LANDFILL GAS EMISSIONS FROM LANDFILLS IN SANTIAGO DE CHILE - STRATEGIES TO REDUCE IMPACT ON LOCAL ENVIRONMENT AS WELL AS ON GLOBAL CLIMATE

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Abstract

The German Helmholtz-Association and Karlsruhe Institute of Technology (KIT) is carrying out an integrated research initiative on the sustainability of mega-urban developments in Latin America, including solid waste management of the Metropolitan Region of Santiago and with the participation of the RWTH Aachen University, Ingeniería Alemana S.A. and other associated local institutes.

Treatment of Mixed Solid Waste (MSW) in Santiago de Chile is limited mostly to final disposal at landfills, without any previous biological or thermal treatment, nor any recovery of biomass. Due to the decomposition of the organic fraction of MSW leachate is produced, as well as landfill gas, which contributes to global warming, local air pollution, odour and increased risk of fires, explosions and potential exposure of workers to toxic emissions. Landfill gas emissions and their associated impacts can be mitigated by collecting the gas from the landfill to be burned or used as a fuel source; however the quantities that can be captured are limited by the techniques applied. Another approach is minimizing the amount of organic material disposed of at landfills, which does not only reduce the production of landfill gas, but in addition mitigates most of the more notorious environmental and social impacts of current waste management practices.

In this paper existing and potential CDM activities for landfills in Santiago de Chile are described. In addition different scenarios, including "business as usual" (capture and flaring of landfill gas, plus improved recycling), mechanical-biological treatment of MSW, as well as the separate collection and composting of different shares of the organic fraction are defined. These scenarios are evaluated with respect to their impact on reducing landfill gas emissions and overall sustainability.

Palabras Clave: recolección segregada, relleno sanitario, emisiones atmosféricas, gases de invernadero, modelación, sustentabilidad

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1. The investigation project “Risk Habitat Megacity”

Urbanisation is one of the most dramatic processes of global change. Particularly in mega-urban regions, it induces trends with both regional and global consequences that are not yet well understood. Mega-urbanization is not just connected with unprecedented growth, high population density, and a concentration of economic and political power, but also with a complex variety of simultaneous and interacting processes. They turn the urban habitat into a space of both risk and opportunity.

A research initiative of the German Helmholtz-Association, which started in 2007 [1], analyses mature and developing megacities in Latin America, one of the most urbanized regions in the world. Its large agglomerations are of crucial socio-economic importance for the entire continent. At the same time, urbanisation in this region is about to reach a new dimension. Subject of the first case study is the Metropolitan Region of Santiago de Chile (MRS), which is in relative terms one of the most centralized urban centres of Latin America (with respect to total population and surface). Like other Latin-American urban centres, this agglomeration suffers from typical megacity problems and offers the scope to uncover emerging trends.

Santiago de Chile offers an excellent research infrastructure and research partners with international recognition. From Santiago, the project will be extended to other megacities in Latin America. The investigation initiative will:

- contribute to the **specification of sustainability objectives** for the future development of megacities;
- **assess characteristic risks**, their driving factors and consequences in megacities;
- **design strategies and instruments for risk management** as key tools for sustainable urban development;
- **develop implementation** solutions that take into account the institutional, political, economic, and social aspects within megacities;
- build a platform for continuous learning and application in order to integrate academic research and practice.

The analytical framework of the initiative is innovative due to its integrative and interdisciplinary character, which allows scientists, policy makers and society in general to deepen the understanding of megacities as a system. The *sustainable development* concept serves to formulate the target dimension of the project. The *risk* concept assists in identifying problems and evaluating their relevance, while the governance concept focuses on the actors and options for managing megacities.

Within the project these three analytical concepts are applied to various application fields, which are considered significant for the megacity investigation-concept. Figure 1 gives an overview of the project structure and shows the different fields of application that will be analysed in detail with respect to sustainability, risk and governance.

As already mentioned the work within “Risk Habitat Megacity” will among other specific objectives contribute to the definition of sustainability goals for the future development of waste management in Santiago de Chile. In order to evaluate waste management with respect to sustainability criteria, different sustainability indicators have been worked out [2], including the following:

- specific waste arising (kg/(person*day))
- amount of pre-treated waste that is sent to adequate landfills in relation to total waste arising
- greenhouse gases (landfill gases) emitted due to waste management (CO_2-equivalents per person and year)

In addition, the investigation will contribute to design and evaluate strategies for a more sustainable development within the field of waste management. Keeping this in mind, the elaboration will concentrate on the following topics:

- overview of the actual situation of waste management in Santiago de Chile (“status quo”);
- compilation of different scenarios for the future development of waste management in Santiago de Chile, taking into consideration the separate collection of the organic fraction of municipal solid waste;
- model calculations of greenhouse gas emissions for these scenarios and
- evaluation of the results of these scenarios

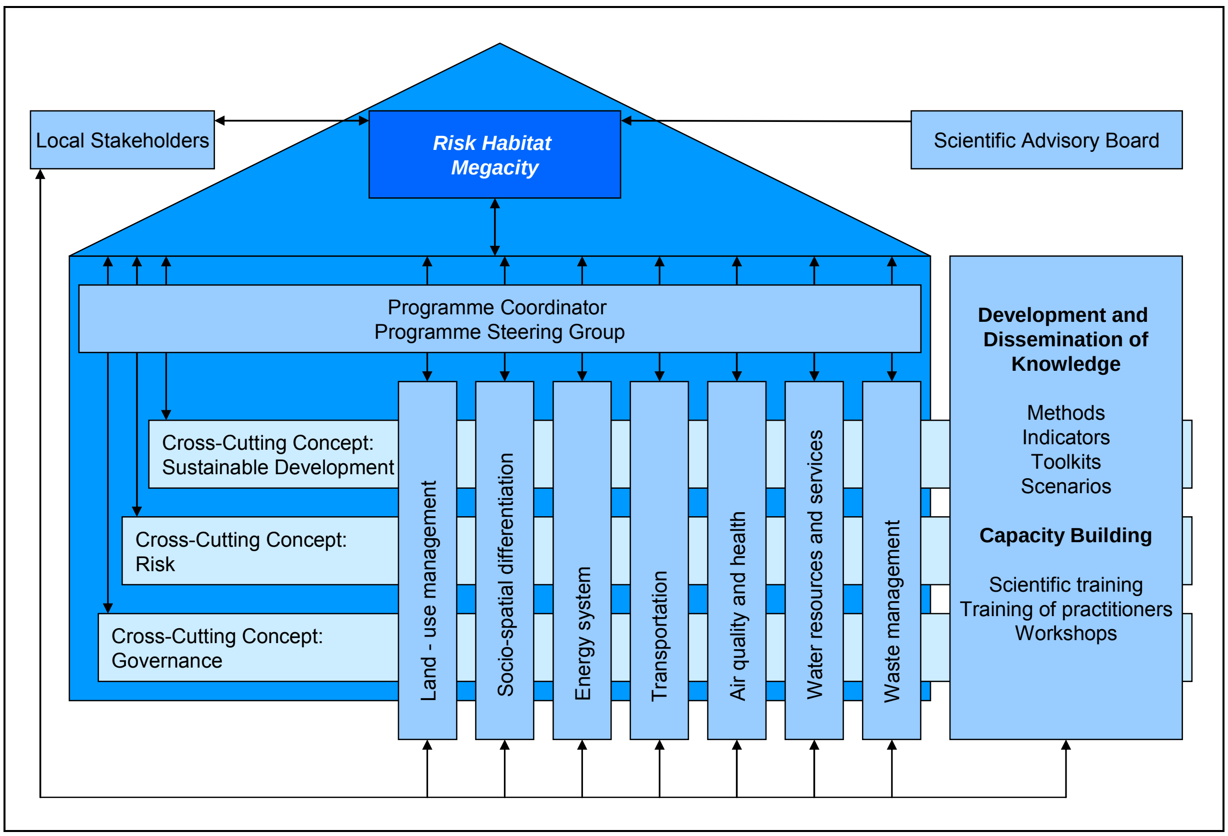

Figure 1: Project structure of "Risk Habitat Megacity"

2. Waste management in Santiago de Chile

In Santiago de Chile the amount of municipal solid waste (MSW) produced increased from about 0.7 kg/(person*day) in 1990 to approximately 1.3 kg/(person*day) in 2008, with an estimated total generation of nearly 3 million tons/year. Although the composition of MSW has changed and the organic fraction decreased from about 68% in 1990 to about 54% in 2004, biomass still remains the most important waste fraction (more than 1.5 million tons per year). [3],[4],[5]

Little more than 10% of the total amount of urban waste is either recycled, mainly due to informal activity and in a lesser extent as a result of municipal solid waste recycling programs (compare Figure 3). Treatment of MSW in the MRS is limited mostly to final disposal, without any previous biological or thermal treatment or recovery of biomass. There are three relatively new landfills operating in the MRS, which receive nearly 90% of total MSW of urban Santiago area.

