MSc Program
Environmental Technology & International Affairs

A Cost-Benefit Analysis of Waste Incineration with Advanced Bottom Ash Separation Technology for a Chinese Municipality – Guanghan

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"Master of Science"

Supervised by

O. Univ. Prof. Dr. Dipl. Natw. Paul H. Brunner

Jiao Tang

1025393

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Abstract

Waste incineration is a common practice of solid waste management in European countries, for it renders useful energy and reduces mass, volume and chemical reactivity of waste components. In contrary, solid waste incineration is by far a less common practice of waste treatment in China, mainly due to the unaffordable investment, operational and maintenance cost when compared to the budget of these countries.

A novel technology for the recovery of non-ferrous metals (aluminium and copper) from bottom ash has been recently developed. The goal of this thesis is to explore the impact this technology may have on the overall economics of waste management by investigating a case study for the Chinese municipality of Guanghan with a population of 210,000.

Two methodologies have been applied to reach the objectives: material flow analysis, and cost benefit analysis. Two scenarios were elaborated for the cost benefit analysis: Scenario I assumes a waste management system in Guanghan with source separation and separate collection of all types of recyclable materials and that the rest waste flows directly to the landfill; Scenario II differs from Scenario I in that metals are not separated at source, but flows with the rest waste to an incinerator before landfilling, where advanced technologies are applied to control air quality and to recovery energy, ferrous metal and non ferrous metals. Data about municipal solid waste and cost are from local statistics of Guanghan and literatures on incineration practices in China, Vienna, and Zurich where the novel technology was developed. The software STAN was used to model the mass flow of waste as well as the substance flow of iron, aluminium and copper in the waste through Guanghan.

The following result has been observed: from the waste management system perspective, the benefit outweighs the cost by two million euro when comparing Scenario II to Scenario I, indicating a higher efficiency in resource allocation. However, the result is highly sensitive to variations in the borrowing cost and the investment cost of equipment and technology.

Regarding Guanghan, the following conclusions can be drawn: the result of the cost benefit analysis indicates potential economic savings for the waste management system in Guanghan as a whole; it is therefore worthwhile for the policy makers to consider adding waste incineration to their agenda of improving the city’s waste management system for environmental protection and for economic efficiency.

Table of Content

Part I. Executive Summary

1.1. Introduction

Municipal solid waste (MSW) management in economically developed countries encompasses four stages of activities: source separation, collection, recycling, treatment and final disposal. It starts in households, where waste is separately disposed of according to designated categories: glass, paper, plastics, metals, E-waste, organic waste and residuals. In certain countries, Switzerland for example, more detailed separation is applied, such as cardboards from paper, and coloured glass from clear glass. Different types of solid waste are then collected separately and sent to recycling companies, and the rest waste is sent to an incineration plant, or directly to a landfill. At the waste incineration plant, the rest waste is incinerated in order to significantly reduce their mass, volume and chemical reactivity, meanwhile resource recovery commonly takes place: the recovery of ferrous metal from the bottom ash, the utilization of heat from the combustion for district heating, and the production of electricity by the steam generated from the combustion process. Eventually, the residual bottom ash is collected and sent to a landfill, the final sink of non-recyclable materials.

Municipal solid waste contains valuable materials that could be recycled and considerable amount of energy that could be recovered as heat and electricity. Recycling, according to Lave, et al. (1999), generally refers to the reuse or remanufacturing of post-consumption products into the same use or a lower value use. Recycling occurs to a small extent within consumers' premises (self-recycling) but mainly after the collection of materials from the households. Kerbside pickup, consumers taking recyclables to a central collection point, and consumers returning them to a retailer or manufacturer (in the case of E-wastes) as part of a refund system, are common recycling collection schemes. Materials such as glass, paper, metal and plastics are then recycled by specialised recycling companies. While waste can also be used as fuel in certain industrial processes, in cement and lime production for example, recovery of energy happens more commonly at waste incineration plants, in the form of electricity or heat or both.

Not only can energy be recovered at incineration plants, but also valuable materials in the residues after combustion could potentially be recovered. In fact, the recovery of raw materials from secondary sources is a highly promoted strategy in the urban mining concept. Urban mining, the systematic recovery and reuse of raw materials at the end of product lifetime from urban areas (Brunner, 2011), leads to long-term environmental protection, resource conservation and economic benefit. Mining of resources, particularly during the extraction and processing stages, produces large amounts of pollution: such as methane, particulate matters, sulphur dioxide emissions in the air; lead, sulphate, mercury emissions in the water. At the current rate of extraction, certain resources will soon become scarce. Recovering materials from end-of-life products consisting of substances from primary extraction reduces the need of primary extraction, thus preserve the resource reserve of our planet. With the soaring price of raw materials, economic benefit of recovering precious metals, making them available for use again is becoming apparent. The question lies in the balance between the cost of recovery and the benefit from recovering the resources, which will be the aim of the cost benefit analysis in this study. One of the areas in urban anthroposphere where considerable quantity of resources can be recovered is municipal solid waste. So far, the focus of recovery is mainly set on the recycling of municipal solid waste. The European Union (EU) set a recycling target of 50% by 2020. Some EU countries have already achieved a level of recycling of municipal solid waste above 50%, with the residual waste being composted, incinerated and landfilled. It is noteworthy that there is also a considerable potential to recover materials from incineration residues, which relies heavily on technological development. Currently most materials in incineration residues are not being recovered, due to lack of technology.

