

# **Environmental and Economical Assessment of MSW Management in Europe: An Analysis between the Landfill and WTE Impacts**

**Veronica R. Polzer**

PhD student of Mackenzie University, São Paulo, Brazil - Department of Architecture and Urbanism. Scholarship from CAPES Foundation – Process: 5550-14-9

Visiting PhD student of Department of Building & Environmental Technology, Division of Water Resources Engineering, Lund University, Fax +46 46 222 44 35, P.O. Box 118, SE-221 00, Lund, Skåne, Sweden

Corresponding author: veronica.polzer@tvrl.lth.se, +46 76 774 3316

**Kenneth M. Persson**

Department of Building & Environmental Technology, Professor of Division of Water Resources Engineering, Lund University, P.O. Box 118, SE-221 00, Lund, Skåne, Sweden, +46 73 412 8167

DOI: 10.6007/IJARBSS/v5-i6/1649 URL: <http://dx.doi.org/10.6007/IJARBSS/v5-i6/1649>

## **ABSTRACT**

Every year two billion tons of MSW are produced globally. Due to the impact of solid waste and population growth, it is necessary to develop an integrated solid waste management plan. Such a plan, holistic in scope, would aim to minimize the negative impact of this material in the environment while being economically viable. The designation and terming of any one mode of waste treatment as superior or preferable is an intricate issue in which a large set of standards and measures should be taken into account. The decision must consider not only economic and political aspects and realities but also environmental ones in the long term. According to the traditional method of life cycle assessment (LCA), it is possible to evaluate the environmental impact of different technologies and systems used for solid waste management such as recycling and biological treatments, waste-to-energy facilities and landfills. In order to provide examples and bases for comparison, several previous LCA studies are considered in this paper. Furthermore, various pros and cons of landfills and waste-to-energy facilities, taking into consideration European environmental, financial, and political realities are verified as well as the importance of European regulations and economic instruments adopted in several member countries. The results prove that the MSW hierarchy (avoid, reuse, recycle, recovery energy and landfill) present in the European regulation is the most adequate way to treat waste.

## **KEYWORDS**

Municipal Solid Waste Management; waste-to-energy; landfill; life cycle assessment; clean technologies

## 1 INTRODUCTION

Annually, roughly two billion tons of MSW are generated around the world and it is estimated this figure may reach about 6.1 billion tons in 2025 (World Bank, 2012). Waste production is increasing at an accelerated rate when compared with global population growth. According to the United Nations (2014) the world population in 1825 was one billion people, by 1930 it had doubled to two billion, and by 1975 had doubled again to four billion, reached seven billion people in 2011. Indeed, the population doubled over increasingly smaller periods, yet the increase in waste generated during those periods has been markedly higher. The activities of collection, treatment and disposal of solid waste represent a challenge for all municipalities around the world. In order to determine the best solutions for this problem, it is necessary to develop not only an LCA (life-cycle assessment) study, but also complementary analyses regarding costs, performance and logistics. With the aid of these analyses, municipalities are able to choose the most sustainable solid waste management plan and course of action.

Consumption and the resulting waste production is also increasing in developing countries, where government implemented policies promote consumption by those of the lowest income brackets in efforts to stimulate economic growth. As an aggravating factor, these levels of encouraged consumption lead to levels of waste accumulation significantly higher than those of previous decades. According to the World Bank report *“the higher the income level and rate of urbanization, the greater the amount of solid waste produced”* (World Bank, 2012, p.8). Countries with a lower per capita income present a solid waste generation average of 0.60 kg/person/day. By contrast, countries with a high per capita income have a solid waste production about 2.13 kg/person/day. By 2025, it is predicted that regions with lower, lower-middle and upper-middle per capita income will produce over 43%, 66% and 38%, respectively, more waste than current levels (World Bank, 2012).

In addition to the production of MSW, energy consumption has increased exponentially. The rates of both solid waste generation and demand for energy have increased at a faster pace than corresponding growth in population. Despite prior use of incinerators in disposal of solid waste, the 1970s saw European countries profoundly affected by the Middle Eastern oil crisis, wherein those countries converted existing incinerators to utilize new technologies capable of generating district heating and electricity. Additionally, increasing environmental protection regulations forced the upgrading of existing incinerators to a more modern and updated standard, including new technologies to control and minimize emissions to air, water and soil (Lemann, 2008).

Due to this recent increase in solid waste production treatment to divert materials from landfills is becoming more common around the world. Treatments such as recycling, composting and anaerobic digestion are increasing regardless of choices of final disposal. These treatments can generate income and employment for the local population. In addition, the reuse and recycle programs can prevent the extraction of natural resources, reducing the

environmental impacts caused by human activity. Hence, the municipality should consider not only the environmental benefits but also the economic and political aspects and potential benefits.

Several regulations around the world, as well as the European Directive 2008/98/EC, established the same priority in the allocation of solid waste. The first step is to avoid producing waste, the second is to reuse the material produced, the third is to recycle and compost (or another type of biological treatment), the fourth is to recover energy and the last step is the final disposal of solid waste in landfills (EC, 2008). Not only European countries and other developed countries, such as Japan, USA and Canada, pursue these targets but also several countries in the developing world are beginning to change their current solid waste process in order to promote a circular economy and to save resources and energy.

Furthermore, economic instruments established by the member countries of the European Union encourage conservation and minimization of waste, considering that the landfill tax is the highest of all facilities. Therefore, it is an economic advantage diverting waste from landfills to pre-treatments such as recycling or composting, followed by incineration. Along with the economic instruments are the European regulations such as EU's Waste Framework Directive (EC, 2008) and Landfill Directive (EC, 1999). Both documents are responsible for setting the primary targets to 2020 (EEA, 2013).

According to Lemann (2008, p.36) "*treatment of waste is a metabolic conversion,*" which means that each kind of treatment (recycling, energy recovery, composting, landfilling and others) generates new products in the form of emissions, effluents and residues. These unwanted products must be neutralized or avoided with the ultimate goal of mitigating the environmental impact from waste treatment.

The solid waste management companies have the responsibility not only to follow the regulations and pursue the targets indicated in the laws, but also to research new methods and technologies to decrease the impact of solid waste in the environment and to perform this activity in a sustainable and economically viable way. Consequently, these companies have a fundamental role in society, transforming waste into resources through recycling, composting, recovering energy and other treatments. Additionally, they also create jobs and income in the entire waste management chain.

In regard to environmental analysis, a Life Cycle Assessment (LCA) aims to analyze the environmental impacts generated by a product or a system during its life cycle, from raw material extraction to final disposal (cradle-to-grave) in a scientific and methodological way. According to the ISO (International Organization for Standardization) number 14.040 (ISO 14.040, 2006), which establishes the methodology and guidelines for an LCA study, this analysis is based on the inputs and outputs calculation during a particular process. This study is done through four specific phases: 1 – definition of scope and objective of the study; 2 –

development of an inventory table with the relevant inputs and outputs; 3 – development of an impact assessment based on the inputs and outputs chosen; and 4 – interpretation results. The last phase would check whether both the objective and scope were reached and analyze their relation to the other phases. The study is cyclic and the phases can be re-evaluated several times during the research. This kind of analysis is fundamental and essential to ensuring the environmentally sound choices and policies. As this tool does not comprise economic, logistical and performance issues it is necessary to consider in parallel these complementary parameters before any final decisions are reached.