Lomas Los Colorados landfill is the biggest and oldest of the currently operating landfills, situated in Tiltil county about 60 km north of Santiago. It began receiving waste from the respective transfer station in Quilicura in 1996, initially by trucks and since 2003 by train (in both cases using silos with external compaction). At the moment the landfill input is at a rate of about 150,000 tons of waste per month. Although the current contract will end in 2011, it is automatically renewed for 16 years if none of the parties cancel the contract early. The landfill, which is operated by KDM, an international company specialized in solid waste management, is anticipated to reach the end of its capacity around 2045. Landfill gas is collected and flared [6]. According to KDM energetic utilization of landfill gas will start end of 2009 [7].

Santa Marta landfill is the second biggest of the three existing disposal sites in operation. Its operation started in 2002 and Consorcio Santa Marta (CSM) will continue landfilling until at least 2022, the year when the contract ends (however estimates of landfill capacity predict an extended operation time). The current waste disposal rate is approximately 80,000 tons per month. The total amount of waste disposed of at Santa Marta Landfill until the end of 2008 was about 4.7 million tons. About 80% of the waste disposed is received at the transfer station (direct discharge, no compaction) and subsequently transported with special containers to the landfill. Landfill gas is flared by five flare stacks with 1.000 m^3/h capacity each. [9],[10],[11]

Santiago Poniente landfill is the newest, and also smallest, of the three landfills. It started operation in October 2002 and exhibits a current filling rate of about 45,000 tons per month. The landfill is anticipated to reach final capacity around 2025. Waste is transported directly to Santiago Poniente (without a transfer station) [10]. Proactiva, the operating company, has recently received the environmental authorization for the capture of landfill-gas, treatment and utilization in the gas system.

In addition to the operating landfills, there is a number of old, abandoned landfills in Santiago, which still produce landfill gas and therefore require post-operative treatment. One of the first sanitary landfill for urban residues, La Feria, started its operation in 1977 and received 60% of the solid residues from the city of Santiago at that time. In 1978 the landfill Cerros de Renca started its operation, receiving 30 % of the residues. 1979 a third sanitary landfill called Lepanto began operation receiving the remaining 10 % of the residues. In 1984 La Feria reached its end of lifetime and was replaced by Lo Errazuriz, which in turn was replaced by “Lomas Los Colorados” in 1997 and partly by Lepanto, which continued to operate for the majority of municipalities in the south of Santiago until 2001. [12]

According to information obtained during on-site research in 2008 in Santiago, more than 90% of the recycled material is collected, classified and prepared by the informal sector. The amount of people, working in the informal sector is difficult to estimate. Most informal activities are not recorded in official statistics and the actors are not registered and tend to change jobs when economical or market conditions change. In a research project, carried out in 1998 (Alaniz), about 4,000 primary collectors for MRS are estimated for the informal sector. Current estimations correspond to approximately 4,000 – 10,000 collectors. [13],[14]

Therefore, a promising alternative to municipal recycling programs (and subsequent elimination of the informal sector) with a positive social impact is the inclusion of "cachureros" into formal recycling activities and improvement of working conditions, thereby achieving higher overall recycling rates at relatively low cost.

Collection costs in Santiago range between US$ 15 and 60, with an average of US$ 26 per ton. Disposal costs are approximately US$ 10 and US$ 15, sometimes including transfer and transport costs to the landfill.

3. CDM-activities for landfills in Santiago

Chile has no specific laws setting down the degree of biogas collection required in a sanitary landfill, except for venting to avoid the hazardous storage of gases; so practically all of the projects for landfill capture, efficient destruction or utilization have been implemented as clean development mechanism (CDM) measures.

Due to the decomposition of the organic fraction of MSW landfill not only leachate but biogas is produced, contributing to global warming, local air pollution, odours and/or other nuisance. Due to the potential for landfill gas migration outside of the landfill's boundaries, there are not only direct risks such as fires, explosions and exposure of workers to toxic emissions, but also potential impacts for surrounding population and/or structures. Landfill gas emissions and their associated impacts can be mitigated by collecting the gas from the landfill, by simply burning it in high temperature flares for methane destruction or using it as a fuel source for energy generation. Other possible energy applications for landfill gas include use as a fuel at an industry off-site, or purification and injection into a natural gas pipeline. Mitigating of landfill gas emissions (including alternatives presented in this paper) can be encouraged economically by the generation of CO_2 certificates in the frame of the Clean Development Mechanisms (CDM).

CDM was established under Article 12 of the Kyoto Protocol adopted by the Third Conference of the Parties to the Framework Convention on Climate Change on December 11, 1997 [15]. The dual goals of the CDM are to promote sustainable development in developing countries and, at the same time, allow industrialised countries to earn emissions credits from their investments in emission-reducing projects in developing countries. To earn credits under the CDM, the project proponent must prove and have verified that the greenhouse gas emissions reductions are real, measurable and additionally demonstrate would have occurred in the absence of the project. In the following some project designs for CDM activities in the field of landfill gas emissions will be described shortly.

Under the current CDM system, which is valid until the year 2012, private landfill operators have relatively little interest in energy recovery from landfill gas, since the relatively high investment cost for gas-to-energy plants is much less attractive than CDMs for simple methane destruction (flares). Apart from incentives for small power plants (the so called “Ley Corta”), there is currently very little incentive in Chile for energy use of landfill gas.

Landfill Lomas Los Colorados (gas collection and flaring resp. electricity generation). The objective of Lomas Los Colorados Landfill Gas Project is to develop a landfill gas collection and utilization system for electric energy production. Up to now this involves only the operating a system for landfill gas collection and flaring; however from July 2009 (end of the year according to newer information) part of the landfill gas collected is to be put to energy use, the generation of electricity for use at the landfill site and for sale to users elsewhere. Estimated emission reductions will be about 4 million tons of CO_2-equivalents in the period 2007 to 2014 [6].

According to the latest information, the company is currently installing 2 modules of gas motors to produce electricity for the Sistema Interconectado Central (SIC); expandable in two phases to 14 MW (2011) and 27 MW (2025) [8].

Santa Marta Landfill Gas Capture Project. The project will last 16 years, from 2007 to 2022. The purpose is to install a highly efficient landfill gas collection system. This will involve investing in a gas collection system, airtight covering of the landfill and flaring equipment.

At the initial stage of the project, no electricity will be generated from the collected biogas. This is due to high investment costs in power generation equipment and grid connection and the current low price of electricity. Another reason is the uncertainty and the variation in the actual production of biogas. The feasibility of electricity generation will be revised every three years once the project is fully operating.

The expected efficiency of the capture system will be at least 65 %; however these are values which have not yet been proven under practical operation conditions. The baseline emissions until 2022 are estimated at 751,751 tons CO_2-equivalents. Total burning of methane due to the project was estimated at 6,712,426 tons CO_2-equivalents [6].

The company does not consider any energy recovery from the landfill gas in the near future; it is currently investing into a 5.000 m^3/hr. flare (total capacity 10.000 m^3/hr.).

Landfill Santiago Poniente (injection of landfill gas into the natural gas grid). The project considers injection of landfill gas into to the metropolitan gas grid, displacing the use of natural gas (as it was done previously at the Lo Errazuriz landfill). However, before biogas is fed into the distribution grid, it has to be treated in an upgrading facility, where most of the non-methane gases will be removed from the stream to meet the sales specifications of Metrogas S.A.

It is expected that an average of 70 million m^3 of biogas per year can be injected to the distribution grid in the first 7-year crediting period, avoiding the consumption of an average of 37 million m^3 of natural gas per year.

The emission reductions estimated for the first 7-year crediting period are more than 420,000 tons CO_2-equivalents [16].