Generated at different stages during the incineration process, incineration residues include bottom ash, fly ash and grate siftings, among which bottom ash contains the majority of materials (15-20% by mass of the incinerated waste) (Grosso, Biganzoli and Riganmonti, 2011). The main components of bottom ash are glass, minerals, magnetic metals, diamagnetic metals, synthetic ceramics and unburned organic matter (Chimenos, Segarra, Fernandez and Espiell, 1999). According to Chimenos et al. (1999), magnetic metals in the bottom ash are made up mainly of pieces of steel and iron, and their oxidised products in the combustion furnace, such as Magnetite (Fe_3O_4), hematite (Fe_2O_3) and wüstite (FeO); while diamagnetic metals are made up mainly of melted drops of aluminium (90% by mass), and small amounts of copper wire and melted drops of copper alloys. Currently best available recovery technologies at waste incineration plants recover ferrous metal (iron) and non-ferrous metals (aluminium and copper). At the incineration plant in Doel, Belgium, for example (Van Brecht, Wauters and Konings, 2012), pieces of ferrous and non-ferrous metals are sieved and separated into different size fractions in order to be recovered by magnetic force and eddy-current method respectively. To increase the recovery efficiency of non-ferrous metals in finer fractions of incineration bottom ash is a technological challenge. A pioneer in this field, ZAR (Development Centre for Sustainable Management of Recyclable Waste and Resources) in Switzerland, has been developing first class technologies in the separation and the recovery of non-ferrous metals from fine bottom ash. By the end of 2011, they had developed and put into practice a break-through technology to separate and recover aluminium in fine bottom ash (particle sizes: 0.7-5mm), reaching a recovery rate as high as 96.8% (ZAR, Böni and Di Lorenzo, 2011).

In light of advanced separation and recovery technologies for the recovery of high-value metals, it is time to reassess the economic feasibility of applying waste incineration treatment in developing countries. The obstacles for developing countries to build waste incinerators have been mainly the high cost of investment, and operational and maintenance costs associated with waste incineration. Public concern over air pollution could be countered by application of sophisticated flue gas treatment technologies, which again is highly costly. In fact, air pollution control is the major determinant of incineration cost, comprising two thirds of initial investment cost in environmental protection stringent countries (Schuster, 1999). Consequently, the net treatment cost per metric ton of waste is significantly higher than other alternatives such as landfilling, even with the revenue gained from the recovery of electricity and heat. The WRAP Gate Fees Report 2009 (WRAP, 2009) provided that the waste incineration fee was on average EUR 84-175 per ton, while the landfilling fee was on average EUR 50 (Hogg and [illegible], 2012). Although the World Health Organization (WHO) recommends the range of 0.5 – 1.0% of Gross Domestic Product (GDP) as affordable for waste management (including public hygiene maintenance) (Scharff, 2006), countries typically spend 0.2%-0.4% of GDP on waste management (Brunner and Fellner, 2006). Brunner and Fellner (2006) further emphasise that there is a hierarchy of waste management objectives, and therefore countries with a low income level should first implement waste management strategies to achieve the primary objective: protecting human health, i.e. waste incineration is not so necessary to be of primary consideration. The cost benefit analysis of this study will find out that lower-income countries may be able to afford strategies to achieve higher objectives.

This study focuses on the application of waste incineration in China, taking a mid-sized municipality as a case for cost benefit analysis. China has been undergoing rapid economic and population growth, accompanied by a fast growing amount of municipal solid waste. In the past, it was argued that incineration of MSW was technically not an effective treatment because of the high proportion of organic waste (low heat value) and the low amount of high heat value materials like plastics. As urbanisation proceeds, the lifestyle of Chinese has experienced a considerable degree of change. These changes include a decreased proportion of organic waste and an increased amount of sophisticated plastic packages in the waste composition. Consequently, the increased incentive for energy recovery from the change in waste composition as well as the fast growing amount of MSW has stimulated private investment of waste incineration plants in China. A recent study (Dong, 2011) reported the increase of Chinese waste incineration capacity from 2.2 million tons/year at the beginning of the century to 23.5 million tons/year in 2009. By 2009, there were 93 operating incineration plants in China [Dong, 2011]. Nevertheless, public debate over landfilling and incineration persists at different levels of society: among policy makers, scientists, investors and the general public. At the core of the debate is the potentially toxic air pollution released from incineration plants, due to the lack of advanced flue gas cleaning application and/or the opaque emission control practice of the operator. These issues can be solved by applying state-of–the-art flue gas cleaning technologies and by increasing transparent monitoring to the public. These solutions mean further costs in the investment and the operation of the incineration, a discouraging factor for investment consideration. This study thus aims to assess the impact of the metal recovery technology on the overall economics of the waste management system by conducting a cost-benefit analysis of a potential waste incineration plant in a mid-sized Chinese municipality, Guanghan, with energy recovery, advanced flue gas cleaning technology and advanced technology in separation and recovery of metals from the bottom ash, in comparison to a baseline scenario without incineration. Eventually, the result of the study should serve as a general decision support on incorporating waste incineration in the municipal solid waste management system in Guanghan.