Through the LCA tool it is possible analyze the life cycle of an integrated solid waste management system. Each scenario should contain its detailed LCI (Life-cycle-inventory), which represents the total of mass and energy needed in every solid waste management phase analyzed. The inputs and outputs are then characterized according their impacts in the LCIA phase (Life-cycle inventory analyses). All types of emissions (gases, solids and liquids) are distributed according to their specific impact categories (abiotic resources, global warming, land use, stratospheric ozone depletion, among others) (EEA, 1997).

This paper studies two systems after the MSW pre-treatments, the landfills and waste-to-energy facilities. To provide a comparison between these technologies, the most relevant regulations, economic instruments and environmental impacts based on LCA analysis were identified. Among other reasons this is relevant in finding functioning solid waste management strategies for the rapidly growing economies of the world such as Brazil and China. European solid waste regulations may serve best as a template for management of this challenge and inspire policy makers in emerging markets regarding methods of further developments in solid waste management.

## **2 LANDFILL REGIME IN EUROPE**

Some definitions are necessary to present the main landfill concepts (e.g. the distinction between landfills and dumps). Dumps, also labeled as open-dumps, are sites where the MSW is abandoned without any environmental treatment, which represents a risk to public health. Not only the soil is contaminated in this way but also the water and the animals, which have access to the dump. This kind of disposal of MSW must be avoided because it contributes to the spreading of diseases and has an enormous negative environmental impact. Although the dumps are not considered appropriate sites for disposal of solid waste, they are still in operation in developing countries. On the other hand, the landfills are sites where through engineering techniques, the disposal of MSW is done, without causing damaging to the public health and with less environmental impact in comparison with dumps.

In a typical landfill, the soil is compacted and receives a geomembrane of HDPE (High Density Polyethylene). This geomembrane does not allow liquid infiltration produced by organic

material, contaminating the soil and groundwater. Above the geomembrane there is another layer of compacted soil, which ensures mechanical protection preventing perforations in the geomembrane. A layer of gravel is placed over the mechanical protection soil, gravel which helps in draining the leachate that will be produced in the landfill. This liquid is directed to a container for future treatment. A horizontal drain is installed after each cell of solid waste fills the landfill, and the process is repeated layer after layer. The methane is collected by the vertical drains and directed to a biogas plant to generate energy. Each cell of solid waste is covered with a layer of soil, which keeps the waste confined and isolated from the external environment. As protective procedures, landfills generally receive a barrier of vegetation, preventing view and access by people and animals. In addition, the groundwater is monitored by piezometers, ensuring that the underground water is not being contaminated. The topography is also observed, preventing erosion and decay. When all the cells of a landfill are filled, the landfill is sealed and landscaped with soil and grass. The purpose of the grass is to hinder rain infiltration. Thus, the stormwater is directed by horizontal drains to receive treatment and not increase the level of leachate produced inside the cells (Polzer, 2012).

According to EEA (2011), for many years, landfills were the predominant choice in Europe for final disposal of MSW. The rate for solid waste landfilling in 1995 was 68%, but this number fell to 40% in 2008, and continues to decrease. It is expected that less than 28% of MSW will be disposed of in landfills by 2020. The most significant milestone to replace the landfills was the waste priority in the Landfill Directive in 1999. The reasons were evident, such as the capacity of landfills and the environmental impacts produced by greenhouse emissions and contamination of groundwater and soil. The law has been successful in reducing the disposal of MSW in landfills and promoting the use of less environmentally compromising techniques.

According to the Landfill Directive (EC, 1999), organic material should be diverted from landfills to biological treatments. The law also requires the collection of methane and the monitoring of emissions during all landfill life cycle. As the biodegradable material buried in a landfill is responsible for methane production, through microbial and abiotic reactions, the trend is to decrease the emissions gradually as more organic material is diverted from these sites. The targets indicated in the law were based on 1995 emissions and they were represented by the percentages: 75% in 2006; 50% in 2009 and 35% in 2016.

Each European country has varying factors to consider in order to effectively divert organic material from landfills, factors such as socio-economic situations, population density, and level of urbanization, among others. All these issues considered, the process of managing organic materials differs in time and speed in each country, region or municipality. Some of these areas struggled greatly with modernization of the solid waste systems: Italy, Estonia and Hungary, where there were no separate collections for organic material. However, in countries such as Germany, Austria and Belgium (Flemish Region) the targets indicated in the law were easily met because these areas had already implemented the modifications needed to treat biological waste before the European regulations were implemented (EEA, 2009).

Some countries have already reached the 2016 target, such as Sweden, Germany, Austria, Denmark, Belgium, the Netherlands and Luxemburg; others countries are close to the goal: Finland and France. Some of them have much work to do in this regard: Italy, Greece, Portugal, Ireland and others. These countries requested a postponement of the goals from the European Union. The subsequent derogation requires that each country meet each target with a granted four year delay: 2010 instead of 2006; 2013 instead of 2009 and 2020 instead of 2016 (EEA, 2010; EEA, 2010a).

To comply with the law the member countries of the European Union are utilizing biological treatments to divert organic material from landfills. Generally, these treatments are: recycling of some biodegradable material such as paper, cardboard, wood, among others; composting of food waste, manure, etc.; and recovery of energy through anaerobic digestion, fermentation and incineration (Eurostat, 2014).

To adhere to the Landfill Directive, several countries have addressed various alternatives to the taxation of landfilling. According to EEA (2009) the landfill tax must be high to dissuade landfilling of waste. Other incentives to decrease the disposal of waste in landfills also proving effective are “pay-as-you-throw” and various finished product charges. However, all these schemes should be developed in a way that modify the behavior of residents, producers and the waste companies significantly.

In addition to the Landfill Directive, other relevant European Union regulations help to decrease the disposal of organic material in landfills. The Packaging Directive (EC, 1994) requires that all municipalities have separate collection for packaging materials. Some countries (e.g. Estonia and Hungary) have initiated a specific collection for biodegradable packaging (wood, paper, cardboard), sending these materials for recycling. Another piece of effective regulation in this matter was the Renewable Energy Directive (EC, 2001), which requires targets for renewable energy for all member nations. As waste-to-energy is considered a renewable energy source, this law also encouraged recovery-energy and other treatments for organic material, diverting them from landfills. Indeed, diverting waste from landfills is based on the integration of public policies along with the participation of all agents (consumers, government and production). To succeed, the countries need to combine several kind of systems such as recycling, composting, waste-to-energy and others instead of focusing on just one system (EEA, 2009).

