7b

Waste to Energy

Contents

Strategic insight

1. Introduction and Global Status

Waste-to-Energy (WtE) technologies consist of any waste treatment process that creates energy in the form of electricity, heat or transport fuels (e.g. diesel) from a waste source.

These technologies can be applied to several types of waste: from the semi-solid (e.g. thickened sludge from effluent treatment plants) to liquid (e.g. domestic sewage) and gaseous (e.g. refinery gases) waste. However, the most common application by far is processing the Municipal Solid Waste (MSW) (Eurostat, 2013). The current most known WtE technology for MSW processing is incineration in a combined heat and power (CHP) plant.

MSW generation rates are influenced by economic development, the degree of industrialisation, public habits, and local climate. As a general trend, the higher the economic development, the higher the amount of MSW generated. Nowadays more than 50% of the entire world's population lives in urban areas. The high rate of population growth, the rapid pace of the global urbanisation and the economic expansion of developing countries are leading to increased and accelerating rates of municipal solid waste production (World Bank, 2012). With proper MSW management and the right control of its polluting effects on the environment and climate change, municipal solid waste has the opportunity to become a precious resource and fuel for the urban sustainable energy mix of tomorrow: only between 2011 and 2012, the increase of venture capital and private equity business investment in the sector of waste-to-energy - together with biomass - has registered an increase of 186%, summing up to a total investment of USD 1 billion (UNEP/Bloomberg NEF, 2012). Moreover, waste could represent an attractive investment since MSW is a fuel received at a gate fee, contrary to other fuels used for energy generation, thus representing a negative price for the WtE plant operators (Energy Styrelsen, 2012).

However, an increasingly demanding set of environmental, economic and technical factors represents a challenge to the development of these technologies. In fact, although WtE technologies using MSW as feed are nowadays well developed, the inconsistency of the composition of MSW, the complexity of the design of the treatment facilities, and the air-polluting emissions still represent open issues for this technology.

The development of WtE projects requires a combination of efforts from several different perspectives. Along with future technical developments, including the introduction in the market of alternative processes to incineration, it is nowadays crucial to take into account all the social, economic and environmental issues that may occur in the decision making process of this technology.

Growing population, increased urbanization rates and economic growth are dramatically changing the landscape of domestic solid waste in terms of generation rates, waste composition and treatment technologies. A recent study by the World Bank (2012) estimates that the global MSW generation is approximately 1.3 billion tonnes per year or an average of 1.2 kg/capita/day. It is to be noted however that the per capita waste generation rates would differ across countries and cities depending on the level of urbanization and economic wealth.