There has been a limited amount of literature on metal recovery and a great amount on waste incineration practices in China. Muchova, Bakker and Rem's (2009) study on the recovery of gold and silver iterated the economic viability of separating precious metals from bottom ash. Although the study focused specifically on the recovery of gold and silver in small quantities, it further reiterated the necessity to first classify bottom ash into different size fractions in order to separate more types of precious metals with a higher efficiency. A study by Grosso, Biganzoli and Rigamonti (2011) provides insightful assistance to the material flow analysis, in which the amount of aluminium and a minor amount of other non-ferrous metals recoverable from incineration bottom ash is quantified. Academic focus has been set on the recovery rate and the factors that influence it. A Swiss study found that in Switzerland more than half of the ferrous scrap contained in bottom ash was recovered and the recovery of non-ferrous metals increased to 31% (Hügi et al., 2008, cited in Spoerri, Lang, Staeubli and Scholz, 2010). Hu, Bakker and de Heij (2011) analysed the product life cycle and emphasized the influence of aluminium packaging on the aluminium recovery rate at waste incineration plants. Because waste incineration is a relatively new waste treatment option in China, literature on resource recovery in this field has been primarily focusing on energy recovery. A few studies, Zhang & He (2009) and He et al. (2003) for example, conducted brief analysis of bottom ash composition and called for the development of technologies for the recovery of ferrous and non-ferrous metals. A noteworthy study in Chinese bottom ash composition (Solenthaler and Bunge, 2003) however suggested that it was currently not economically viable to recover metals from Chinese bottom ash as the metal content was too low (3.3% in China versus 12.6% in Switzerland). There has not been a comprehensive analysis on the economic impact of a waste incineration plant with the application of advanced resource recovery technology in China. This study aims to fill in the literature gap between the technical studies of metal recovery from bottom ash and the economic impact of its practical application in China, through a cost-benefit analysis of an advanced waste incineration plant to be built in a municipality in Guanghan.

1.2. Objectives and Research Questions

The goal of this study is to deliver support for decision-making on investment in waste incineration in China, particularly in the municipality of Guanghan. In an investment decision-making process, the decision maker must first define the ultimate goals and outcome. For the municipal government of Guanghan, it is important that not only the cost of waste treatment will be affordable according to its budget, but also that the efficiency of resource allocation of waste management system as a whole is increased, and that the environmental impact will be minimal. Currently, municipal solid waste is dumped directly on a sanitary landfill 20 km outside the city, for which the government pays 90 Yuan[1] per ton of waste. Direct landfilling of waste takes up large area of land; additionally the environmental impact associated with untreated waste include potential pollution to ground water and soil, emissions of greenhouse gases and odour. The consideration of the government would be to pay within the framework of its budget for waste management, and at the same time reduce negative environmental impact from waste. In this study, a cost-benefit analysis will illustrate whether the inclusion of a waste incinerator with the advanced bottom ash separation and recovery technology improves the economic efficiency of the waste management system in Guanghan.

In order to reach the goal of the study, the following major research questions have to be answered: How much of the recoverable substances is there in the municipal solid waste in Guanghan? Since the advanced separation technology applied here is tested as being successful in recovering aluminium and copper in Zurich, the substances of focus in this study will be aluminium and copper, in addition to the commonly recovered substance: iron. Secondly, how much does it cost to extract the recoverable substances? The cost includes investment cost of the equipment and operational and maintenance costs of the incineration plant. Finally, what is the value of the recoverable substances? Market prices of aluminium, copper and iron will be used to calculate the referred value.

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[1] Yuan: unit of Chinese currency (denoted as CNY on currency market). EUR:CNY is 1: 7.92, a three-month average at of 10 August, 2012.

1.3. Methodology and Procedure

To answer the first research question, a material flow analysis (MFA) of the waste management system in Guanghan will be conducted with the assistance of STAN, a software for substance flow analysis. The MFA will be conducted on the mass level of waste, as well as on the substance level of the recoverable metals: Al, Cu and Fe. The MFA in the current waste management system is at first analysed, followed by two hypothetical scenarios, one as the baseline scenario for the cost-benefit analysis, another as the subject of the cost-benefit analysis: a waste management system that includes a waste incinerator with advanced air pollution control and metal recovery technologies.

A cost-benefit analysis is then conducted, where the full range of costs and benefits arising from the subject scenario in comparison with a baseline scenario is analysed. The Net Present Value as the result of the cost benefit analysis will be presented, together with a sensitivity analysis. Practically, not all costs and benefits can be known, nor can every known impact be measured reliably in economic terms. Therefore, at the beginning of chapter IV the assumptions and boundaries of the cost-benefit analysis are defined, where impact parameters are also identified, such as cost of land acquisition, cost of construction, and cost of technology and equipment, operation and maintenance cost, energy sales, revenue from selling recovered metals and the waste treatment fee willing to be paid by the municipal government. Environmental and social externalities will not be included in the quantification but will be discussed briefly after the analysis.