As the greenhouse gas emissions encompass the epicenter in solid waste management plans, diverting organic material from landfill has become a priority. Biodegradable waste continues producing methane for decades after being buried. For this reason, those countries that allocate a significant quantity of solid waste to landfills could take advantage of diverting the organic material to biological treatments. This primacy action will reduce the landfill gas emissions dramatically and it will also contribute to combating global warming. In the same way, countries that present reduced landfilling rates can increase the recycling and recovery energy, avoiding greenhouse gases emitted through production of new products and saving



natural resources and energy. It is observed that countries with high recycling rates also have high levels of incineration with energy recovered, and when the recovery rate is satisfactorily high the solid waste sector contributes to reaching the Kyoto protocol goals (EEA, 2011).

The greenhouses gases (GHG) emissions have been calculated by the European Environment Agency (EEA), which identified the proportion of GHG represented by each kind of facility in the solid waste management. The incineration without energy recovery represents 3% of the emissions in this sector, the landfill is the most impactful with 95% of the emissions, with the remainder accounted for by other types of waste treatment operations. The waste sector contributed with 11% of the cuts in 2011 in GHG emissions, which represents 1.8% of total emissions. The waste-to-energy facilities emissions are not included in this calculation because they are considered in the energy sector (Eurostat, 2014).

The emissions calculated in the landfills are the fugitive emissions, which are modeled not measured with consideration for the temperature and humidity of a specific locale. In order to develop the model, it is necessary to consider the three phases of a typical landfill. In the first phase, the landfill is active and is not sealed, thus the material buried suffers the action of aerobic and anaerobic microorganisms, and methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) are emitted. The second phase, termed methanogenic, the landfill is sealed and a considerable quantity of methane is produced. In the last stage, several materials with different rates of degradation continue producing methane for an indefinite period (IPCC, 2006). The challenge is to capture the methane, mainly during the second phase, to produce energy through burning. According to IPCC (2006) the most accurate equation for calculation of greenhouse emissions is called FOD (first-order decay), by which the emissions produced depend on the quantity of organic material buried in a given period.

Although methane and carbon dioxide compose the principal emissions from landfill, about 1% of the landfill gas is comprised of 120 to 150 different substances, of which 90 were present in all landfills studied. Some of them (see table 1) represent a considerable toxicological impact (Parker et al., 2012). Consequently, these fugitive emissions in a landfill represent a potential risk to human health.

Table 1 – Toxic substances present in landfills

Benzene	Chloroethane	Chloroethene	2-butoxy ethanol
Arsenic	Mercury	Methanal	1,3-butadiene
1,1-dichloroethane	1,1-dichloroethene	Tetrachloromethane	Trichloroethene
Hydrogen sulphide	Furan	1,2-dichloroethene	Carbon disulphide
Chloromethane	Tetrachlorodibenzodioxin		

**Table 1 – Ranking the substances with the highest toxicological impact present in landfills (Parker et al., 2012, p.vi)**

The landfill gases collected are water saturated, representing about 50-60% of CH<sub>4</sub>, 40-50% of CO<sub>2</sub>, and other substances. Due to the presence of methane, the landfill gas presents an energy rate of 18-22 MJ m<sup>-3</sup>. In order to recover and utilize this methane, a vertical pipe collection is built, which sends the gas to a combustion system, generating electricity. The biogas can also be used as fuel, replacing fossil fuels in vehicles. The production of electricity may vary from 30kW to 50 MW, depending on the quantity of methane collected and the size of turbines used (Spokas et al., 2005). According to Bogner and Spokas (1993), the methane produced in a landfill is divided into five groups: recovered, discharged to the environment, sideways migrated, metabolized by methanotrophs and interiorly stocked. The equation below represents the total methane generated in a typical landfill (Bogner & Spokas, 1993, p. 377).

Equation 1:

$$CH_4 \text{ generated} = CH_4 \text{ emitted} + CH_4 \text{ oxidized} + CH_4 \text{ recovered (flared)} + CH_4 \text{ migrated} + \Delta CH_4 \text{ storage}$$

Conventionally, landfill gas capturing is not possible until the cells are finalized and covered. For this reason, collection efficiency is comprised of two factors: the landfill's lifetime rate and the immediate rate (Matthews, 2012). Immediate rates between 50-75% were documented in the U.K., indicating that rates higher than 85% can just be reached in covered cells on account of very little duct pouring. 60-70% lifetime rates could be reasonable, however, only at facilities with rigorous control (Kohler et al., 2011). A reliable and efficient parameter, promoted by several researchers, consider the following rates: 50% for immediate efficiency collection and 25% for lifetime (Kohler et al., 2011; Amini & Reinhart, 2011; Dever et al., 2011). An LCA study in Toronto, Canada assumed that 75% of the greenhouse gases had been collected and that the remaining had escaped to the environment (Assamoi & Lawryshyn, 2012). These rates depend on several factors, one of the most relevant being the type of cover used in the landfill, which can be a GCL (Geosynthetic Clay Liner) or clay (Spokas et al, 2005).

After much research and analysis, the uttermost technically achievable methane recovery rate is assumed to be 50%. There may be variations in this value according to some landfill parameters, such as cover type, percentage of the area covered by recovery system, and phase of operation, among others (IPCC, 2006). In addition, an efficiency of 33% in the production of electricity is assumed (CIWM, 2003). The equation to calculate the avoided emissions from landfills is indicated below (EEA, 2011, p.40).

Equation 2:

$$CO_2 \text{ savings} = \text{methane for recovery (kg)} \cdot \text{HHV (MJ/kg)} \cdot \text{efficiency (33\%)} \cdot \text{CO}_2 \text{ emissions/ MJ for electricity}$$

A biogas plant can produce energy from methane gases produced by organic waste degradation, which expresses to generate energy it is necessary to bury biodegradable material. However, if the organic waste must be diverted from landfills to be used in biological



treatments and result in compost, fertilizer and biogas, it is not cost-effective to build a biogas plant in a landfill that does not catalyze enough methane to beget electricity or fuel. Diverting organic waste from landfills is the established procedure and current trend of waste management in Europe. Several countries banned biodegradable waste from landfills some time ago and they are sending to these plants only residues of incineration and inert material, which means the emissions of these facilities are decreasing year after year.

### **3 WASTE-TO-ENERGY REGIME IN EUROPE**

Currently, it is estimated that roughly 2,500 waste to energy facilities are in existence in the world. Most of them are located in Asia, representing 2,000 plants, 460 in Europe, 100 in USA and Canada and ten in other areas (Avfall Sverige, 2007). The first incinerator came into operation in 1874 in Nottingham, U.K. due to the increase in waste produced by the large population in the industrialized areas in England during the Industrial Revolution. In that time the cities suffered from a lack of basic sanitation, precarious hygiene conditions and the spreading of diseases like cholera. Therefore, the incinerators for solid waste emerged with the mission to clean up and improve the hygienic conditions in urban areas. In 1876 and 1877, others incinerators utilizing a new method called “incineration cell” were built in Leeds, Manchester and Birmingham. After that, more than 50 British cities installed their own incinerators. In Germany, following the British example, the first incinerator came into operation in 1896 in Hamburg and at the beginning of the 20th century other German municipalities established similar facilities in order to clean the cities. In 1904, the Swiss built their first incinerator in Zurich, the fourth in mainland Europe. In 1954, Bern inaugurated its plant and the energy created supplied heating to a school and two hospitals (Lemann, 2008).