Figure 1

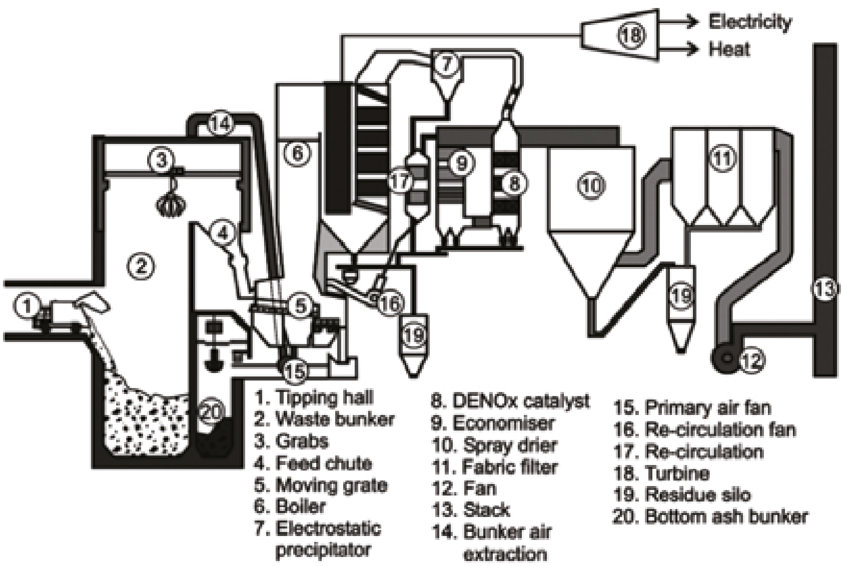


Figure 2

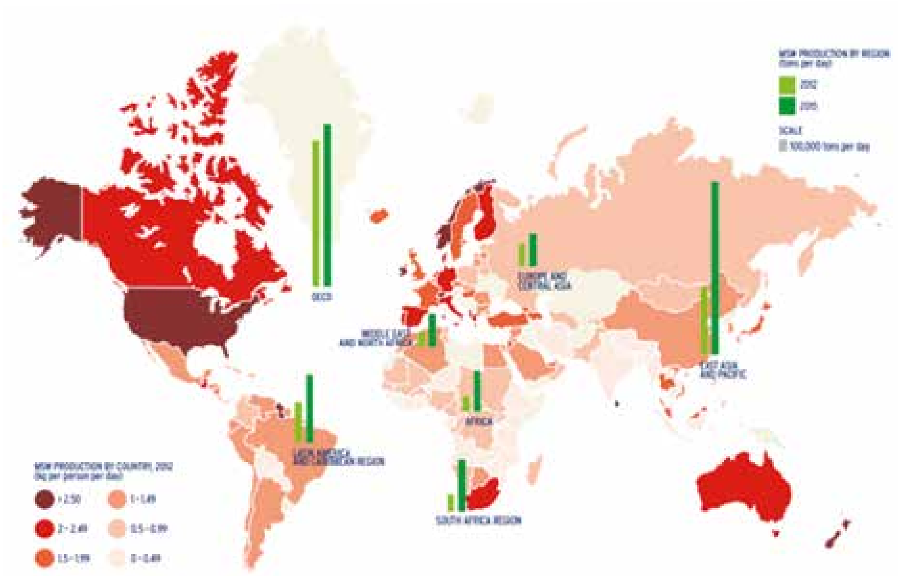
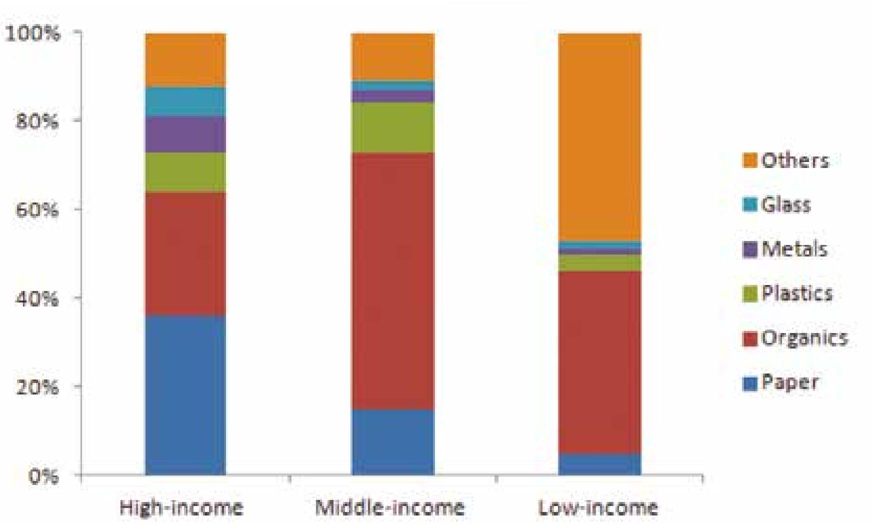


Figure 3



The amount of municipal solid waste generated is expected to grow faster than urbanization rates in the coming decades, reaching 2.2 billion tons/year by 2025 and 4.2 billion by 2050 (World Bank, 2012; Mavropoulos, 2012).

Today, the majority of MSW is generated in developed countries (North America and European Union) as shown in Figure 2. However, the fastest growth in MSW generation for the coming decade is expected mainly in emerging economies in Asia, Latin America and South Africa.

In terms of waste composition, there is a shift towards an increased percentage of plastic and paper in the overall waste composition mainly in the high-income countries, as shown in Figure 3 (UNEP, 2010). It is expected that both middle- and low-income countries would follow the same trends with the increase of urbanization levels and economic development in these countries.