Lepanto Landfill Gas Management Project. The purpose of the project at this landfill (which was closed in 2002) is to develop works and equipment to capture and destroy the methane produced by the Lepanto Landfill using a highly efficient controlled flaring system. However in the case of Lepanto the landfill gas has been used for many years in the past in nearby industries (which provided gas cleaning system, hence practically no investment for the operator).

The basic objectives of the project include an improvement in the existing impermeabilisation system, the implementation of new biogas extraction wells and a conveyance piping system, assisted by suction and pressure pumps, to carry the biogas to a treatment plant where it will be flared. The plant will be capable of treating a maximum flow of 5,000 m^3/hr (an average of 2,700 m^3/hr is expected).

In the future the project might also include the generation of electrical or thermal energy, however, this is not a current proposal. Because of the complexity of the system and the lack of experience in this type of project in Chile, it is commercially not attractive and difficult to implement. Nevertheless, both possibilities are under evaluation [17].

4. The situation in Europe and in Germany

Diverting waste from landfills is an important element of EU policy, aimed to improve the recovery, efficient use of resources and reduce environmental impacts of waste management facilities. In particular, in pursuance of the Landfill Directive (Directive 1999/31/EC) on landfill of waste, Member States are obliged to set up national strategies for reducing the amount of biodegradable municipal waste being landfilled:

- to 75 % of the total amount of biodegradable municipal waste generated in 1995 by 2006;
- to 50 % of 1995 levels by 2009;
- to 35 % of 1995 levels by 2016.

Member States who landfilled more than 80% of their municipal waste in 1995 can apply for a prolongation of the above time limits not exceeding four years [18].

Regarding the emissions of green-house gases, waste management contributed to 2.6 % of total green house gas emissions in the EU-15 [19]. The German strategy on biodegradable waste has focused not only on separate collection and recycling of secondary raw materials (paper and biowaste), but also on mechanical-biological treatment or dedicated incineration of MSW (combined with energy recovery).

Although a landfill ban was adopted in 1993, initially it was not implemented properly due to several loopholes, which were closed by the Waste Landfilling Ordinance (2001), confirming the deadline of 1 June 2005 for implementing the landfill ban. Final disposal at landfills is now limited to waste with an organic content of not more than 3 %. Additionally special limit values for the organic content of waste that has undergone mechanical-biological treatment were introduced. Since the deadline, the amount of municipal waste landfilled has fallen to 1% [18].

Due to the landfill ban for the organic fraction of waste since 2005, the amount of waste deposited after 2005 will not contribute to the emissions of landfill gas. Therefore the emissions of landfill gas will be determined by the amount of waste which was deposited before 2005. Figure 2 shows the estimated emissions of methane from German landfills for the time period 1990 to 2020. The emissions decreased from about 1.7 million tons in 1990 to about 0.4 million tons in 2007 and will further decrease to about 0.17 million tons in 2020 [20].

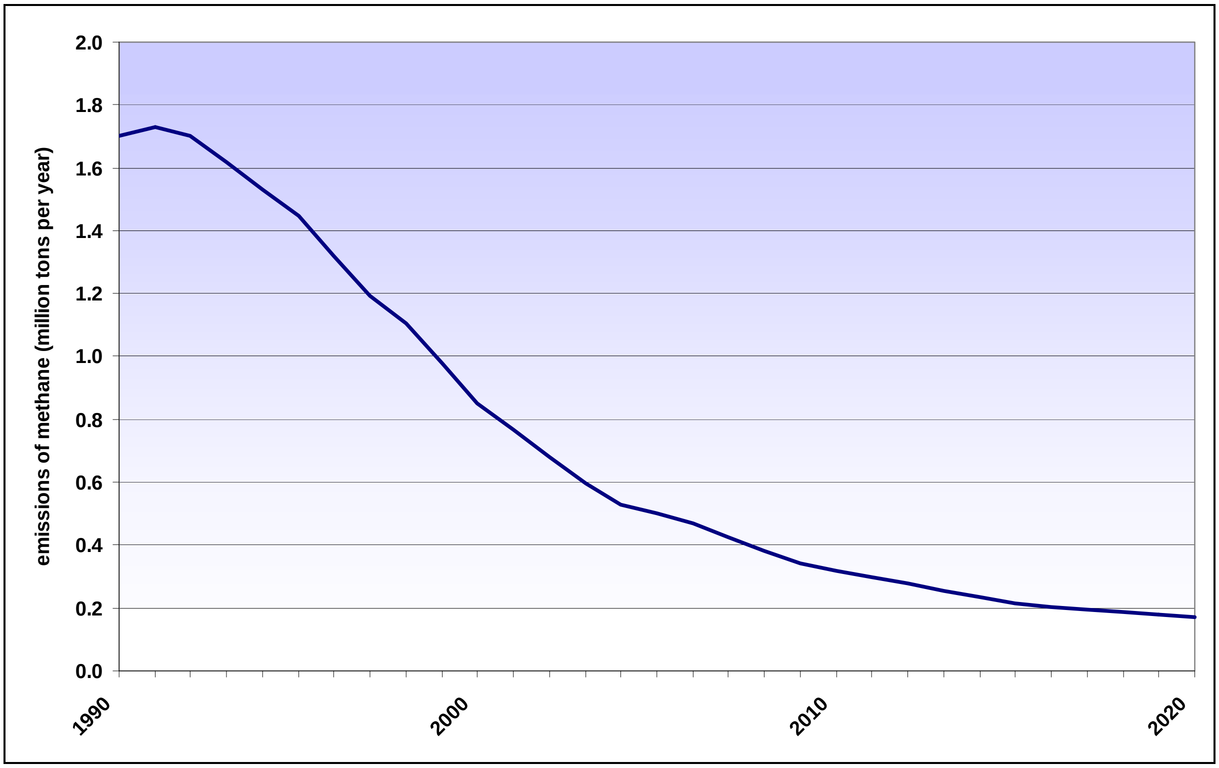

Figure 2: Calculated emissions of methane from landfills in Germany (according to [20])

While waste management strategies in the 90ies focused on recycling, the paradigm of sustainable waste management has evolved to a more integrated approach. It is based not only on recycling, but also on pre-treatment of solid waste for final disposal and reduction of CO_2-emissions.

5. Comparison of Available Technologies for Waste Minimisation

Public policy in Chile focuses on waste minimisation, including reduction at the source, recycling and only eventually pre-treatment of waste determined for final disposal, acknowledging the fact that most final disposal facilities are privately owned and do not take any commercial interest in waste reduction. While recovery targets of 25% of the waste have been discussed on a regional level for MRS, no pre-treatment standards have been defined by local authorities so far. However, based on currently available technology and depending on the most feasible recollection logistics the following alternatives for minimisation should be considered, both for recyclable materials and biomass:

- Separation at the source
- Partial separation, recollection and centralized treatment
- Recollection and centralized treatment of mixed waste

Minimizing the amount of organic material disposed of at landfills - either by separate collection of this fraction or by mechanical-biological pre-treatment of the mixed waste - would not only reduce the production of landfill gas more effectively, but in addition mitigate most of the more notorious environmental and social impacts of current waste management practices (odours, presence of sanitary vectors).

5.1 Waste Separation and Minimization ("Business As Usual")

The base scenario (BAU = "business as usual") was evaluated considering improvements with respect to waste minimization at the source, separate recollection and, eventually, separation at a centralized separation plant.

5.1.1 General considerations

Recycling has been taken place in Chile since the 1970's, but mostly as an informal activity carried out by independent groups of people (in Chile referred to as "cartonero", "cachucheros" or "recolectores"), who collect valuable materials in the streets of residential and commercial zones, using tricycles as transport and working tool. They separate and classify the materials, which improves their monetary value and sell these materials to middlemen who finally deliver them as secondary raw materials to production companies.

Some time ago, the "Comisión Nacional del Medio Ambiente" (CONAMA), the Environmental National Commission, developed a recycling strategy to increase the recycling rate in the Metropolitan Region to 20% in 2006, a goal that has not been achieved so far. A new goal has been established recently to achieve a recycling rate of 25% until 2020. The current recycling rate is about 13%, with a contribution from the informal sector of more than 90%.