The incinerator technology evolved into modern and updated waste-to-energy facilities, whose emissions adhere to current legislation. In Europe, the emissions from WTE’s plants are below to the rates stipulated by the Europe Union and the local governments. According to EEA (2014) 448 waste-to-energy facilities in Europe incinerated 76,875,128 tons in 2010. Several from the 32 European countries analyzed beget less than a quarter of incineration capacity, seven of them generate 50% of capacity and in two countries the waste generated is not sufficient to fill all facilities.

Strict governmental standards on emission control notwithstanding, incineration capacity has increased dramatically, though this rate varies by country. In some countries such as Germany, Sweden, Denmark and Switzerland, waste-to-energy facilities are quite common; the rates exceed 30% of solid waste produced. However in other countries, issues such as public objection and high levels of concern about emissions and impacts on public health based on lack of knowledge of this technology make it difficult to shift to the incineration system. In the case of Finland, another relevant aspect should be considered: the challenges of integrating new waste-to-energy plants with the existing district heating and energy systems.

Consequently, in countries such as Finland, Poland and Hungary the capacity of incineration is still low (EEA, 2009).

Overcoming the problem of negative public perceptions of incineration is an obstacle to be faced in several countries around the world. Some of the countries could solve the issue by distributing to the residents guidelines explaining the incineration process, which uses the best available technologies. Additionally, campaigns explaining this waste management scheme are important, as well as continuing communication with local populations regarding the importance of household waste separation (EEA, 2009).

A typical waste-to-energy facility utilizes a technology which burns solid waste in environmentally sound ways and under safe conditions, generating district heating and electricity. In a simplified manner, the organic components produce CO<sub>2</sub> and H<sub>2</sub>O and the inorganics generate slag and fly ashes. The system also liberates energy, sludge, and emissions to the air and water. Most moderns and high-technology plants have various engineering procedures to minimize emissions to the air and water and to be efficient in energy production (Sundqvist, 1999).

According to the IPCC (2006, p.2.11), municipal solid waste is composed of diverse materials, such as “*food waste; garden waste; paper and cardboard; wood; textiles; nappies (disposable diapers); rubber and leather; plastics; metal; glass and other.*” Each one represents different quantities of degradable organic carbon (DOC). In addition, the composition and amount of DOC can vary between countries and distinct regions in Europe. Likewise, the MSW is comprised of a mixture of different states of materials: solid, liquid or paste forms.

To calculate the emissions produced by incineration, the mass balance of carbon and the waste characteristics is calculated through the equation below (EEA, 2011, p.36).

Equation 3:

$$\text{kg CO}_2/\text{year} = \text{kg MSW for incineration} \cdot \text{oxidation factor of carbon in incinerator (0,98)} \\ \cdot \text{conversion factor of C to CO}_2 (3.67) \cdot \sum(\text{waste fraction}_i \text{ (in \%)} \cdot \text{dry matter content}_i \cdot \\ \text{carbon content}_i \text{ (g/g dry weight)})$$

According to Lemann (2008) the material balance parameters for incineration, in general, are:

Input: 1kg of waste and 5kg of air (combustion)

Output: 5.77kg of flue gas, 0.20kg of slag and 0.03 kg of ashes

The energy balance is composed of several components; the principal is the heating value of each material presented in the burnable waste. According to Boie equation, each material has a specific quantity of some elements (C= Carbon; H = Hydrogen; S = Sulphur; N = Nitrogen; O = Oxygen; W = Water) which allow calculation of its heating value by equation 4 (Lemann, 2008, p.161).

Equation 4:

$$H_u = 34.8 \times C + 93.9 \times H + 10.5 \times S + 6.3 \times N - 10.8 \times O - 2.5 \times W \text{ (MJ/kg)}$$

The incineration process induces a representative decrease of weight and volume. For instance, 1m<sup>3</sup> of waste results in about 0.1m<sup>3</sup> of slag and fly ashes. This solid residue part is considered inert and sterile, which means free of microorganisms and pathogens. Moreover, part of the waste is transformed into gases such as water vapor and carbon dioxide. The flue gas system is responsible for treating and neutralizing hazardous gases such as HCL, So<sub>x</sub>, NO<sub>x</sub> and others (Lemann, 2008).

The technology, called flue gas cleaning in waste-to-energy facilities, is effective for reducing greenhouse gas emissions. This part of the equipment is responsible for removing hazardous substances from the flue gas. It is composed of various systems, such as mechanical precipitation (gravity, inertia, centrifugal or filtering); electrostatic precipitation; wet precipitation (scrubber tower, packing bed column, venture scrubber, condensation scrubber); and combination equipment (Lemann, 2008).

According to Lemann (2008), the ashes, produced by MSW incineration, in general, are composed by:

- 25 to 30% of silicates (SiO<sub>2</sub>);
- 5 to 10% of lime (CaO);
- 5 to 10% of aluminum oxide (Al<sub>2</sub>O<sub>3</sub>);
- 1 to 2% of lead oxide;
- 1 to 2% of copper oxide;
- 0.1 to 0.5% of cadmium oxide;
- 2 to 4% of other oxides each (iron, magnesium, potassium and zinc);
- 3 to 6% of gypsum (CaSO<sub>4</sub>);
- 3 to 6% of sodium (NaCl);
- 0.1 to 0.5% of calcium fluoride (CaF<sub>2</sub>).

Particles smaller than ash are removed through methods such as agglutination and condensation. These particles may vary in quantity and may not be present, depending on the type of waste incinerated and the results of the neutralization process. It is possible to find the following substances: hydrochloric acid (HCl) and ammonium chloride (NH<sub>4</sub>Cl) or metallic mercury (Hg<sub>met</sub>) (Lemann, 2008).

According to Lemann (2008), regarding gases is common to find:

- 25% of air (21% O<sub>2</sub> and 79% N<sub>2</sub>);
- 47% of nitrogen N<sub>2</sub>;
- 19% of water stream H<sub>2</sub>O;
- 9% of carbon dioxide CO<sub>2</sub>;
- 100 to 1600mf/Nm<sup>3</sup> of hydrochloric acid HCl;

- 5 to 25mg/Nm<sup>3</sup> of hydrofluoric acid HF;
- 50 to 1000mg/Nm<sup>3</sup> of sulphur dioxide SO<sub>2</sub>
- 300 to 500mg/Nm<sup>3</sup> of nitrogen oxide NO<sub>x</sub>.

An efficient plant must mitigate the production of hazardous substances and recycle them after their production. Furthermore, the plant needs to save energy and resources during its operation and provide a safe environment during continual 24 hours per day operation without pause (Lemann, 2008).

