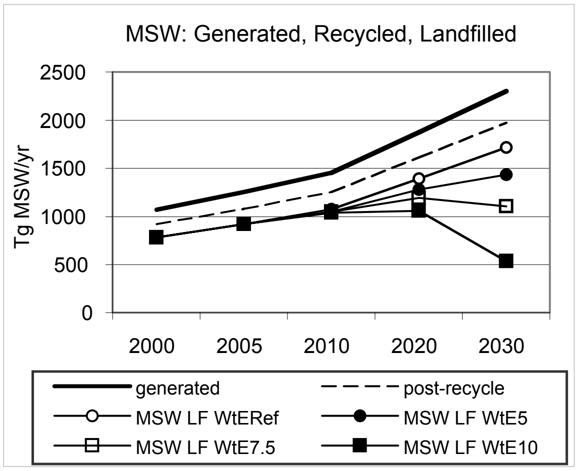


Fig 2. Generated and post-recycle MSW (constant for all scenarios) and landfilled MSW under four WtE scenarios

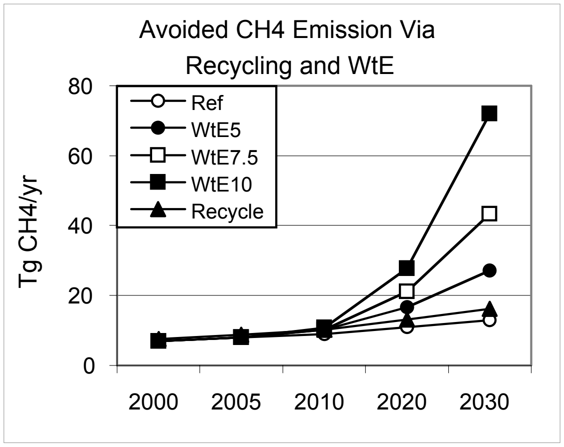


Fig. 3. Avoided CH_4 emission under four WtE growth scenarios.

Economic considerations

The revenues of a WTE facility derive from a) the “tipping fee” per ton of MSW, paid by the communities that send their solid wastes to the WTE; b) the sale of electrical and thermal energy produced by the WTE; and c) the sale of scrap metals recovered from the combustion ash. It should be noted that combusting the biogenic, and renewable, fraction of MSW (65 to 70 percent of the carbon in U.S. MSW) does not result in additional greenhouse gas (GHG) emissions. Therefore, WTE results in a GHG reduction because it avoids the generation of methane in landfills. The GHG advantage is about one ton of carbon dioxide per ton of MSW combusted rather than landfilled. Therefore, in countries where there is a tax or credit for CO2 emitted or avoided, this provides and additional source of revenue. For example, in China electricity generated in a WTE or other renewable energy source commands a price differential of about $30 per megawatt-hour of electricity.

Tipping fees paid to WTE power plants are determined by the availability of landfills in the same area. In the U.S., reported tipping fees (Simmons et al, 2006) range from $20 to $98 per ton of MSW. However, it has been estimated that the new, regulated landfills will cost $40-50 per ton of MSW landfilled.

The major operating cost is the repayment of the capital cost of the plant. In the U.S., a new grate technology plant may cost from $130,000 to $200,000 per daily ton, i.e., $400-$600 per annual ton of capacity, depending on the plant size. In China, a plant of the same technology and quality apparently costs one third of the above numbers.

Despite the high capital cost, U.S. companies and communities that invested in WTEs in the nineties, where the energy prices were one half or less of what they are now, have profited from their investment.

The Global Perspective

The Waste-To-Energy Research and Technology Council (WTERT; *www.wtert.org*) is headquartered at Columbia University in New York City and keeps a close watch on the thermal treatment technologies used worldwide. Table 3 provides the waste-to-energy capacities in several nations.

Table 3. Global waste-to-energy capacity as of 2000

Nation	Million tons of MSW to WTE	Nation	Million tons of MSW to WTE
EU 25	48.8	China	3.0
Japan	40.0	Switzerland/Norway	3.8
USA	26.3	South Korea	1
Taiwan	7.0	All other	9
Singapore	4.0	Total	143

In 2006, WTERT solicited nominations for the 2006 WTERT Industrial Award to be presented to an operating WTE facility judged by an international committee to be among the best in the world on the basis of the following criteria:

- 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
- aesthetic appearance of facility
- acceptance of facility by host community.