2. Technical and economic considerations

WtE technologies are able to convert the energy content of different types of waste into various forms of valuable energy. Power can be produced and distributed through local and national grid systems. Heat can be generated both at high and low temperatures and then distributed for district heating purposes or utilized for specific thermodynamic processes. Several types of biofuels can be extracted from the organic fractions of waste, in order to be then refined and sold on the market.

As of today, the most common and well-developed technology is in the form of Combined Heat and Power plants, which treat Municipal Solid Waste - and possibly a combination of industrial, clinical and hazardous waste, depending on the system settings - through an incineration process. Technical and economic considerations will be therefore limited to this type of plant.

By definition, waste incineration is carried out with surplus of air. This process releases energy and produces solid residues as well as a flue gas emitted into the atmosphere (Hulgaard T. & Vehlow J., 2011). Because of emission and safety concerns, there is a certain temperature range that is demanded for this type of process. In the case of mixed waste, a furnace temperature of 1050°C is required. A generic description of an incineration process is represented in the following figure (Figure 1). As depicted in Figure 1, waste is first deposited and then extracted from a bunker, and then it is processed on a moving grate in order to achieve a correct combustion. Before undergoing the combustion phase, the incoming waste may be exposed to pretreatment, depending on its quality, composition and the selected incineration system.

The combustion products (flue gases) then exchange heat in a boiler, in order to supply energy to a Rankine cycle. This cycle will then provide power and heat by activation of a turbine and by means of a heat exchanger respectively. The choice of the boiler type is strictly related to the choice of the desired final use of the produced energy.

Within the incineration plant, the flue gas cleaning system (which can be designed in different ways - from filters to electrostatic precipitators) and a series of fans ensure both a correct combustion process and controlled emissions. However, there will be a certain percentage of substances emitted into the atmosphere, depending on the MSW composition and on the type of cleaning systems used. The common pollutant particles in the flue gas are CO_2, N_2O, NO_x, SO_x and NH_3.

Furthermore, it is possible to achieve energy recovery within the cleaning system, when focusing on the flue gas flow. Apart from flue gases that are used to produce heat and power in the incineration plant, the other main product of the process consists of solid residues, mostly in the form of bottom ash or slag and fly ash; some of which can be reused in applications such as filling in the building and construction industries.

The efficiencies for the described incineration process, in terms of energy production, are typically around 20-25% if operating in CHP mode and up to 25-35% in the case of power production only. The size of CHP plants can vary significantly, both in terms of waste input capacity and of power output. A typical capacity is of one (or few) process units, each one dealing with 35 tonnes/hr of waste input (Energinet, 2012). According to the Energy Styrelsen report about Technology Data for Energy Plants (2012), the best example of available WtE incineration technology is the Afval Energie Bedrijf CHP plant in Amsterdam, in operation since 2007. It is the largest incineration plant in the world (114.2 MW) and is able to process 1.5 million tonnes of MSW per year with an electricity generation efficiency of 30%.

It is typical for the described technology to be running at full load during all operation hours, and therefore to be utilized as a base load unit within the electricity generation mix. However, especially in new plant designs, it is possible to achieve significant flexibility of operations through down-regulation, without exceeding the fixed limits for steam quality and environmental performance.

The most important economic difference between WtE technologies and other combustion-based energy generation units is strictly related to the nature of the input fuel. Waste has a negative price, which is regulated by prefixed gate-fees, and is usually considered as the main source of income for the WtE plant owners. In this sense, incineration facilities have the primary purpose of waste treatment. Generation of electricity and heat can be considered as a useful byproduct, with relative additional earnings. Furthermore, the dispatch of power from WtE units is prioritized over other generation units, thus yielding a guaranteed income form during all operations.

Regarding the technology-related costs, the initial investment costs for the construction of the plant play an important role because of the large size of these facilities and of the main installed components. Capital costs, however, can vary significantly as a function of the selected processes for the treatment of flue gases and other produced residues. Operation and maintenance costs have a lower impact on the total expenses of the facility and are mainly related to the amount of treated waste.