The WTE facilities are a complementary process in an integrated MSW management chain, responsible for the treatment of mixed waste and refuse from several sources, such as households, hospitals, industries, businesses and others. The recyclable material, as well as food waste, sorted at source, should have separate collection and destinations for recycling and biological treatment.

Hence, the WTE does not compete with the recycling and composting programs but acts at the end of the system, reducing the volume of refuse in a cleaned and controlled process. Moreover, the WTE generates energy in the form of electricity, district heating and cooling. The waste is considered as renewable energy and can replace the use of fossil fuels, decreasing carbon dioxide emissions.

## **4 RESULTS AND DISCUSSION**

### **a) Environmental aspects:**

The most relevant categories of impact, in the Life Cycle Impact Assessment (LCIA) phase and according to the LCA analysis cited in this study, are the following:

- *Global Warming Potential (GWP<sub>100</sub>)*

According to Eriksson et al. (2005), final disposal of MSW in landfills is the most impactful scenario, with recycling less impactful, followed by incineration. In other studies, the results were the same, which means diverting waste from landfill to recycling and recovery energy is the most adequate solution (Göran et al., 2005). Indeed, comparing landfilling and recycling, the quantity of CO<sub>2</sub> equivalent (kg/t) is much higher in the first option. In addition, comparing the emissions from landfills, WTE and coal-fired power stations, the best solution continues to be the WTE and the worst is the coal-fired power stations, which represents a higher level of GWP (Craighill & Powell, 1996).

- *Eutrophication Potential*

The eutrophication potential in the waste sector is essentially due to emissions of ammonia and NO<sub>x</sub>. The landfilling process represents the largest contributor because of the NO<sub>x</sub> emissions from landfill gas burning and other emissions composed of nitrogen and phosphorus. Biological

treatments producing organic fertilizer also produce emissions through leaching to the soil and water. In this category of impact, recycling and incineration presented the same results (Eriksson et al., 2005).

- *Photochemical Ozone Creation Potential (POCP)*

In this category the most important contributor is the landfill that produces NMVOC (Non-Methane Volatile Organic Compounds) emissions, followed by thermal processes which produce NO<sub>x</sub> and CO. The VOCs are converted into ethylene equivalents in order to compare all substances (Hellweg et al., 2003).

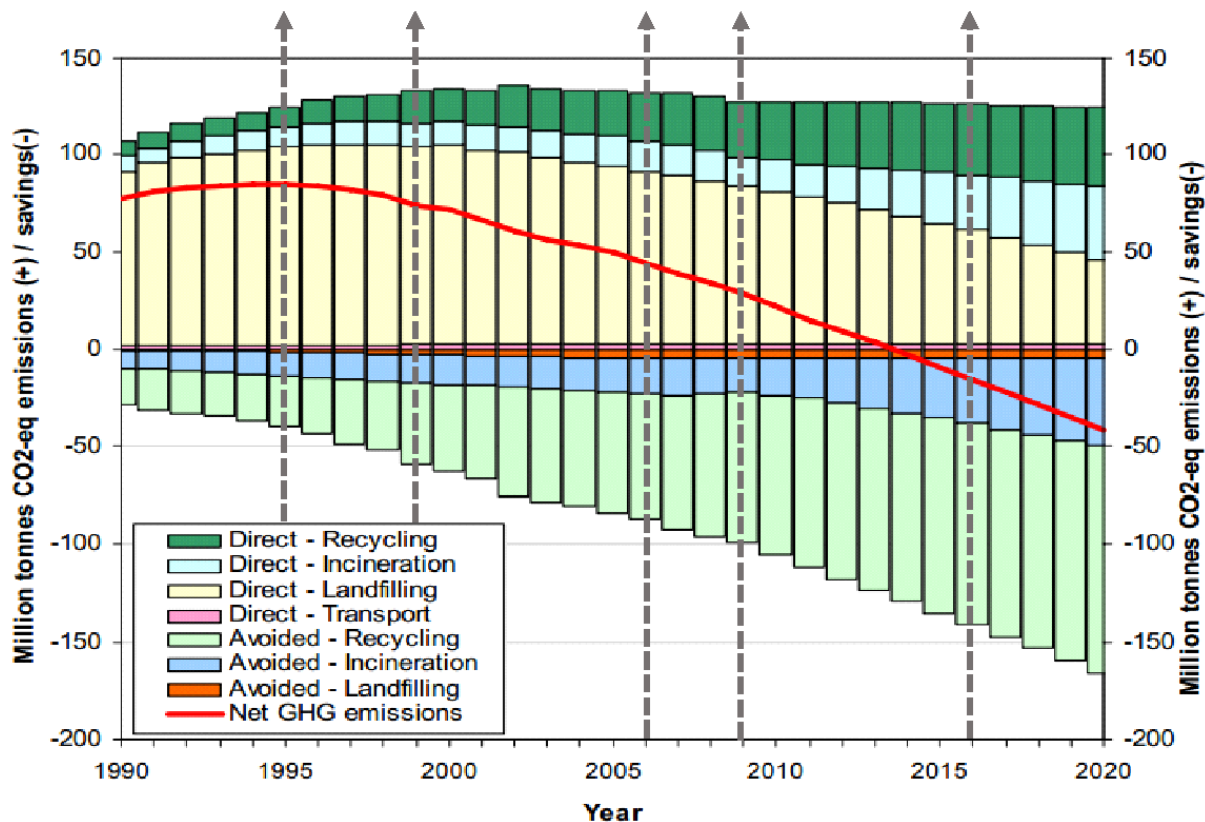
The primary emissions from solid waste management correspond to methane in landfills and pollutants from collection and other phases of the chain. It is possible to avoid significant amount of greenhouse gases through recycling of used material rather than using virgin material and through the energy recovery gotten by incineration and collection and treatment of gases in landfills. The LCA analysis contributes in calculating the avoided emissions with established practices (e.g. recycling), as compared to the use of raw material and incineration (producing heating and electricity), as compared to the use of fossil fuels. Taking into account that between 50 and 60% of the total MSW produced contains material of biogenic origin (food waste, clothes, paper, wood and others) the emissions from an incinerator is much lower in comparison with other industries which utilize fossil fuel as energy (EEA, 2011). In 2007, the methane emissions responsible for the waste sector in Europe were: 65% (CH<sub>4</sub>) for managed waste disposal on land; 6% (CH<sub>4</sub>) for unmanaged waste disposal sites; 7% (CH<sub>4</sub>) domestic and commercial wastewater; 2% (CO<sub>2</sub>) for waste incineration and 20% other emissions (EEA, 2009).