In the last years, some municipalities in the MRS have started recycling programs which include composting, segregated collection and drop-off systems for certain residues. Some activities include education and campaigns to enhance awareness within the residents of these communities on environmental benefits resulting from recycling activities.

5.1.2 Recycling Systems in the Metropolitan Region

As shown in Figure 3, the MSW in the MRS is generally left in bags or containers at the streets where the major part is collected by the formal sector and finally brought to sanitary landfills (about 2.5 Mio tons per year). About 325,000 tons of waste, mainly paper, cardboard and metals are separated and collected by the informal sector. In addition, also formal recycling systems involving segregation at the source are in operation in RMS, which means that recyclable materials are separated by the citizens.

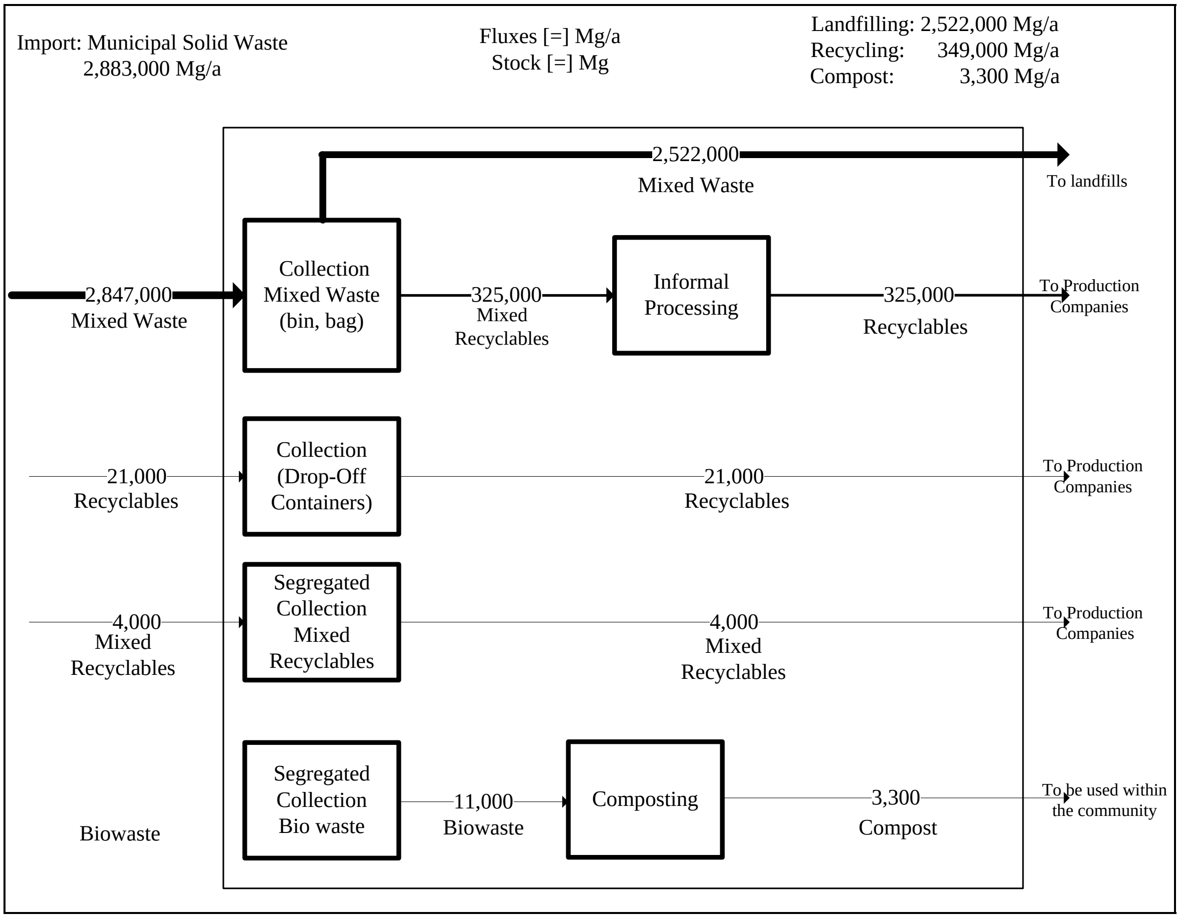

Figure 3: Mass flow of waste in the Metropolitan Region of Santiago de Chile, 2007

These differ mainly on how the waste is collected and can be divided into "differentiated collection" and "drop-off systems". Participation in the differentiated collection is voluntary and the participants are encouraged to allocate their recyclable materials separately from the mixed waste, which are then collected by the municipalities at the homes. The differentiated collection normally takes place at days different from the days when MSW is collected. These systems exist in La Pintana (biowaste), in Ñuñoa (inorganic waste), La Florida (inorganic) and María Pinto (biowaste and inorganic waste).

The drop-off systems involve containers located in public places where citizens deliver their separate recyclable materials. In general, the system is associated with charity campaigns/foundations. A special example is the Clean Point of the municipality of Vitacura, where containers are located in an area of 500 m² for the recycling of paper, cardboard, plastics, ferrous and non-ferrous metals, yard waste, batteries and old medicines.

For the year 2007 collection by drop-off containers, which are significantly less expensive than separate collection systems, amounts to about 21,000 tons of recyclable materials, whereas differentiated collection of mixed recyclables results in about 4,000 tons. Additionally, about 11,000 tons of biowaste was collected separately. Data shown in the figure is based on literature studies, surveys in communes of Santiago de Chile with recycling programs, interviews with people from the informal sector and own estimations ([13],[21],[22]).

The amount of recycling material via differentiated collection is more than 5 times smaller than the amount collected by containers associated with charity foundations. This fact can be attributed to:

- Recycling containers are set up in the whole MRS, whereas differentiated collection takes place in small scale in less than 10 municipalities.
- People prefer collaborating in recycling due to social reasons than to environmental ones, possibly because of the continuous advertisement of recycling associated with charity institutions.

CO_2 saving potential. Table 1 shows estimated reduction of CO_2 emissions due to waste recycling. Based on current quantities of recycled materials, the average savings potential was estimated in 1.150 kg CO_2 per ton of waste recycled; however since most of the above potential is based on metal recycling and the remaining content of recyclable scrap in household waste limited, a value of less than 700 kg CO_2/ton appears to be more realistic. The reduction of methane emission due to the recycling activities is rather insignificant.

Table 1: Reduction of CO_2 emissions due to recycling of different materials [23]

Recycling Measures	Recycling Rate in MRS [Mg/a]	Net Reduction [kg CO_2/Mg]
Metal	77.882 (29%)	2.000
Paper	142.263 (53%)	820
Plastics	10.737 (4%)	410
Glass	10.700 (4%)	180
Other	26.842 (10%)	

Costs related to recycling activities. Costs of formal recycling programs in Santiago include investment in recollection points, classification plants as well as operation costs for the recollection system and facilities. Two recycling facilities are currently installed in the city:

- Recycling Point of Vitacura (“Punto Limpio”), with an estimated investment cost of US$ 1 Mio. in 2005; and
- Materials recovery facility of Ñuñoa with an investment cost of US$ 227,000 in 2003.

Although detailed information on operating costs of both initiatives are not available, a range of US$ 100 to US$ 150 for separate collection of recyclable materials and classification can be estimated for Ñuñoa, based on the number of vehicles, equipment and personal requirements.

In the municipality of Vitacura, costs of MSW management are about 75 US$/ton, which are almost 43% higher than the average in Santiago. One of the reasons for the higher costs might be the operation and maintenance of the Drop Point and separate recollection in this municipality.

In general, drop-off systems do not represent additional costs for the municipality because the costs of collection as well as maintenance of containers are taken by the Charity Foundation associated with the recycling program or by the recycling company itself [24],[25]. Economical benefits of drop-off systems are associated with lower costs for transfer stations and final disposal in landfills.

According to preliminary cost estimates, the economic impact of increasing the fraction of recycled materials from currently 12 to 25% was estimated in at least US$ 10 per ton; average waste hauling costs for a municipality like Maipú would increase to around US$ 35 per ton plus separation in a centralized plant.

5.2 Separate Collection of Biomass and Centralized Composting

This scenario requires a separate collection of organic waste and transport by trucks to a centralized composting plant. Since the current frequency for ordinary recollection of MSW is at least three times per week, it is reasonable to assume that the minimum frequency of biomass collection is twice a week (eventually replacing one hauling cycle for common household waste). Waste hauling costs are expected to increase proportionally (≈ 30%). Collected biomass includes food residues, yard waste; containers may be required.