3. Market trends and outlook

Despite the recent economic crisis, the global market of waste to energy has registered a significant increase in the past few years and is expected to continue its steady growth till 2015. In 2012, the global market for waste-to-energy technologies was valued at USD 24 billion, an average annual increase of 5% from 2008. The waste to energy market is expected to reach a market size of USD 29 billion by 2015 at a Compounded Annual Growth Rate (CAGR) of 5.5% (Frost & Sullivan, 2011).

The main drivers for this growth could be summarized in an increasing waste generation, high energy costs, growing concerns of environmental issues, and restricted landfilling capacities. WtE would help solve these issues by reducing the waste volume and cutting down on greenhouse gas emissions. Moreover, legislative and policy shifts, mainly by European governments, have significantly affected the growth of WtE market as well as the implementation of advanced technology solutions.

Figure 4.1

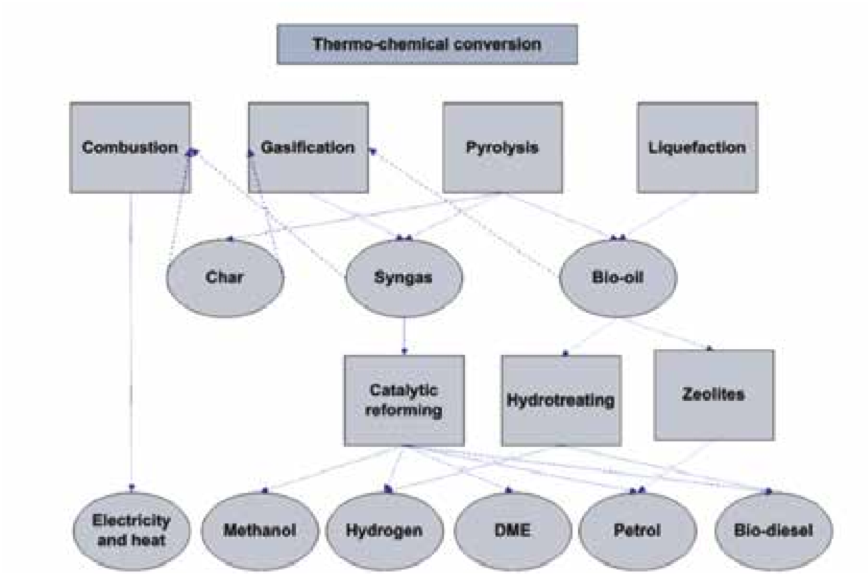
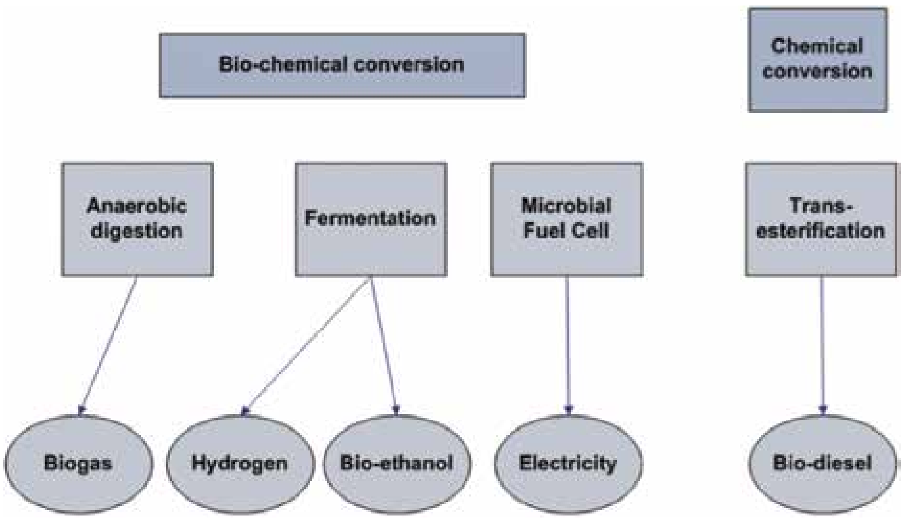


Figure 4.2



The thermal WtE segment is expected to keep the largest share of the total market (approximately 90% of total WTE revenues by 2015). This segment would be expected to increase from 18.5 to reach USD 25.3 billion by 2015 at a CAGR of 6.7%. The biochemical WtE segment would witness a rapid growth from USD 1.4 billion to USD 2.75 billion in 2015 at a CAGR of 9.7% (Frost & Sullivan, 2011).