A considerable number of LCA studies comparing the different kinds of solid waste treatments and final disposal of solid waste in landfills and waste-to-energy demonstrated that energy recovery is less impactful than landfills (Assamoi & Lawryshyn, 2012; Göran et al., 2005; Tan & Khoo, 2006; Funk et al., 2013). However, other studies also documented that recycling and composting programs, diverting recyclables and food waste from landfills and waste-to-energy facilities, minimize the environmental impact and avoid the extraction of more natural resources (Merrild, 2012). Consequently, the promoted hierarchy of solid waste (avoid, reuse, recycle, recovery energy and landfill) adopted in numerous countries has been proven as the most functional method for treatment of MSW (Eriksson et al., 2005). The municipalities have to consider, for their solid waste plan, that all systems should work in an integrated manner, in order to reduce greenhouse emissions and promote sustainable development.

According to Ekvall (2007), through LCA significant benefits in the MSW management have been identified such as: waste to energy replaces the use of other energy sources; recycling prevents the extraction of more raw material; the compost produced by composting replaces artificial fertilizer; the biogas produced by biological treatment substitutes for fossil fuels; slag from incineration can be used as gravel for paving; among other benefits.

Certainly, landfills need to be monitored for decades until they cease production of greenhouse gas production and soil erosion. After that, the locale could become a public park, leisure area or just a green area. To plant trees and bushes into soil with non-degradable materials can be a complex task and needs to involved targeted techniques to promote tree growth.

The results of emissions in Europe produced by landfills, incineration, transport (collection and others activities) and recycling programs are calculated and demonstrated in graphic 1. By LCA analysis is possible represent in the inferior part of the graphic the avoided emissions in each kind of waste treatment. Moreover, the direct emissions are represented in the superior part of the Graphic 1. The recycling system replaces the use of raw materials and saves energy. While waste incineration produces energy and substitutes for the use of fossil fuels. In landfills it is also possible to avoid a portion of GHG emissions, through recovery of methane and production of electricity (EEA, 2011).



Graphic 1 – Net greenhouse gas emissions from MSW in EU-27 + Norway and Switzerland (million tons CO<sub>2</sub> equivalents) Adapted by author. Source: (ETC/SCP, 2011, p.62)



### **b) Economic and Political aspects**

According to Eriksson et al. (2005), in Sweden, as well as in other European countries, landfilling became the most expensive way to dispose of solid waste because of taxes and other inherent costs. In their study, the incinerator represents the most economically competitive method compared to recycling programs, except the biological treatments that produce biogas.

Landfill taxes and extended producer responsibility (EPR) are very effective concepts. Together these instruments are able to divert waste from landfills to recycling, biological treatments and recovery energy. For these reasons, cooperation between governments, producers and solid waste companies is crucial. The responsibilities and the role of each one must be very clear, in order to ensure the success of the integrated MSW management plan.

Accordingly, a dozen European countries impose a high tax for landfilling and incineration while recycling is not taxed. This kind of action drives recycling and reusing programs as a priority. Moreover, the Landfill Directive, the Packaging Directive and the Renewable Energy Directive are of high importance. Through these regulations, government can require that solid waste has the most sustainable and appropriate destination.

Despite the European Union having implemented policies favorable to recovery energy from waste, the hierarchy still must be followed by member countries. The first step is the most challenging, as avoiding production of waste depends on several combined factors. All the agents (society, government, solid waste companies and producers) need to be engaged in this matter to achieve significant results. Even though Europe has achieved relevant results in diverting waste from landfills to recycling and recovery energy facilities, the generation of MSW increases year after year (ETC/SCP, 2011).

Indeed, the citizens can contribute by changing their consumer behavior: planning the week's meals in order to reduce food waste; thinking before purchasing non-essential items; repairing and reusing old things instead of buy a new ones; rejecting the excessive use of packaging, plastic bags and disposable items; and several other substantial actions. The government's role is to indicate the targets, to establish and to enforce the regulations, to create tax incentives and to promote constant environmental awareness campaigns. The producers are responsible for decreasing environmental impacts during all life cycle processes of their products, promoting sustainability, upcycling items and taking back packaging and products to be inserted again in the economic cycle. Finally, the solid waste companies are responsible for keeping the urban and green areas clean, fulfilling the environmental requirements, dealing with generated waste by extracting from them new resources (raw material to recycling industries, compost, biofertilizer and energy).

In order to tackle solid waste production, it is necessary change the consumption and production systems; the shelves in the stores do not need to be filled up all the time. This issue is a mindset change, which the participation of each agent, society, government and producers,

is possible to shift the current situation, achieving sustainable development. Waste prevention is also a key to reducing waste at source. Some actions are already being implemented, such as packaging redesign and reuse of some items. Other sectors need to be developed further, building items to be more durable and that allow for upgrade and repair, avoiding planned obsolescence and the corresponding production of waste.

However, after the waste is generated, the second and third step of the hierarchy are to ensure that the material has the most effective treatment, through reuse and recycling programs. The recyclables come back to the industries as a raw material, saving energy and natural resources. The organic material is sent to the biological treatments, where it can produce biogas, compost and biofertilizer. The biogas can be used as a vehicle fuel, replacing fossil fuels and natural gas and supplying the stoves of residents. The compost and biofertilizer can be utilized in agriculture, landscaping, erosion control and others uses. Moreover, all these actions should provide jobs and income for local populations.

### **c) European Prognosis**

According to EEA (2011), the recycling rate is expected to reach and stabilize at 49% by 2020. The increase of recycling along with incineration with energy recovery (waste-to-energy facilities) can reduce greenhouse gas emissions in Europe substantially. For this reason, programs to divert waste from landfills reduce not only the emissions but help in reaching the targets indicated in both the Kyoto Protocol and the EU regulations for climate change and energy.

By 2020, the European Union intends to reach a level where the waste can be seen as a resource (EEA, 2011). This means that the priority is to increase the rates of recycling in a circular economy and to decrease the level of landfilling radically. The targets for 2020, indicated in the Waste Framework Directive (EC, 2008), require that European countries divert at least 50% of recyclable materials (paper, metal, glass and plastic) from landfills and waste-to-energy to recycling and reusing programs. In addition, 70% of construction and demolition waste must be reused and recycled.

Although zero waste is a visionary target, this concept is fundamental to the search for new technologies capable of reducing the production of waste at source or promoting upcycling of materials. The life cycle of products needs to be revisited in order to avoid the production of more waste. It is a mindset change that must be started in industry and amongst consumers.

The solid waste industries have a challenge to be faced in the coming years due to the increasingly strict regulations and the steady rise in recycling targets by European Union. However, they should treat the matter as an opportunity to develop new technologies and increase efficiencies, with less environmental impacts and greater economic profitability. In addition, these actions should promote not only reducing the impact of solid waste production but also creating new jobs and income for the surrounding populations.

**d) Results of the landfill and WTE comparison**

With the purpose of analyzing the environmental, economic and political aspects of the final disposal of solid waste in landfills or waste-to-energy, an overview about LCA developed by various researchers and discussions about economic instruments as well as the importance of European regulations has been presented in this paper. Table 2 summarizes the main environmental, economic and political aspects. The results were calculated based on 1 ton of MSW.