The composting process includes a range of alternatives, from very simple and inexpensive methods for yardwaste to more expensive and high-tech methods:

- Backyard or Onsite Composting (including Grass cycling)
- Vermi-composting
- Aerated Turned Piles (“Windrow” Composting)
- Aerated Static Pile Composting
- In-vessel Composting

Simple aerated pile composting systems are currently available technologies in Chile, turned pile being the most common method, followed by active aeration in some of the newer plants. Figure 4 shows a flow sheet of a simple aerated pile composting plant:

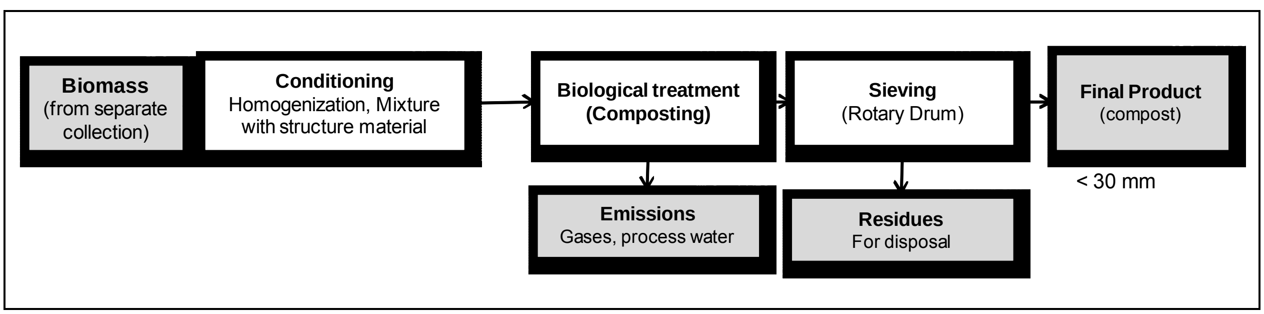

Figure 4: Exemplified flow sheet of a simple composting plant

The duration of the whole process is between 6 and 8 month, however the most frequent aeration is required during the first two month, when leachate generation, nuisance potential and or other emissions are more intense. The residual products of the process are transported to be used within the community or spread on agricultural land. Only a very small fraction of screening residues (estimated in 2 to 3%), is being transported to a landfill for final disposal.

There are air emissions from transport of collected household waste, from the composting process itself (incomplete aeration), from the transport of residues and finally from landfilling and application of compost.

Advantages:

- Smaller plant capacity (only 20% to 30% of total waste quantity)
- Simplicity of the process technology
- Small fraction of residual material
- Useful application of the final product (soil remediation)

Disadvantages:

- Requires active participation of households for separation of biowaste
- Eventual odour emissions (
- Commercialization requires good product quality
- Market limitations with respect to the quantity of compost

Site election of a composting plant is nearly as critical as a landfill in the MRS, a fact that is underlined by the re-location of several existing plants (Armony, Agroindustrial Pullihue) and the rejection of environmental permits for a new composting plant in Maipú.

CO_2 saving potential of Composting in Chile. Reduction potential of biomass and greenhouse gas emissions of this alternative is significant: >10% green waste from public spaces; plus separate food and garden waste from houshouls (>20%).

Treatment Costs. Based on a plant capacity of 50.000 ton/year, treatment costs for segregated biowaste in a simple open pile composting plant are estimated at approximately US$ 20 per ton (Source: IASA, various studies on costs of waste management alternatives, between 2001 and present).

5.3 Mechanical-biological treatment of mixed MSW

Mechanical-biological treatment in Germany. Mechanical-biological treatment of MSW in Germany has increased rapidly in the past decade. In 2007, the installed capacity in Germany reached an amount of about 5.6 Mio tons per year (50 plants) [26], representing a share of roughly 20% of the total mixed MSW. This development has to be seen under consideration of the waste legislation in Germany. Since June 2005, the content of total organic carbon in waste for final disposal on landfills has been restricted. The restrictions defined in the German landfill directive differentiates between waste from mechanical-biological treatment plants (TOC < 18%) and from other sources (TOC < 3%). In addition to the limited total organic carbon, the maximum calorific value, which waste for final disposal may exhibit is 6 000 kJ/kg. The relatively low investment costs of MBT compared to waste incineration plants have made MBT an attractive option.

Before starting the evaluation, it has to be clear that mechanical-biological treatment is a collective term that relates to a number of alternative processes, involving both a mechanical and a biological treatment. Whether the biological treatment is aerobic or anaerobic, or in which order the process steps are arranged, is not defined. Therefore, an example of the quantitatively more significant process variations existent in Germany, the combination of a mechanical and an aerobic biological treatment, is discussed here. As displayed in the simplified flow sheet displayed in Figure 5, the waste is fed to the mechanical treatment prior to the biological treatment. There, the material is separated according to the particle size, whereas the fraction > 60 mm features the main share of unwanted components with respect to the subsequent biological treatment. These are often higher calorific waste components, i.e. plastic foils, which may be removed via air classifier or concentrated in fractions with greater particle sizes (> 120 mm in the example below). Then, ferrous and non-ferrous metals are removed from the waste with magnets or eddy current separators to produce pre-concentrates for subsequent purification and application in the steel industry.

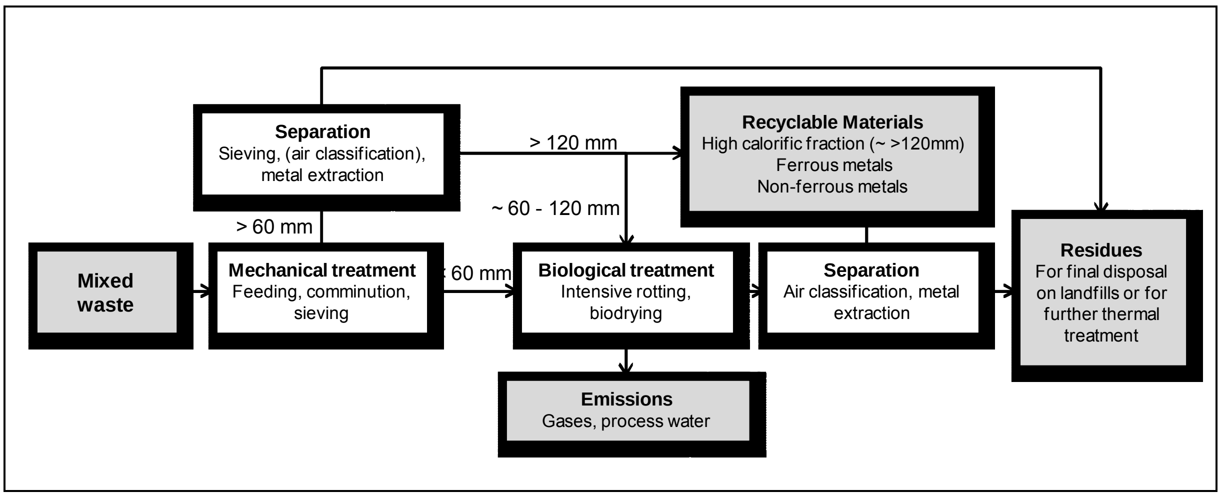

Figure 5: Exemplified flow sheet of MBT in Germany

The share of biodegradable organic waste components increases with decreasing particle size. The material < 60 mm is fed to the biological step without further processing in most cases. A separation of potential recyclables from this waste stream, akin to that of the greater sized material described above, is more feasible after biological treatment because recyclable materials can be separated more efficiently in the dried waste.

During aerobic biological treatment, the biodegradable organic substances are decreased, while air is introduced into the rotting pile. Furthermore, water is added to promote the processes. The aim of the mechanical treatment is the extraction of extraneous material (e.g. great particles like plastic foils), which may prohibit sufficient fluctuation of air and water that is needed to provide a stable ambience for the aerobic processes. At the end of the biological treatment, the elevated temperatures in the piles are used to dry the waste.

Table 2 summarises the output materials from MBTs in 2006. More than 50% of the output generated was determined for energy recovery in appropriate incineration facilities. One fourth of the output material could be landfilled without further treatment, while the low calorific fraction with a share of 8.3% had to be treated thermally in waste incineration plants.