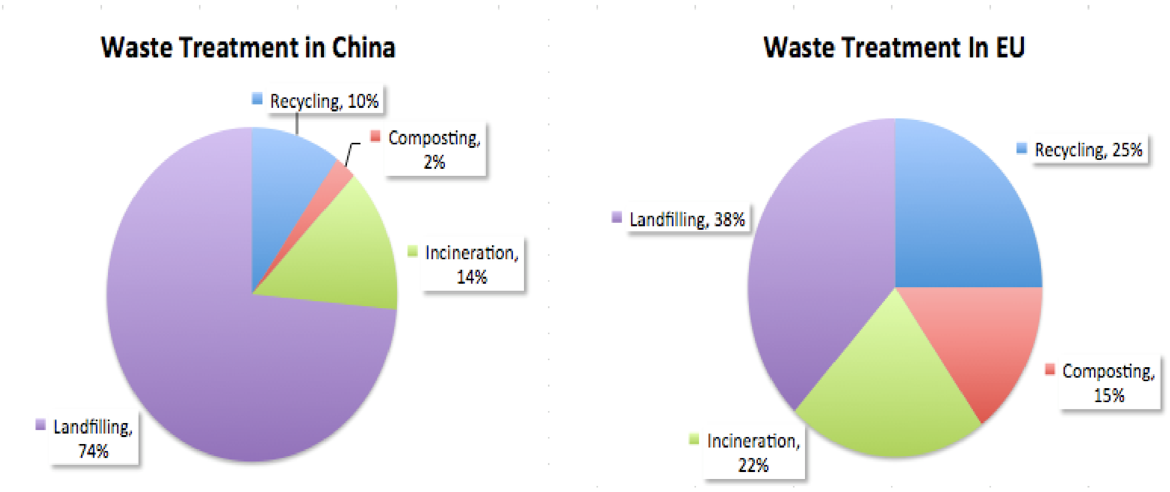
This study will begin with an exploration of waste incineration practices in European countries and in China, and a description of the most advanced technologies surrounding waste incineration. The following section describes the current waste management system in Guanghan (with MFA charts), its environmental impact and the future outlook of the debate between landfilling and incineration in China. The core of this study: the cost-benefit analysis, then follows. Afterwards, other considerations outside the scope of the cost-benefit analysis will be briefly discussed, followed by the conclusion.

Part II. Waste Incineration

2.1. Waste Treatment: EU Countries Compared to China

Due to the difference in economic development and to some extent in lifestyle, waste composition and waste treatment practices vary significantly between EU countries and China. Common waste treatment methods are recycling, biological treatment, incineration and landfilling. Figure 1 depicts the differences in the application of these treatment methods between EU countries and China. Landfilling is by far the most common treatment practice in China. This is not only due to its financial affordability but also indirectly due to the lack of waste separation at source that is crucial to the possibility of recycling and composting at a later stage. Source separation allows the removal of hazardous items, which could be toxic, flammable, corrosive or explosive, including paint, rat poison, plant killer, paint thinner, spray enamels, cleaning fluids and nail polish remover, etc. (Bass, Calderon and Khan, 1990). In addition, waste separation at source is the key to improve recycling and composting options, eventually reducing the amount of municipal solid waste to be disposed of at landfill. Waste composition is another crucial factor that determines which type of treatment method is most suitable for a certain type of waste in order to achieve sustainability. Organic waste, for example, is best to be composted into fertile soil; glass, paper, cardboards, E-waste, scrap metals and recyclable plastics (such as PET bottles) are best to be separated, recovered and recycled; non-recyclable materials with high heat value like non-recyclable plastics and the rest are best to be incinerated altogether so that recovery of energy is possible and that the weight, volume and chemical reactivity of waste are substantially reduced for safe landfilling.

Figure 1: Differences in waste treatment between EU 27 and China



Source: Wang and Nie, 2001
Zhang, et al., 2011
Eurostat, 2012

Recycling amounts and recycling rates in China are the most difficult statistics to obtain. Current statistics on waste recycling in China are based on a variety of assumptions, offering an opaque view of the situation. To clarify the picture, firstly the understanding of the concept "municipal solid waste" has to be differentiated from that in the EU countries. The general public as well as the relevant government agencies do not regard waste materials with a high economic value like paper, cardboards and metals as "waste", which are informally collected by scavengers and household collectors for recycling. The proportion of recycled materials in Figure 1 (10%) refers to the amount informally collected. Secondly, the proportion of recyclable materials in the waste composition is a reflection of consumption patterns, which correlates to lifestyle and living standard. The proportion of food consumption in total consumption for instance, is higher in China than in the EU countries, hence the higher proportion of organic waste in waste composition. These are some of the important underlying factors to help understand the differences in waste treatment practices between European countries and China.