From the nominations, 10 finalists were selected and requested to submit a specified set of 2005 operating data. The list of finalists included nine stoker grate (mass burn) facilities and one refuse-derived fuel (RDF) plant, the SEMASS facility operated by Covanta Energy (Table 4).

Table 4. Finalists for the WTERT 2006 Industry Award

Name/operator	Location
Afval Energie Bedrijf (AEB)	Amsterdam, Netherlands
ASM Brescia	Brescia, Italy
Covanta Energy	Montgomery County, Maryland, USA
Veolia Environmental Services Waste -to-Energy (Veolia ES WTE)	Montgomery County, Pennsylvania, USA
SELCHP (Veolia)	London, UK
SEMASS (Covanta Energy) – RDF plant developed by Energy Answers Corporation	Massachusetts, USA
Spittelau	Vienna, Austria
SYSAV	Malmo, Sweden
Umeå Energi	Dåva, Sweden
Veolia Environmental Services Waste -to-Energy (Veolia ES WTE)	York County, Pennsylvania, USA

The competition was intense, as all 10 finalists had demonstrated good performance and very low emissions. The three top rated plants were Brescia (ASM Brescia, Italy),. Amsterdam (AEB Amsterdam, Netherlands), and Malmo (SYSAV, Sweden). Table 5 compares the average emissions of all 10 plants with the corresponding EU and US environmental standards. It can be seen that the environmental performance of these plants is much superior to that required by the most stringent government regulations. For example, opponents of waste-to-energy usually cite dioxin emissions as one of the reasons for their opposition. It is interesting to note that the 0.02 ng/nNm^3 highlighted in Table 5 corresponds to an emission rate of 0.2 grams of dioxins per million tonnes of MSW combusted in these WTE power plants. The WTERT 2006 Industry Award was won by the ASM Brescia facility for demonstrating the best combination of electrical and thermal energy recovery, low emissions and aesthetic appearance.

Table 5. Emissions to air of the top three contenders for the WTERT 2006 Award

Emission	**Average of 10 finalists (mg/Nm^3)**	**EU standard (mg/Nm^3)**	**US EPA standard (mg/Nm^3)**
Particulate matter (PM)	3.1	10	11
Sulphur dioxide (SO_2)	2.96	50	63
Nitrogen oxides (NOx)	112	200	264
Hydrogen chloride (HCl)	8.5	10	29
Carbon monoxide (CO)	24	50	45
Mercury (Hg)	0.01	0.05	0.06
Total organic carbon (TOC)	1.02	10	n/a
Dioxins (TEQ), ng/m^3	0.02	0.10	0.14

Discussion and conclusions

Sustainable management of MSW requires every possible effort to be made to separate recyclable or compostable materials from the MSW stream. Experience has shown that it is best for these materials to be separated at source, i.e. at households, businesses and institutions. The cost of source separation is then shared by the generators (in terms of time and effort to separate recyclable materials) and by the municipalities (in terms of separate collection vehicles and systems). However, it is essential that the source-separated materials are marketable, otherwise they will end up in landfills. An example of the lack of markets is the fact that over 80% of the plastic wastes generated in the USA are landfilled; less than 10% are actually recycled and another 10% are combusted in WTE facilities for energy recovery.

Increasing the global waste-to-energy capacity has the greatest potential for controlling future methane emission from landfilled waste. Waste-to-energy has definite environmental, and in many case economic, advantages over landfilling of municipal solid wastes. Accelerating the rate of growth of this technology will require wide implementation of supportive policies (such as those enacted in E.U. and Japan where landfilling of decomposable material is banned) and provision of economic incentives for the recovery of energy from MSW, as provided by law in China where energy recovery from solid wastes is considered to be renewable energy and commands a price differential on the electricity generated.

For the long term horizon of a nation, WTE development provides several additional benefits including investing in the future, avoiding the increasingly difficult and frequent necessity of building landfills near large population centers, reducing use of primary fossil fuels, and decreasing the greenhouse-gas emissions associated with landfilling.