Table 2: Output of 56 German MBTs in 2006

Fraction	Mass [Mg]	Share [%]	Further treatment
Landfill material	1 192 307	24.9	Final disposal
Low calorific fraction	399 454	8.3	Incineration plant; final disposal
Medium calorific fraction	1 918 928	40.0	Energy recovery; final disposal
High calorific fraction	598 825	12.5	Energy recovery; final disposal
Ferrous metals	151 589	3.2	Subsequent purification; re-use
Non-ferrous metals	10 880	0.2	Subsequent purification; re-use
Impurities	156 735	3.3	Incineration plant; final disposal
Other	363 892	7.6	Incineration plant; final disposal
Sum	4 792 610	100.0	

Fractions suitable for material recycling are ferrous and non-ferrous metals, together representing a share of 3.4% of the MBT output. In comparison hereto, the generation of plastics determined for material recycling only represented 0.08% of the total output [27]. This fact is easy to understand considering the relatively low market value, the high complexity of generating rudimentary sorted plastic fractions and the organic and mineral surface contaminations on the extracted recyclables. Material recycling of clean or separately collected plastics from waste types that are separated in origin is more feasible.

It is important to underline that the high calorific fractions produced as fuels or fuel substitutes are not sold with a positive market value. Fuels from waste contain numerous contaminants that require special attention. The cleaning of the exhausts and/or the application of resistant construction materials as in waste incineration plants is necessary, due to the presence of aggressive substances (e.g. HCl resulting from the chlorine contained; primarily in PVC). Accordingly, the elevated operating efforts of installations designed for waste incineration or energy recovery from waste is mirrored in the high investment and the high operational costs. The operators of plants utilizing these alternative fuels, charge for their receipt. Considering this, it becomes clear that the main objective of MBTs in Germany is to decrease the total mass of waste that has to be incinerated, and the high costs associated with it. The additional recovery of materials can be seen as a way of lowering the operational costs. Of course actual benefits result from material recovery, but clearly MBTs should not be seen as end-of-pipe solutions but as a pre-treatment that always involves further, but more advanced treatment of the generated output streams.

CO_2 saving potential of MBTs in Chile. When evaluating the implementation of MBTs into the Chilean waste management system, different aims have to be defined under consideration of the existing infrastructure. The legal framework in Chile does not oblige the waste sector to fulfil certain standards with respect to the final disposal of mixed MSW. Still, in both countries it needs financial motivation to enforce this treatment path. The constraint to fulfil legal requirements in Germany (which are connected to environmental benefits) is limited to a number of different solutions, of which those with the lowest possible costs are generally utilised. In Chile the motivation is to enhance environmental safety, while covering the costs via generation of CDM certificates.

In general, MBTs offers several ways of decreasing CO_2 emissions. In order to give a realistic assessment of the possible generation of CDM certificates, only the most basic alternative, the reduction of the content of organic waste, is evaluated in this work. The result can then be considered a minimum perspective with further optimisation potential. However, the other possibilities of CO_2 reduction, as well as the benefits deriving from them, will be briefly discussed:

- Reduction of the organic content of the waste that is disposed on landfills
- Substitution of fossil fuels by producing a high calorific waste fraction
- Substitution of primary raw materials (e.g. metals)
- Substitution of fossil fuels by energy recovery from biogas produced in the anaerobic treatment
- Utilisation of stabilised fine fraction as filter material for the methane oxidation cover on landfills

The only noteworthy pathway for energy recovery from waste in Chile is the substitution of regular fuels in cement plants. Partially, these capacities are already used to treat hazardous wastes. Thus, there is a great uncertainty regarding the capacities available for energy recovery from high calorific fractions. Anaerobic treatment and use of biogas will not be considered, since this means increased process complexity and investment costs. In addition to the process complexity, operating these plants has shown to be extremely sensitive, regarding the heterogeneous characteristics of the treated materials.

Production of concentrates of ferrous and non-ferrous metals is relatively simple regarding the technology used. However, these pre-concentrates require further cleaning in order to utilise them as secondary raw material. In the case of ferrous metals only impurities have to be removed, whereas in the case of non-ferrous metals additionally the different metals, i.e. aluminium or copper, have to be sorted in order to reach purities qualifying them as secondary raw materials. Besides the relatively high market value of the metals and the chance of establishing or extending the recycling sector in Chile, great energy savings (and CO_2 savings respectively) are connected with the optional metal extraction. A standardised model application for savings of greenhouse gases however, does not yet exist.

The use of some of the biological stabilised fraction as a methane oxidation layer for landfills is not practical in Chile, because this option is adequate for landfills where the generation of landfill gas is too low for a thermal reduction or a substitution of fossil fuels.

Costs of operation are in a range between 15 and 70 €/ton depending on the technical standard applied in the MBT [28]. The investment is in the range between 11 € and 21 € per ton [29]. For comparison, the mass specific investment for waste incineration starts at about 22 €/ton [29].

Advantages of MBTs:

- Besides the decrease of gas emissions, the potential of contamination of ground water due to leachate from the landfills is minimised
- Recycling rates increase and waste is exploited as a resource
- Can be pursued without active participation of waste generators

Disadvantages of MBTs:

- The more diverse products are generated, the more complex the treatment has to be and the more expensive it is
- Treatment costs may be higher than the benefit from emission trade / product distribution
- Downstream processing and utilisation structures must exist
- Compost products suitable for agricultural use cannot be produced

6. Comparison of scenarios for waste management in Santiago de Chile, taking into consideration the separate collection of the organic fraction of municipal solid waste

6.1 Methodology

In order to set up and evaluate different scenarios for waste management in Santiago de Chile a set of data and boundary conditions has to be defined.

Time horizon. Due to the fact that one of the three landfills in Santiago de Chile – Santa Marta landfill – which started its operation in 2002, will continue land filling only until 2022, model calculations will take into consideration the time span from 2001 to 2022.

Population development. The last census in Chile, which was performed by the Instituto Nacional de Estadisticas (INE) in 2002, was taken as a basis for the population development for the time span from 2001 to 2022 [30]. The rate of population growth was also taken from [30], starting from 5,828,254 people for 2001 and resulting in a total population of 6,970,295 in 2022.

Waste arising. Municipal solid waste (MSW) that is disposed at to one of the three landfills in Santiago de Chile, is weighed at the entrance of the landfill. As a result, data for total MSW deposited in Santiago de Chile during the last years are available [31]. For the scenario calculations this data has to be modified, because in addition to municipal solid waste from households also waste resulting from cleaning public areas are brought to landfills and are not accounted for separately. These amounts are not directly correlated with the amount of waste accessible from households and businesses in Santiago and were therefore not taken into consideration.

In order to estimate the share of waste resulting from public areas, in 2007 the disposal at the landfill "RS Santiago Poniente" has been observed on sight over a period of 2 weeks, whereas it became clear that great parts of the waste from cleaning public areas could be identified via the type of the vehicle delivering. These amounts have been calculated and extrapolated to the whole region of the RM Santiago, resulting in an estimated 356,000 tons per year [10] that are not directly linked with population growth.

With the above mentioned data specific arising of municipal solid waste (kg per person and year) was calculated for the years 2001 to 2007. Accordingly, the generation of household waste per capita in 2007 was estimated at 0.98 per person and day. For the years 2008 to 2022 a constant value of 1 kg per person and year was chosen, resulting in total waste arising for the model calculations of about 1.81 million tons in 2001 and about 2.54 million tons in 2022 with a total of about 50 million tons for the time span from 2001 to 2022 (see Figure 6).