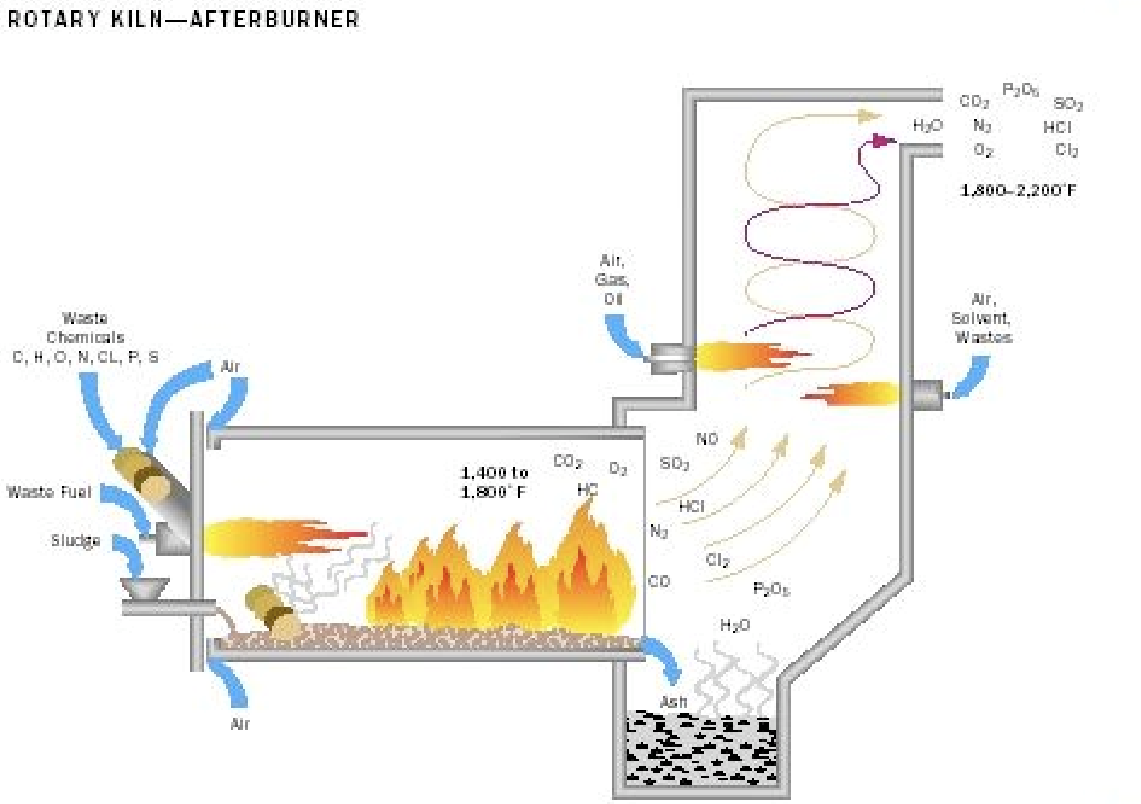
Composting should be an ideal treatment for a considerable portion of the municipal solid waste in China, as organic waste consists of over 50% of total waste. The reason why composting applies to merely 2% (Figure 1) of the collected waste is largely due to the absence of source separation. In addition to other hazardous waste mixed with organic waste at source, coal ash containing heavy metals from coal burning for heating in northern parts of the country makes composting from mixed waste unrealistic (Giusti, 2009). For incineration, coal ash also makes the burning less efficient. Nevertheless, waste incineration has been rising in the past decade in China, mainly driven by the lack of land in urban areas for landfill sites and the recoverable energy potential. Still, it is the most expensive treatment method; therefore financial consideration is the key factor leading to the difference in the application of waste incineration between the EU and China. The proportion of landfilling practice in China is almost twice of that in EU countries (Figure 1). This is in short the result of three factors: the low cost of landfilling, the high cost of incineration, and the limited practicality of recycling and composting as discussed hitherto due to lack of source separation. In fact, there is no optimal waste management system that fits all places or situations due to differences in energy sources, availability of disposal options, and differences in waste characteristics. Therefore environmental impact and sustainability assessments need to be conducted according to a specific region in order to design a customised optimal system.

2.2. State of the Art Waste Incineration Technologies

Incineration technology

There are three main types of combustion technologies in commercial practice: rotary kiln, moving grate and fluidised bed. Rotary kilns are commonly used for combusting industrial and hazardous wastes, but is also used in some municipal solid waste incinerators. The principle design (Figure 2) consists of two thermal treatment chambers: a slightly inclined primary chamber where waste is fed in (together with inlet of hot exhaust air with oxygen), rotated and thermally decomposed by the heat radiation from the secondary chamber: the re-combustion chamber positioned at the rear of the kiln where the decomposition air and the rest waste is completely burnt with the supply of secondary air. Rotary kilns have the advantage of producing a low level of NO_x and thermal destruction of hazardous chemicals (GEC, 2002).