In terms of markets, the Asia-Pacific region is the fastest growing market for WtE and should witness a significant growth by 2015 with major expansions in China and India. Many of these countries see WtE as a sustainable alternative to landfills. The European market is expected to expand at an exponential rate for the next decade with European Union's efforts to replace the existing landfills with WtE facilities. Moreover, there is a current trend with the private sector actively developing large-scale WtE projects as opposed to the traditional public sector monopoly. This would influence the future of WtE as more players would be expected to enter the market which would help decrease prices and increase technological advancements.

Currently, CHP incineration is the most developed and commercialized technology for WtE conversion. However, a number of different technological configurations are already available for this purpose and, with a constant R&D, many others are envisioned to become valuable alternatives in the future.

The following classification illustrates the possible methodologies which can be used in order to obtain energy from waste.

Thermo-chemical conversion

Looking at thermo-chemical conversion processes, in which the energy content of waste is extracted and utilized by performing thermal treatments with high temperatures, the choice of fuel strongly determines the type of process.

- **Incineration:** With mixed waste input, simple incineration is often utilized by means of the previously described CHP plant technology.
- **Co-combustion:** Co-combustion with another fuel (typically coal or biomass) is an alternative that makes it easier to control the thermal properties of the fuel; in particular the Lower Heating Value. Also, co-combustion is an attractive alternative to simple coal combustion both in terms of costs and emission levels (Rechberger H., 2011).
- **Residual Derived Fuel (RDF) Plant:** The possibility to achieve higher energy contents is the main advantage of Refuse-Derived Fuel (RDF), which can be achieved from different kinds of waste fractions. Its high and uniform energy content makes it attractive for energy production, both by mono-combustion and co-combustion with MSW or coal (Rotter S., 2011).
- **Thermal Gasification:** Thermal gasification is a process which is able to convert carbonaceous materials into an energy-rich gas. When it comes to gasification of waste fractions, it is often agreed that this technology is not yet sufficiently developed in comparison to combustion. However, this process could present many favorable characteristics such as an overall higher efficiency, better quality of gaseous outputs and of solid residues and potentially lower facility costs (Astrup T., 2011). Thus gasification, with proper future technology developments, could be considered a valuable alternative to combustion of waste.

Bio-chemical conversion

Energy can also be extracted from waste by utilizing bio-chemical processes. The energy content of the primary source can be converted, through bio-decomposition of waste, into energy-rich fuels which can be utilized for different purposes.

- **Bio-ethanol production:** Bio-ethanol can be produced by treating a certain range of organic fractions of waste. Different technologies exist; each of which involving separate stages for hydrolysis (by enzymatic treatment), fermentation (by use of microorganisms) and distillation. Other than bioethanol, it is possible to obtain hydrogen from the use of these technologies, which is a very useful and promising energy carrier (Karakashev D. & Angelidaki I., 2011)
- **Dark fermentation and Photo-fermentation producing bio-hydrogen:** Dark fermentation and photo-fermentation are techniques that can convert organic substrates into hydrogen with the absence or presence of light, respectively. This is possible because of the processing activity of diverse groups of bacteria. These technologies can be interesting when it comes to researching valuable options for waste water treatment (Angenent et al., 2004).
- **Biogas production from anaerobic digestion:** Anaerobic digestion is a biological conversion process which is carried out in the absence of an electron acceptor such as oxygen (Angelidaki I. & Batstone D.J., 2011). The main products of this process are an effluent (or digest) residue and an energy-rich biogas. The entire conversion chain can be broken down into several stages (Figure 5), in which different groups of microorgan-

isms drive the required chemical reactions. The obtained biogas can be used either to generate power and heat or to produce biofuels. The digest can also be utilized in many different ways depending on its composition. Several technologies utilizing this process have been developed throughout the years but are still considered to be immature and not economically competitive compared to other WtE technologies.