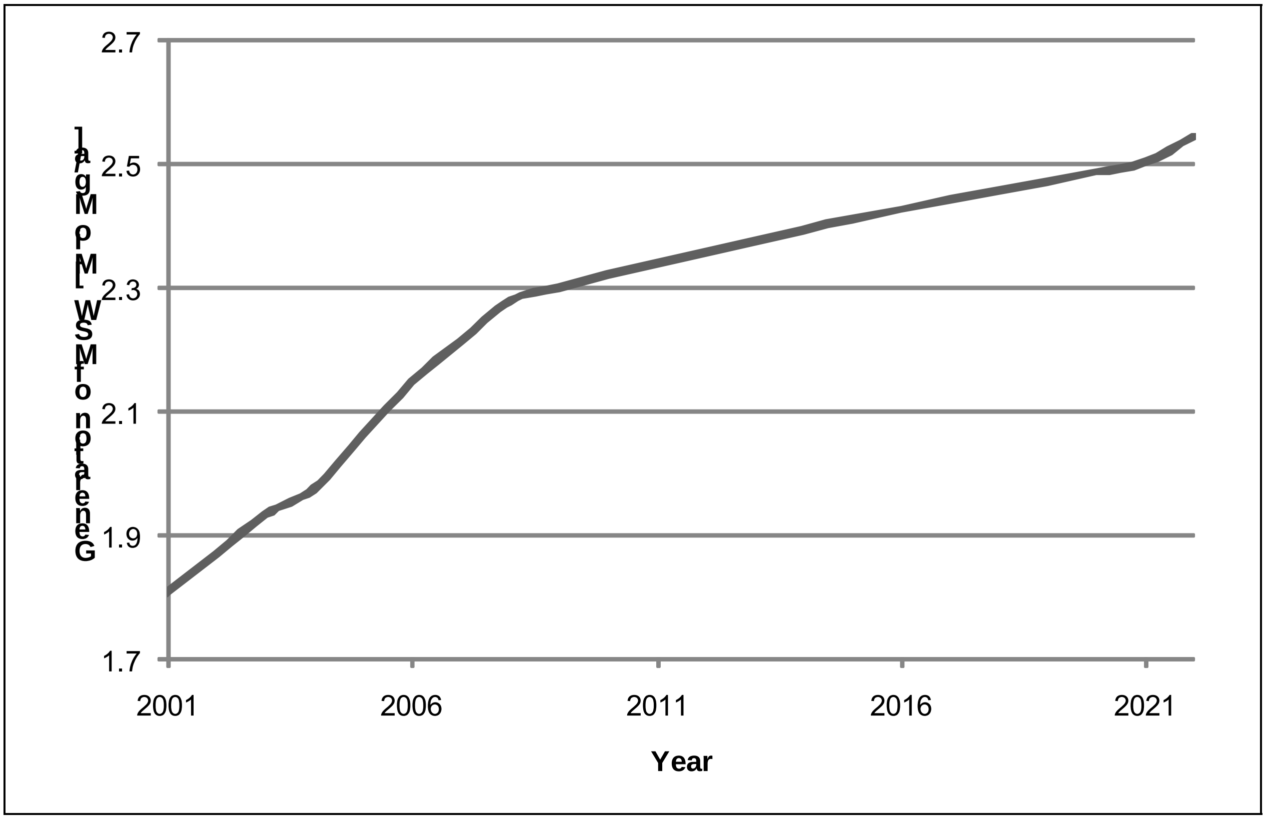

Figure 6: Estimated annual waste generation in the MRS

Waste composition. Data for waste composition was taken from a study, performed by the Universidad Catolica de Valparaiso in 2006 [32]. Within the scenario calculations separate collection was taken into account only for food waste (share of 37.41 %) and garden waste (share of 12.08%).

Waste characteristics. Data for water content of waste and total carbon content of waste had to be taken from literature [33],[34] due to lack of this information in [32]. Table 3 shows the waste characteristics, used for the model calculations the share of the different waste fractions, their water content and the content of biodegradable organic carbon of the different waste fractions. In the last column, calculated values for the organic carbon content in 1 kg of MSW, resulting from the specified waste fraction is given; that means, that the contribution from food waste (residuos de alimentos) to the organic carbon content of 1 kg of MSW is 65.1 g, that of garden waste (residuos de jardín y poda) 19.79 g etc. In total, the organic carbon content of 1 kg of MSW amounts to 156.78 g. This value changes, when different fractions of organic waste are separated and thus are not disposed of at landfills.

Table 3: Waste characteristics representing mixed MSW

Fraction	Share in MSW [%]	Water content [%]	Biodegradable Corg in dry substance [%]	Biodegradable Corg in MSW [g/kgMSW]
Food waste	37.4	62	458	65.10
Garden waste	12.1	62	431	19.79
Paper	15.1	22	377	44.41
Paper board	2.8	22	397	8.74
Plastic	13.6	18	0	0.00
Tetra Pak	0.6	19	276	1.26
Diapers	6.9	63	389	9.95
Rubber	0.0	7	0	0.00
Leather	0.0	7	0	0.00
Glas	4.7	1	0	0.00
Metal	1.7	2	0	0.00
Wood	0.2	14	0	0.00
Textiles	2.0	15	314	5.39
Dirt and ashes	1.2	28	105	0.93
Batteries	0.0	1	0	0.00
Bones	0.2	2	204	0.49
Fruit stones	0.3	14	0	0.00
Ceramic	0.6	2	0	0.00
Others	0.1	28	204	0.21
Not specified	0.4	28	204	0.51
Sum	100.0			156.78

6.3 Calculation of methane emissions

In the frame of this valuation, secondary emissions, such as exhaust fumes from transport or emissions resulting from the operation and energy consumption of the facilities, are not taken into consideration. Neither will emission reductions due to the application of compost instead of nitrogen fertilizers be included. When presenting the results according to the Kyoto Protocol [13], emissions of CO_2 resulting from the decomposition of organic material are not taken into consideration when calculating the CO_2-equivalents, because CO_2 had been taken up by the plants from the atmosphere when growing.

Total landfill gas emissions. Calculations were performed for the emissions of CH_4 resulting from the total amount of MSW (depending on the scenario taken into consideration) in the time span 2001 to 2022. Total landfill gas emissions were calculated according to the formula of Tabasaran & Rettenberger [35], whereas the share of CH_4 was assumed to be 55% by volume. The temperature within the landfill was assumed to be 39°C.

$$G_e = 1.868 * c_{org} * (0.014T + 0.28)$$

G_e = total amount of gas produced in Nm^3/ton of waste

c_{org}= biodegradable organic carbon content in kg/ton of waste
T= temperature within the body of the landfill in $^{\circ}C$

Figure 7 shows the time dependent generation of landfill gas. Assuming a value of c_{org} = 156.78 g/kg (see Table 3) the decomposition of 1 ton of waste is producing a total amount of about 240 Nm^3 of landfill gas or 132 Nm^3 of methane respectively. In other words, the mass specific methane generation amounts to 95 kg CH_4/ton MSW or 1995 kg CO_2/ton MSW.

Considering the assumptions made with respect to the generation of MSW in Santiago in the period from 2001 to 2022, the total methane emissions resulting are 6.67 billion Nm^3 or 4.76 million tons of methane respectively. Expressed in CO_2 equivalent emissions, the total methane emissions equal 99.96 tons of CO_2.

After a landfill has been closed (in Figure 7 this would be the maximum of landfill gas generation in 2022), no fresh organic material is fed to the landfill and the generation of landfill gas decreases. At some point after landfill closure, not only the generation of the gas but also the share of methane decreases. This has to be seen critical with respect to the capture of landfill gas because the effort of methane destruction (or its utilisation for energy production) rises while the benefits per captured gas volume decreases. In the evaluation of the BAU scenario this fact is not paid special attention to. However, when evaluating one single landfill it has to be considered that only a limited share of the total landfill gas potential stands available for capture.