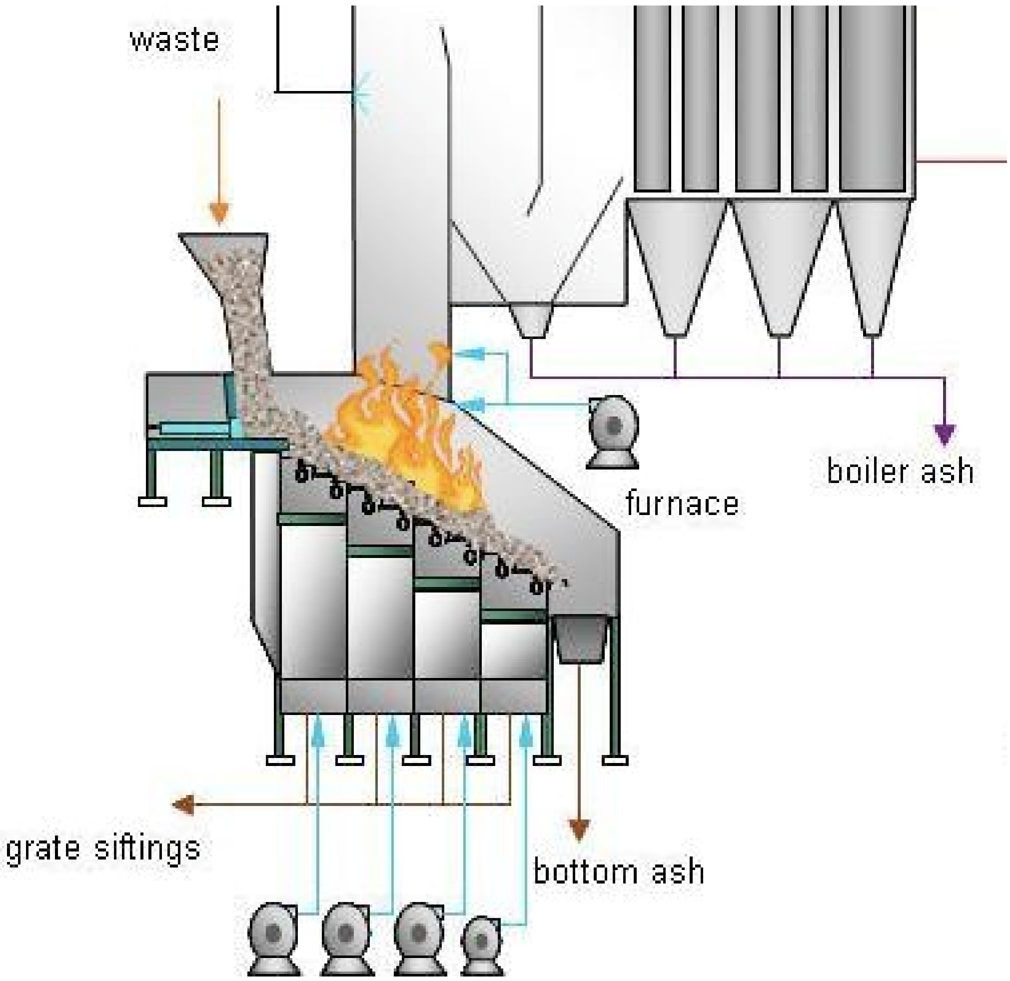
Figure 2. A rotary kiln incinerator



Source: Pollution Issues, 2012

A moving grate is a typical combustion design of a municipal solid waste incinerator. Waste is dropped by a crane onto the descending grate, which moves into the combustion chamber and eventually moves down to drop the burnt residuals into an ash pit at the other end of the grate (Figure 3). The moving grate is a metallic porous bed, allowing primary combustion air to flow through from the bottom. Secondary combustion air is supplied by nozzles from above the grate, facilitating a complete combustion by the introduction of turbulence. Certain incinerators have a secondary combustion chamber connected after the moving grate where secondary combustion air is supplied, to ensure sufficient time to keep a high temperature so that toxic organic pollutants decompose (Asthana, Ménard, Sessiecq and Patisson, 2010).

Figure 3. A moving grate incinerator



Source: Winderickx, 2012

Fluidised bed combustion has recently increased in application in municipal solid waste incinerators, although it is still mainly used for the combustion of hazardous waste. There are different types of fluidised bed combustors (bubbling, rotating and circulating fluidised bed), but the principle of the design remains the same: waste particles are suspended by the upward flow of combustion air injected from beneath so that it seems like a fluid, by which the turbulence created enhances uniform mixing and heat transfer hence an increased combustion efficiency (Figure 4). The advantage of fluidised bed technology is the enhanced combustion efficiency, however the pre-condition of that is the homogenisation of waste inputs in size as well as in heat value, which requires extensive pre-treatment of waste including typically size reduction and mixing (Van Caneghem et al., 2012).