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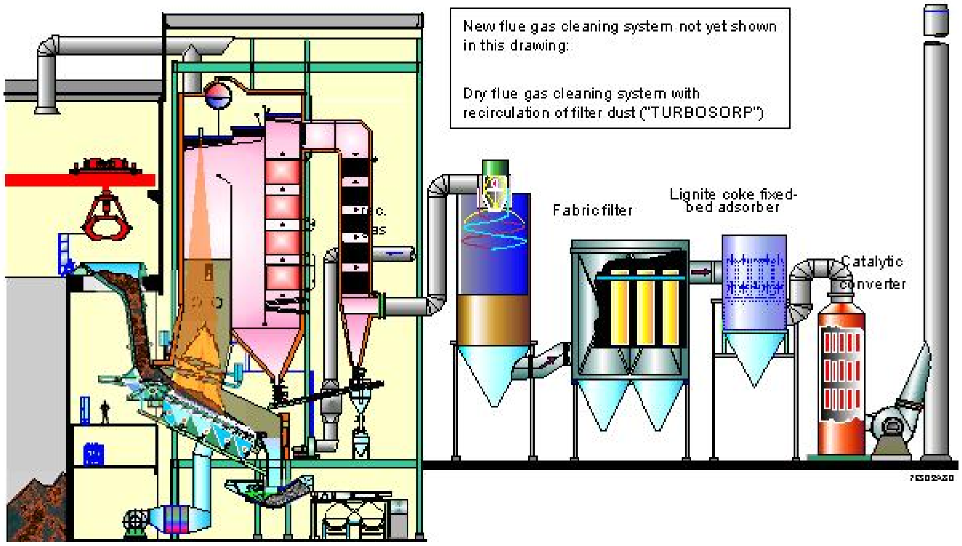
Traditional landfills are a non-sustainable use of land and resources

Modern landfills are much superior but still not sustainable

Winner of WTERT 2006 Industry Award: ASM Brescia, Italy

600 kWh of ,electricity+600 kWh of heat per ton MSW

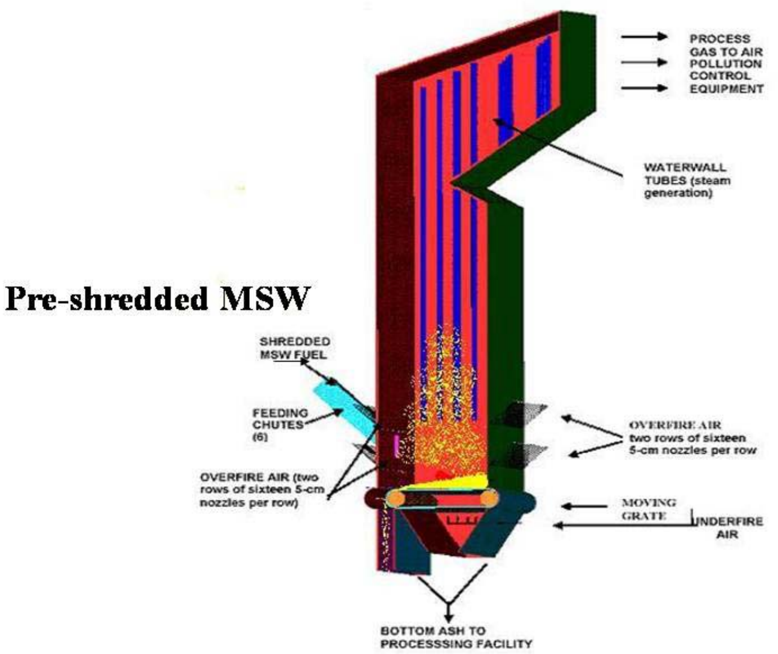
Brescia, Italy WTE, winner of 2006 WTERT Industry Award



New flue gas cleaning system not yet shown in this drawing:

Dry flue gas cleaning system with recirculation of filter dust ("TURBOSORP")

Schematic diagram of the most modern WTE grate technology



U.S. Innovative WTE technology - SEMASS. Mass: part of combustion in suspension, part on grate

The SEMASS RDF WTE of Covanta Energy was developed by Energy Answers International

The new Hiroshima WTE uses the Martin grate technology