Table 2 – Landfill and WTE comparison

Unit = 1 ton of MSW	Landfill	WTE	References
<b>Environmental Aspects</b>			
Global Warming Potential (kg CO <sub>2eq</sub> )	(+) High production of greenhouse (40-50% CO <sub>2</sub> + 50-60% CH <sub>4</sub> ) emissions 746.4556 kg CO <sub>2eq</sub>	(-) Emissions of CO <sub>2</sub> 424.4022 kg CO <sub>2eq</sub>	(Spokas et al., 1993; Zaman, 2010)
Eutrophication Potential (kg PO <sub>4eq</sub> )	(+) Emissions of ammonia and NO <sub>x</sub>	(-) The flue gas system treats the hazardous gases (HCl, SO <sub>x</sub> , NO <sub>x</sub> , etc)	(Eriksson et al., 2005; Lemann, 2008)
Photochemical Ozone Creation Potential (kgC <sub>2</sub> H <sub>4</sub> )	(+) Emissions of NMVOC 0.116526 kgC <sub>2</sub> H <sub>4</sub>	(-) Emissions of NO <sub>x</sub> and CO -0.00778 kg C <sub>2</sub> H <sub>4</sub>	(Hellweg et al., 2003, Zaman, 2010)
Land disposal	(+) High demand for land	(-) Reduces the volume of waste to be landfilled; 1 ton of waste = 200 kg of slag + 30 kg of ashes	(Lemann, 2008)
Production of leachate	(+) Contamination of groundwater and soil	(-) Not likely to be emitted	-
<b>Note: (+) Most impactful; (-) Less impactful</b>			

Economic and Political Aspects			
Energy generated	217.3 kWh/ton	550 kWh/ton	(Spokas et al., 2005; Kaplan et al., 2009)
Electricity generated	41-84 kWh/ 1 ton of MSW	470-930 kWh/ 1 ton of MSW	(Kaplan et al., 2009)
Close to urban centers	(+) Should be considered a distance and availability for land	(-) Can be inserted into the urban centers	-
Landfill Directive	Combustible and organic material should be diverted from landfills	Receive combustible and mixed waste	(EC, 1999)
Tax of landfilling EPR Pay-as-you-throw	High taxes for landfilling; Incentives to decrease the disposal of waste	Promotes the WTEs	(EEA, 2009)
Renewable Energy Directive	The organic material has to be diverted from landfills	Considered a renewable energy source	(EC, 2001)
Operation time	Monitoring for decades	No necessary monitoring	-
Costs of operation	Most expensive due the economic and political instruments	The most economically competitive; production of energy	(Eriksson et al., 2005)

**Table 2 – Landfill and WTE comparison (Polzer, 2015)**

According to Table 2, the landfill presents the highest impactful environmental alternative in comparison to the WTE. The landfill has the higher value in Global Warming Potential and Photochemical Ozone Creation Potential. Moreover, the landfill also collaborates with ammonia and NOx emissions (Eutrophication Potential) while the WTE has a flue gas system which treat the hazardous gases mitigating emissions. The landfill also has the disadvantage of demand for land and should be located in a safe area in accordance with the technical regulations regarding access and proximity to urban areas. The landfill produces leachates, which have to be treated, while the WTE does not produce leachate, with the water used in the flue gas cleaning being treated and reused.

Regarding to the economic and political aspects, the WTE is the most competitive option by reason of the energy generation being constant and more efficient than landfilling. In the landfill the production of energy varies and depends on the operation phase, decreasing after its closure. Furthermore, the landfill has to be monitored until all emissions cease. Consequently, the landfill presents the highest costs of operation and maintenance because of economic factors and regulatory restrictions.

## **5 CONCLUSIONS**

According to the results of several LCA studies mentioned in this paper, it is noted that the landfill scenario represents the most immediate option, adopted by various countries around the world. On the other hand, it is also the most environmentally impactful. Therefore, waste-to-energy is less environmentally impactful and the more economically competitive option. Independent of the choice of final disposal of MSW between landfills or WTE's, it is important to consider in adopting an integrated solid waste management plan all treatments available and to follow the hierarchy of solid waste. First, avoid generating more waste, then promote the repair and reuse of materials, and finally promote the treatments needed: recycling, biological treatments and others treatments for hazardous and special waste (bulky, electronics, pharmaceuticals, tires, etc.). Only material that is not possible to recycle, compost or receive another special treatment should have as final destination landfills and WTEs. Certainly, there is a fraction of waste that is mixed and that will consequently go to incinerators and landfills. Decreasing this fraction through awareness campaigns and other incentives promoted by the government along with the producers may increase levels of recycling and composting. The crucial point in this situation is the proper separation of waste at the source. Consequently, to obtain the best results it is necessary to engage the entire population. Moreover, before treating the waste produced it is necessary to avoid generating waste at the source, with several actions required in all sectors (producers, society and government).

In terms of energy, if the landfills in Europe are prohibited from receiving food waste, the collection and production of biogas will be insignificant. Hence, the best option is still waste-to-energy along with the biological treatments for food waste. The target for European countries in 2015 is to collect and treat 50% of food waste. This means that the other 50% will continue to be mixed with refuse. Therefore, this mixed fraction could be directed to waste-to-energy, producing electricity and district heating. This cohesion between the waste and the energy sector is fundamental to guarantee the return of the initial investment in the WTE construction and to make the system profitable.

The importance of an integrated solid waste management plan is to develop a system that meets local needs where the plan will be deployed. All the agents' roles must be clear and they also must be committed. Each one has its responsibility and must work together, otherwise the system can fail. Consequently, the government has to set regulations and targets and promote the infrastructure required to perform all the activities along the solid waste chain. The citizens must to sort their waste at the source properly and avoid producing waste as much as possible. The producers have to abide the laws and avoid generating more waste. In addition, the solid waste industry has to treat the waste with consideration for environmental, economic and political aspects, utilizing the best technology available.

Finally, MSW management requires a holistic view. It is a public policy, which along with others sectors, can be responsible for creating a clean and sustainable urban environment. The actions

indicated in the plan must be in accordance with the environmental, political and economic aspects. It is not only the public sectors that are connected in this process but also all the agents (government, society, producers and solid waste companies). To guarantee the success of the plan, the municipalities need to take into account all scenarios studied, regarding LCA, economic and performance parameters.

## REFERENCES

Amini, H.R., Reinhart, D.R. (2011). Evaluating landfill gas collection efficiency uncertainty. In Proceedings, Sardinia 2011, Thirteenth International Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, Italy, 3-7

Assamoi, B., Lawryshyn, Y. (2012). The environmental comparison of landfilling vs. Incineration of MSW accounting for waste diversion. *Waste Management*, volume 32, issue 5, 1019-1030

Avfall Sverige (2007). Towards a greener future with Swedish Waste-to-energy. The world's best example. Avfall Sverige: Malmö

Bogner, J., Spokas, K. (1993). Landfill CH<sub>4</sub>: rates, fates, and role in global carbon cycle. *Chemosphere* 26, 366–386

CIWM (The Chartered Institution of Wastes Management) (2003). *Energy from Waste: A good practice guide*.