- **Biogas production from landfills:** Other than in an anaerobic digester, it is possible to extract biogas directly from landfill sites, because of the natural decomposition of waste (Tchobanoglous et al., 2002). In order to do so, it is necessary to construct appropriate collecting systems for the produced biogas. Biogas in landfills is generally produced by means of complex bio-chemical conversion processes, usually including different phases like Initial Adjustment, Transition Phase, Acid Phase, Methane Fermentation and Maturation Phase (Zaman, 2009).
- **Microbial fuel cell:** A microbial fuel cell is a device that is able to produce electricity by converting the chemical energy content of organic matter. This is done through catalytic reaction of microorganisms and bacteria that are present in nature. This technology could be used for power generation in combination with a waste water treatment facility (Min B., Cheng S. & Logan B.E., 2005).

Chemical conversion (Esterification):

The chemical process of esterification occurs when an alcohol and an acid react to form an ester. If applying this process to WtE treatment, it is possible to obtain various types of biofuels from waste. (Nic et al., 2006).

Figure 5

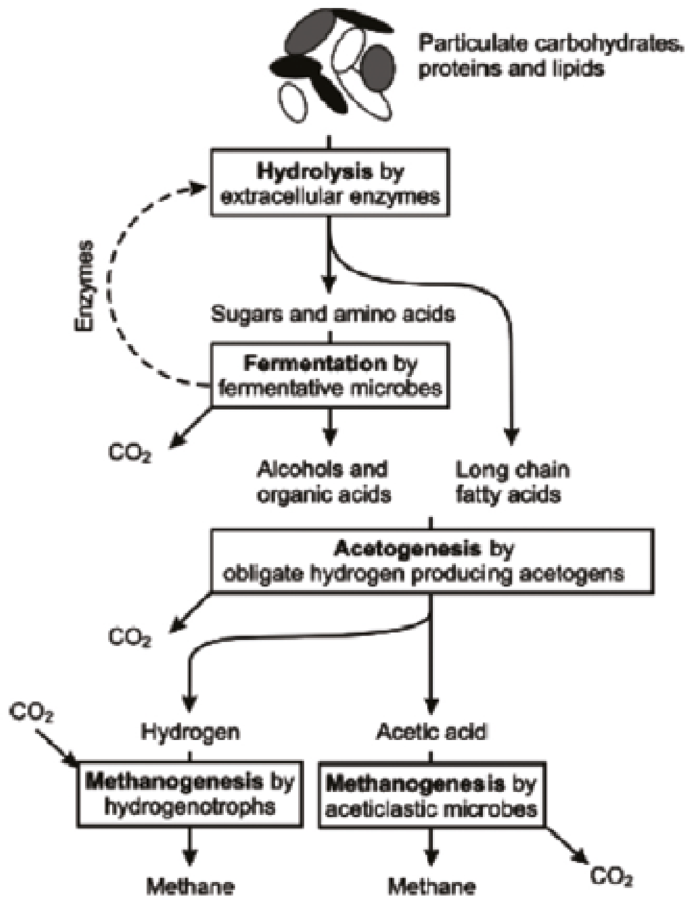


Figure 6

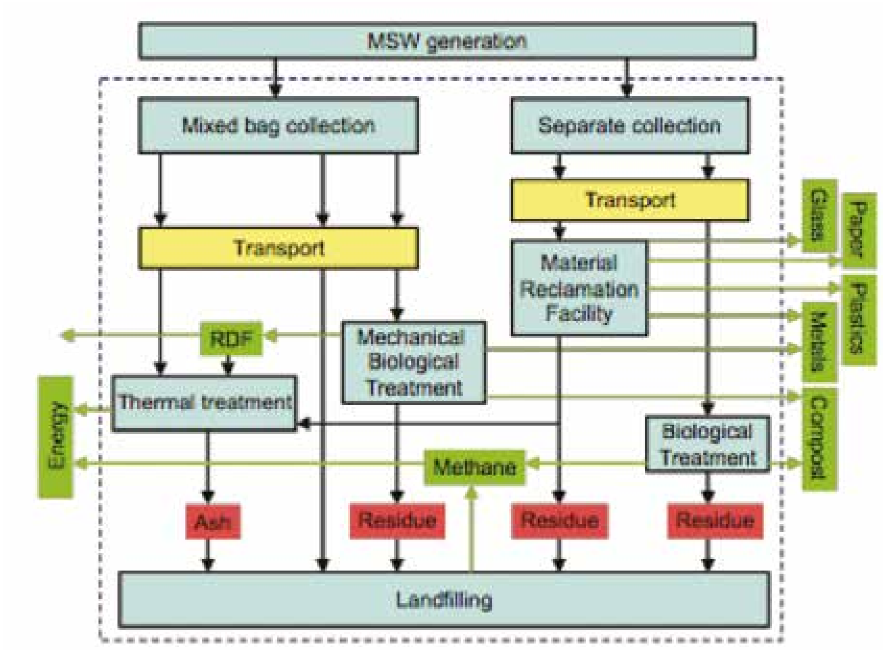


Figure 7

	Low Income Countries	Lower Mid Inc Countries	Upper Mid Inc Countries	High Income Countries
Income (GNI/capita)	<$876	$876-3,465	$3,466-10,725	>$10,725
Waste Generation (tonnes/capita/yr)	0.22	0.29	0.42	0.78
Collection Efficiency (percent collected)	43%	68%	85%	98%
Cost of Collection and Disposal (US$/tonne)				
Collection[1]	20-50	30-75	40-90	85-250
Sanitary Landfill	10-30	15-40	25-65	40-100
Open Dumping	2-8	3-10	NA	NA
Composting[3]	5-30	10-40	20-75	35-90
Waste -to-Energy Incineration[4]	NA	40-100	60-150	70-200
Anaerobic Digestion[5]	NA	20-80	50-100	65-150

NOTE: This is a compilation table from several World Bank documents, discussions with the World Bank's Thematic Group on Solid Waste, Carl Bartone and other industry and organizational colleagues. Costs associated with uncollected waste–more than half of all waste generated in low-income countries–are not included.