Figure 4. A fluidised bed incinerator

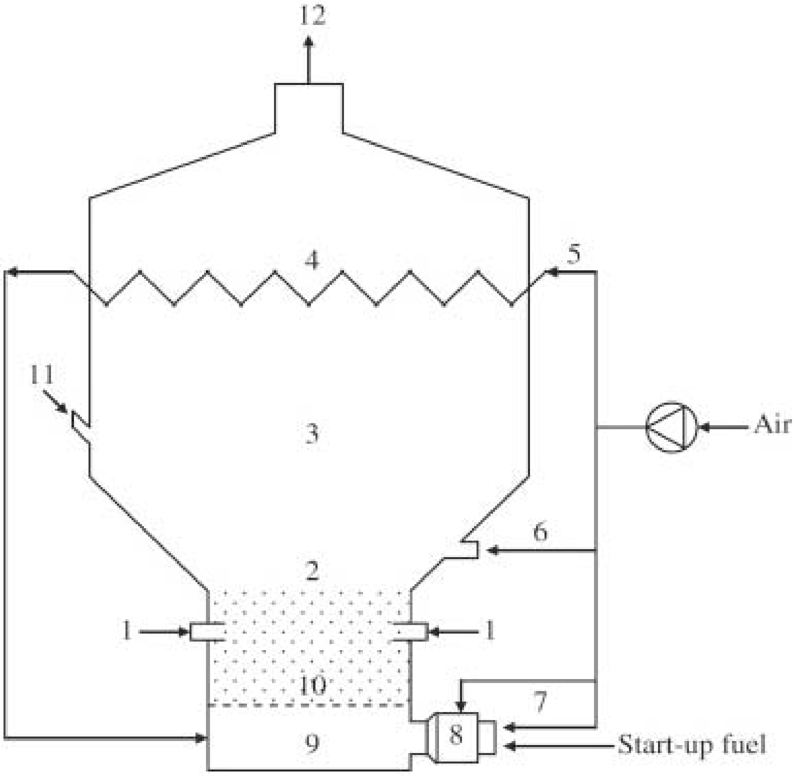


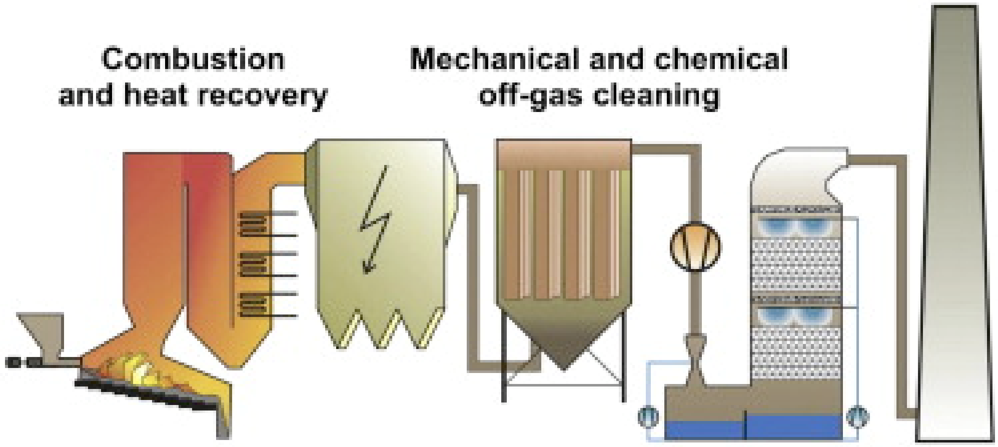
Fig. 2. BFBC of sewage sludge at Brugge (Belgium) [40] (1) sludge feed, (2) fluidized bed, (3) freeboard, (4) pre-heater of primary air, (5,6) secondary air, (7) air to start-up burner (8,9) windbox, (10) distributor, (11) make up sand, (12) exhaust to further heat recovery, ESP, pollutant abatement, stack.

Source: Van Caneghem et al., 2012

Flue gas cleaning technology

Mechanical and chemical methods are used to clean flue gas after incineration, by either taking away the pollutants or neutralizing them. Solid particles are removed by cyclones or multi-cyclones using gravitational and centrifugal forces. The more expensive electrostatic precipitator is used to remove smaller particles. Filtration is used to achieve an even higher efficiency of solid particle removal. Combined with catalysis of pollutants, pollutants such as PCDD/Fs and NO_x can also be filtered. In addition, solid particles can be washed out by fine water drops, in a combined system of Venturi scrubber and packed column. Acidic gaseous pollutants, mainly SO_2, NO_2, HCl and heavy metals, can be eliminated in this combined system by adding reactive agents, injecting a dry or semi-dry alkaline agent, and carbonaceous sorbents can be injected to remove PCDD/Fs and heavy metals. Selective non-catalytic reduction (SNCR) eliminates NO_x by reaction with ammonia agents added to the flue gas flow, generally achieving a removal efficiency of 60%. While selective catalytic reduction (SCR) achieves an efficiency as high as 90%, it is more costly because of the catalyst required. Such separation and absorption technologies reduce emissions to a level way below legislative requirements and are deemed as sound environmental practices (Tabasová, 2012).

Figure 5. Scheme of an up-to-date incinerator with mechanical and chemical flue-gas cleaning system



Source: Tabasová, 2012

Energy recovery technology

Energy recovery in the form of electricity and heat is achieved based on the following operational set-ups: water pipes are lined on the wall at the top inside the furnace, so that the heat from combustion can be utilised by converting water into high pressure steam, which is routed into a turbine that drives an electricity generator; in the case of cogeneration, the steam passing through the turbine then arrives at a heat exchanger that transfers the heat from the steam to district heating system. There are designs where heat is extracted before the turbines for district heating, increasing heat utilisation while reducing electricity generation (Fruergaard, Christensen and Astrup, 2010).