International Solid Waste Association, The Chartered Institution of Wastes Management.

Craighill, A. L., Powell, J. C. (1996). Lifecycle assessment and economic evaluation of recycling: a case study. *Resources, Conservation and Recycling Journal*, 17, p.75-96

Dever, S., Clingan, T., Wang, X., Bateman, S. (2011). Evaluating landfill gas emission at the Wollert landfill, Australia. In Proceedings Sardinia, Thirteenth International Waste Management and Landfill Symposium. S. Margherita di Pula, Cagliari, Italy, 3-7, CISA, Sardinia.

EC (European Commission) (1994). Council Directive 1994/62/EC of 20 December 1994 on packaging and packaging waste. *Official Journal of the European Communities*. No L 365/10

EC (European Commission) (1999). Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. *Official Journal of the European Communities*. No L 182

EC (European Commission) (2001). Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy



sources in the internal electricity market. Official Journal of the European Communities. No L 283/33

EC (European Commission) (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Official Journal of the European Communities. No L 312, 3–30

EEA (European Environment Agency) (2009). Diverting waste from landfill. Effectiveness of waste-management policies in the European Union. EEA, Copenhagen

EEA (European Environment Agency) (1997). Life Cycle Assessment (LCA). A guide to approaches, experiences and information source. Environmental issue series no 6. EEA, Copenhagen

EEA (European Environment Agency) (2013). Managing municipal solid waste – a review of achievements in 32 European countries. EEA, Copenhagen

EEA (European Environment Agency) (2011). Municipal Solid Waste Management Capacities in Europe. EEA, Copenhagen

EEA (European Environment Agency) (2010). Percentage of biodegradable municipal waste landfilled in 2006, 2009 and 2010 compared with the amount generated in 1995 – countries without derogation periods. EEA, Copenhagen

EEA (European Environment Agency) (2010a). Percentage of biodegradable municipal waste landfilled in 2006, 2009 and 2010 compared with the amount generated in 1995 – countries with derogation periods. EEA, Copenhagen (2010a)

EEA (European Environment Agency) (2014). Projections of Municipal Waste Management and Greenhouse Gases. EEA, Copenhagen

Ekvall, T., Asefa, G., Björklund, A., Eriksson, O., Göran, F. (2007). What life-cycle assessment does and does not do in assessments of waste management. *Journal Waste Management*. Volume 27. p. 989-996

Eriksson O., Reich, M. C., Frostell, B., Björklund A., Asefa, A., Sundqvist, J. O., Granath, J., Baky, A., Thyselius, L. (2005). Municipal solid waste management from a systems perspective. *Journal of Cleaner Production* 13, p. 241-252

ETC/SCP (2011). Projections of municipal waste and greenhouse gas emissions. ETC/SCP working paper 4/2011

EUROSTAT (2014). Greenhouse gas emissions from waste disposal.

[http://epp.eurostat.ec.europa.eu/statistics\\_explained/index.php/Greenhouse\\_gas\\_emissions\\_from\\_waste\\_disposal](http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Greenhouse_gas_emissions_from_waste_disposal) (2014). Accessed 11 December 2014.

Funk, K., Milford, J., Simpkins, T. (2013). Waste Not, Want Not: Analyzing the Economic and Environmental Viability of Waste-to-Energy (WTE) Technology for Site-Specific Optimization of Renewable Energy Options. Technical Report. JISEA, Joint Institute for Strategic Energy Analysis. Denver, USA

Göran, F., Johansson, J., Lind, P., Moberg, Å. (2005). Life cycle assessment of energy from solid waste — part 1: general methodology and results. *Journal of Cleaner Production*,13, 213–229

Hellweg, S., Doka, G., Göran, F., Hungerbühler, K. (2003). Ecology: Which Technologies Perform Best?, in *Municipal Solid Waste Management. Strategies and Technologies for Sustainable Solutions*. Christian Ludwig, Stefanie Hellweg and Samuel Stucki (eds) Springer-Verlag, Berlin-Heidelberg

IPCC (Intergovernmental Panel on Climate Change) (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5. Waste. IGES, Japan

ISO 14.040 (2006). Environmental management - Life cycle assessment - Principles and framework. Genève: Switzerland

Kaplan, P. O., Decarolis, J., Thorneloe, S. (2009). Is it better to burn or bury waste for clean electricity generation? *Environmental Science & Technology*. Vol. 43, NO. 6, p. 1711-1717

Kohler, N., Gregory, R.G., Cornish D. (2011). Developing landfill gas to energy systems in South Africa. *Proceedings Sardinia 2011, Thirteenth International Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, Italy, 3-7, CISA, Sardinia*

Lemann, M. F. (2008). *Waste Management*. Bern, Germany, Peter Lang AG, International Academic Publishers

Matthews, E. (2012). Good news from the dump. Methane emissions from solid waste: current conditions and future prospects. Clean Air Task Force, Boston

Merrild, H., Larsen, A. W., Christensen, T. H. (2012). Assessing recycling versus incineration of key materials in municipal waste: The importance of efficient energy recovery and transport distances. *Waste Management* 32 1009-1018

NI, J. R., Wei, H. L., Liu, Y.S., Zhao Z. J. (2002). Life cycle analysis of sanitary landfill and incineration of municipal solid waste. *Trans. Nonferrous Met. Soc. China*. Vol. 12 no 3

Parker, T., Dottridge, J., Kelly, S (2012). Investigation of the Composition and Emissions of Trace Components in Landfill Gas. R&D Technical Report P1-438/TR. Bristol, Environment Agency

Polzer, V. R. (2012). Management of Solid Household waste in São Paulo and Vancouver. Dissertation (Master of Architecture and Urbanism) – Mackenzie University, São Paulo (*in Portuguese*)

Polzer, V. R. (2015). Table: Landfill and WTE comparison

Spokas, K., Bogner, J., Chantin, J. P., Morcet, M., Aran, C., Graff, C., Moreau-Le Golvan, Y., Hebe, I. (2005). Methane mass balance at three landfills sites: What is the efficiency of capture by gas collection systems? *Waste Management* 26, p. 516-525

Sundqvist, J. O. (1999). Life cycles assessments and solid waste – Guidelines for solid waste treatment and disposal in LCA. IVL, Swedish Environmental Research Institute. Naturvårdsverket (Swedish Environmental Protection Agency), Stockholm

Tan, R. B.H., Khoo, H. H. (2006). Impact assessment of waste management options in Singapore. *Journal Air & Waste Management Association*, 56(3), 244–254

United Nations (2014, November 06). The World at Six Billion. <http://www.un.org/esa/population/publications/sixbillion/sixbilpart1.pdf>

World Bank (2012). What a waste. A Global review of Solid Waste Management. No 15. World Bank, Washington

Zaman, A. U. (2012). Comparative study of municipal solid waste treatment technologies using life cycle assessment method. *International Journal Environmental Science & Technology*, volume 7, Issue 2, pp 225-234