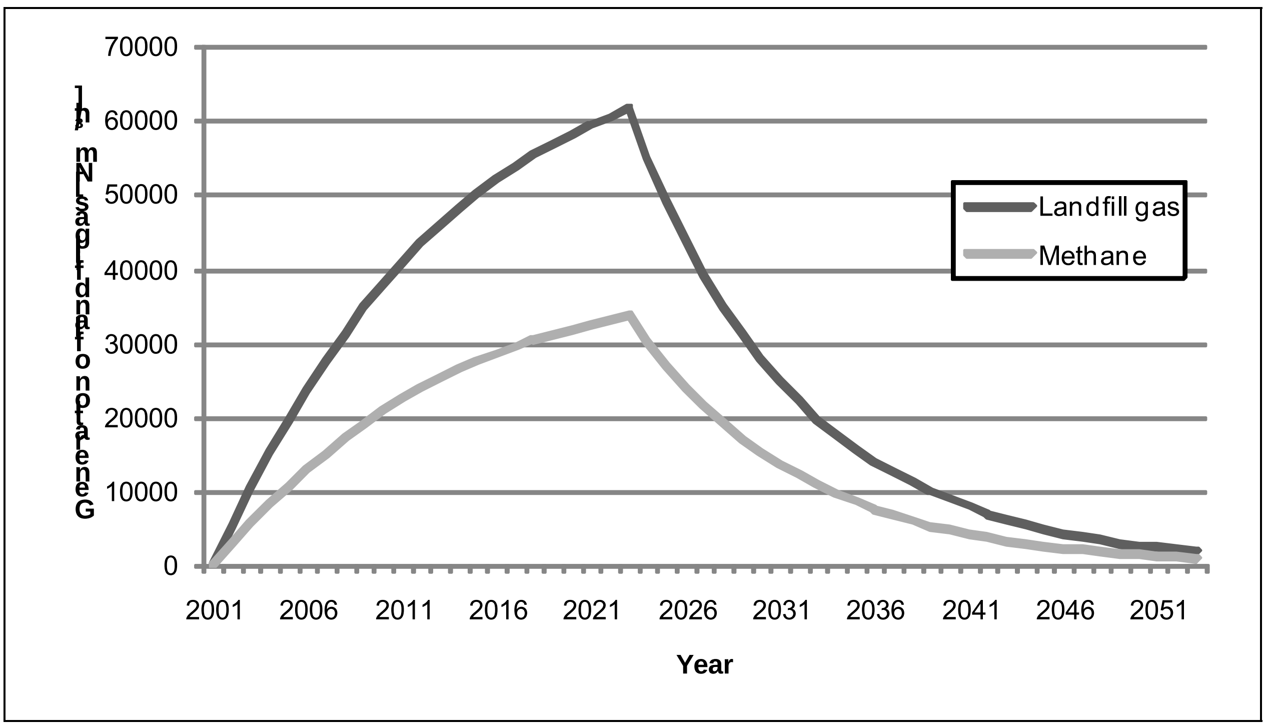

Figure 7: Emissions resulting from MSW landfilling between 2001 and 2022

BAU scenario. Due to the fact that collection and flaring has become a standard operational measure at landfills in the RM, the baseline scenario should involve gas capture and thermal reduction of the methane. This scenario will be taken as basis for the evaluation of the alternative scenarios “composting” and “mechanical-biological pre-treatment. As mentioned earlier, losses of gas due to insufficient landfill gas generation or due to diffuse emissions during operation are not exclusively considered. Assuming an overall efficiency of the gas capturing system of 50%, total methane emissions of 2.38 million tons (50 million CO_2 equivalent tons) emerge from the deposited MSW. Accordingly, the mass specific methane emissions also account for 50% of the mass specific methane emission when landfilling without capturing and flaring the gas.

Compost scenario. In order to identify the impact of the different scenarios, realistic maximum and minimum emission reductions are needed. Participation and separation efficiency of households vary considerably with geographic and demographic or social boundary conditions and strongly influence the acquisition of organic waste. Realistic values for the relative separate acquisition of the organic waste (food waste and garden waste) are seen to be in a range between 10% and 50% (for comparison, in 2003 the acquisition of biological household waste in Germany was around 58% [37]). With alternating relative acquisition rates of biowaste the organic carbon content the waste that is brought to landfills changes. This also has an impact on the total methane potential, which is displayed in Table 4.

Table 4: C_{org} and CH_4 emissions from deposited MSW against acquisition of biowaste

Relative acquisitions of food and garden waste	C_{org} calculated [g/kg$_{Waste}$]	Methane potential [Mg CO_2]	Methane emissions compared to Landfilling without flares [%]
0 %	156.8	1.00E+08	100.0
10 %	155.3	9.41E+07	94.2
20 %	153.9	8.84E+07	88.4
30 %	152.5	8.28E+07	82.8
40 %	151.0	7.72E+07	77.2
50 %	149.6	7.18E+07	71.8

During aerobic biological treatment with an optimal oxygen supply no CH_4 is emitted. Due to anaerobic fields that build up in real composting processes, small amounts of CH_4 are emitted during composting. A value of 0.65 kg CH_4/ton of organic substance was chosen to account for the diffuse emissions in this study [36].

MBT scenario. As discussed before, the type of treatment chosen for the estimation of the CO_2-equivalent emissions within this scenario is a mechanical-biological pre-treatment and subsequent final disposal of the output material. The MBT involves a mechanical treatment with the goal of extracting material disturbing the biological process. The following biological treatment process is anaerobic rotting of piles covered with bio-filter material. The lower content of biodegradable carbon in the landfill material then results in a decreased landfill gas generation.

According to Fricke et al. the degradation rate of the biodegradable waste fractions in Germany can be estimated with a value of 65% [28]. Recent studies of the applicability of the FABER AMBRA Process in Villa Aleman in Chile showed that this aerobic treatment is feasible. The waste input material used for the tests exhibited an organic content of about 55% and based on analysis, the total organic carbon (TOC) was determined to be 29.2%. The reduction of the TOC after about 9 month, a time span that is deemed necessary in order to stabilise the waste so that the limitations in Annex II of the German landfill directive allow final disposal, was between 70% and 85% [38]. To include the fact that the higher content of organic waste in Chile is 15% to 20% higher than in Germany, as a realistic approach for degradation of the biodegradable organic carbon a range between 60% and 75% will be taken for calculations.

Diffuse CH_4 emitted during mechanical-biological treatment is assumed to be 0.65 kg CH_4/ton of input material.

Table 5: C_{org} and CH_4 emissions from deposited MSW against degradation rate

Degradation rate	C_{org} calculated [g/kg_{Waste}]	Methane potential [Mg CO_2]	Methane emissions compared to landfilling without flares [%]
60 %	62.7	4.00E+07	40.0
75 %	39.2	2.50E+07	25.0

Of course, the values given in Table 5 relate to the total MSW generated between 2001 and 2022 under the assumption, that all the waste is processed by a MBT before final disposal. Therefore, these values are only for comparison of the impact of this alternative.

For an integrated assessment, the emissions and emission reductions relating to the mass of MSW generated are more important.

7. Conclusion

Collecting and flaring and/or utilizing landfill gas will improve the local environment by reducing the amount of noxious air pollution arising from the landfill, resulting in a considerable reduction of nuisance caused by the odours and also health risks associated to these emissions. In fact this results in a positive effect on health and amenity in the local area. In addition, properly collecting and destroying flammable landfill gas will reduce the risks of explosions in and around the landfill. This is particularly important as the landfill gas collection system will minimise the potential for landfill gas migration, which can infiltrate zones outside of the landfill's boundaries and pose dangers to the surrounding population and structures.

Regarding the organic fraction the results underline the importance of this fraction for the reduction of greenhouse gases. Separate treatment of the organic fraction yields, besides the reduction of greenhouse gas in economical chances. Taking in consideration that the disposal at landfills is state of the art in Chile today, the implementation of a separate collection and treatment of the biodegradable waste fractions additionally enables the chance of generating emission certificates in the frame of the Kyoto protocol.

Based on existing Policies on Waste Management and with respect to public investment in the waste management sector, treatment technologies should be priorized that not only reduce waste (recyclable materials), but also have a significant effect on greenhouse gas emissiones and other environmental impacts. The proposed strategies are not exclusive, but should be applied depending on their cost-effectiveness:

- Separation of biowaste at the source should concentrate first on yardwaste, waste from market and public parks, which is currently transported separately but dumped at the same landfill together with household waste.

- Some positive experiences exist with separate collection of household biowaste, however the absolute impact of this measure is limited by the degree of participation by the public;
- MBT of MSW does not require separate recollection and can be cost-effective combined with recycling and/or production of an alternative fuel, especially if landfill capacities become scarce.

Other recommendations include:

- Support informal sector with respect to recyclable materials (highest return in terms of economical-social efficiency);
- In the case of Santiago where transfer stations are privately operated, reduction of biomass through biological treatment is currently not realistic, since existing incentives (CDMs) encourage simple flaring; however for small or medium communities MBT may be an alternative for cost reduction in transport and disposal;

In order to meet ambitious national reduction goals (like 25% in 2025), international agreements on greenhouse gas reduction and reduce impacts on local environment (odors, leachate production, landfill capacities), a combination of source reduction measures (education), separate collection (only where economically feasible) and mechanical-biological treatment in centralized installations should be considered.

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