The current WtE market is continuously under development and these and other new technologies are likely to play an important role in the foreseeable future, as long as they can prove to be sufficiently competitive with the more traditional Incineration process from a technical, economic and environmental perspective.

LCA, including current costs, efficiencies and emissions & water for each phase: extraction, transport, processing, distribution, use

In the development of WtE projects, the consideration of the environmental implications is playing an increasingly important role. The Life Cycle Analysis (LCA) approach is more and more used as a support tool in strategic planning and decision-making process of WtE projects (Christensen et al., 2007). However, dealing with a general Life Cycle Analysis for MSW WtE systems could be a challenging task. The inputs and outputs of the WtE systems could markedly vary from project to project: in fact, the composition and cost of the waste strongly depend on the location of the project. Efficiencies and emissions can vary significantly by the WtE plant design and waste composition; so does the size of the markets for products derived from WtE facilities (Mendes et al., 2004).

Zaman (2009) presents a comparative LCA study among four of the main WtE technologies from energy generation perspective. The considered technologies are: 1. Landfill gas production; 2. Incineration; 3. Thermal Gasification; 4. Anaerobic Digestion. The study also includes the environmental impacts associated with the emissions of the analysed systems.

The cradle-to-grave life cycle of a WtE technology (Figure 6) begins with the waste generation e.g. when the owner of a product discards it in the waste collection trash cans. Then, depending on the country and/or regional laws, the waste is collected either via mixed-waste bags or via separate collection; in both cases a dedicated infrastructure for the collection is required (e.g. dedicated bins, dedicated collection vehicles, storage units, etc). The next stage is the transportation of the collected waste to the waste treatment facility: the mixed-waste bag reaches the WtE facility/plant (landfill gas production, incineration, pyrolysis-gasification, anaerobic digestion), whilst the separated waste goes to the Materials Reclamation Facility (MRF). The next stage of the life cycle is then the processing of the waste inside the WtE plant: energy in the form of heat, electricity and fuels are produced, as well as residues and ashes.

Regarding the collection, storage and transportation of the MSW, LCA studies show that the door-to-door collection system has a higher environmental impact than the multi-container collection system (Iriarte et al., 2009). Moreover, the bring systems (where individuals physically bring the waste to the collection points), although widely used in modern waste collection schemes, have higher overall environmental impacts than the curbside collection, where the collection of waste is centralised (Beigl & Salhofer, 2004). Eventually, it is believed that using bigger high-density polyethylene (HDPE) bins in the collection systems will yield a lower environmental impact than if using smaller HDPE bins (Rives et al., 2010). The costs associated with the collection and disposal of the MSW depend, of course, on the considered country. An overview of the estimated solid waste management costs by disposal method is shown in Figure 7 below.

Concerning the WtE processing, LCA studies demonstrate that landfill gas production has the highest emissions of carcinogenic substances among the considered technologies. It has respiratory effects of organic solvent exposure and presents a higher level of toxicity and an overall higher impact on climate change (Zaman, 2009). As reported by Abeliotis (2011) landfills represent the worst management option from a waste management point of view (Miliute & Staniskis, 2010; Cherubini et al., 2009; Wanichpongpan & Gweewala, 2007; Hong et al., 2006; Mendes et al., 2004). Incineration, on the other hand, has a high impact on climate change and acidification and presents respiratory effects of organic solvent exposure. The Thermal Gasification and Anaerobic Digestion processes have significant lower environmental impacts than other considered WtE options (Zaman, 2009). The LCA simulation conducted by De Feo & Malvano (2009) of 12 different MSW WtE scenarios with 16 management phases for each scenario, clearly shows that following the 11 considered impact categories, there is a different "best scenario" option for each category: the MSW WtE management options should be evaluated case-by-case.

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Reserves and production

Table 1
Municiple Solid Waste reserves and production

	Quantity raw waste			Yield of solid fuel	Electricity Generation Capacity	Annual Electricity Generation	Direct Use from Combustion	Total Energy Production
Country	TJ	TTOE	million tonnes	GJ/tonne	kW	TJ	TJ	TJ
Albania		405						
Algeria			5					
Australia			6.9	9	11.4			
Austria			2.4				16421	30270
Belgium			1.1		76600			1765
Botswana							1420	
Brazil			40		41870			2311
Canada			11.856		211187		1.688	
Croatia			1.5		2000	0.0144		
Czech Republic			0.24		3000	42	1966	2008
Denmark	40051					6718		
Egypt			2.4					
Estonia			0.569					
Finland			2.2			2160	2380	4610
France		2394			772800	13586	27209	40795
Germany			0.94		852000	11200		
Greenland				10.5			83	
Hong Kong			7.7					
Hungary			0.2	12.5		1504	28093	62993
Iceland					831	15	56	71
Ireland								1085
Israel			5					
Italy						619475	5602	
Japan			0.601		2230000			
Jordan			2		1000	5142 MWh	5142 MWh	
Korea (Republic)							21153	
Latvia					9400	106		
Lebanon			1.44					
Mexico			37.59			820		
Netherlands						10296	1085	11381
New Zealand					37800	726	280	
Philippines						6		
Poland							675	
Portugal			1		90000	7652		
Romania		545						
Senegal					20000			
Serbia			2.8					
Singapore					135000	3994.68		
Sweden					282	4990		

Switzerland				3316		13562
Syria	4					
Taiwan			583.8	27128.9		
Thailand			5000	94.63		
Turkey			59.65	220		
Ukraine	19.57					
United Kingdom	3.8		375900	7061	2108	9169
United States of America	254		2669000	54255	20833	75088
Uruguay			1000			

County notes

Country Notes for Waste Chapter of the World Energy Resources report are currently being compiled as a subset of the Bioenergy Chapter.