Material recovery technology

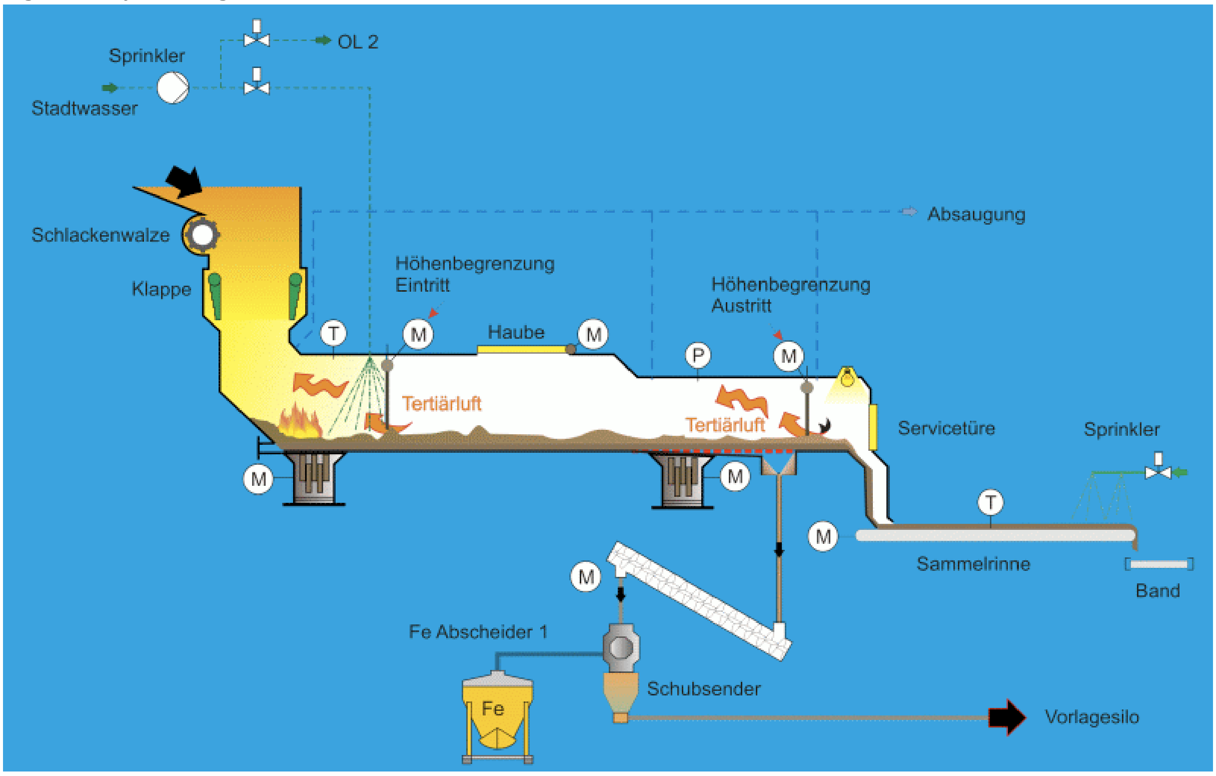
Currently best available recovery technologies at waste incineration plants recover iron and non-ferrous metals (aluminium and copper). At the incineration plant, bigger pieces of ferrous and non-ferrous metals are at first sieved, allowing smaller particles to be further separated. Particles with a larger size are then trommeled, within which iron is recovered again magnetically. The finer particles are further separated into fractions of different sizes. Iron is retrieved magnetically from larger fractions, while non-ferrous metals (aluminium and copper) are retrieved from smaller fractions (6-50mm in the case of a Belgium incinerator) based on eddy-current. The recovery of aluminium and copper in finer fractions below 2mm yields such a low rate by current technology that it does not usually take place. To increase the yield of non-ferrous metals in finer fractions of incineration bottom ash is a technological challenge.

2.3. New Technology to Separate Fine Bottom Ash – Recovery of Aluminium and Copper

To increase the yield of non-ferrous metals in finer fractions of incineration bottom ash is a technological challenge. A pioneer in this field, ZAR (Development Centre for Sustainable Management of Recyclable Waste and Resources) in Switzerland, has been developing first class technologies in the separation and the recovery of non-ferrous metals from fine bottom ash. By the end of 2011, they had developed and put into practice a break-through technology to separate and recover aluminium in fine bottom ash with particle sizes between 0.7 and 5mm, reaching a recovery rate as high as 96.8% (ZAR, Böni and Di Lorenzo, 2011).

With the goal of optimising the recovery of precious materials from incineration residues, ZAR has developed technologies for bottom ash discharge, separation and non-ferrous metal recovery, and has put them into practise at one of the incineration plants in Zurich, the KEZO incineration plant. Unlike most other incinerators which discharge bottom ash after burning in a water-filled trough (wet discharge), at KEZO bottom ash is discharged from the incineration chamber dry. The dry discharge process (Figure 6) is aided by the addition of tertiary air, which supports the incineration process, cools down the bottoms ash, and supports the afterburning of organic parts and the air sifting of the bottom ash. The dry-discharged bottom ash has all substances and particles in their original shape, raising the possibilities for the separation of bottom ash according to size, weight, shape, colour and conductivity. Removal of bigger particles is also made safer and simpler (ZAR, 2012).

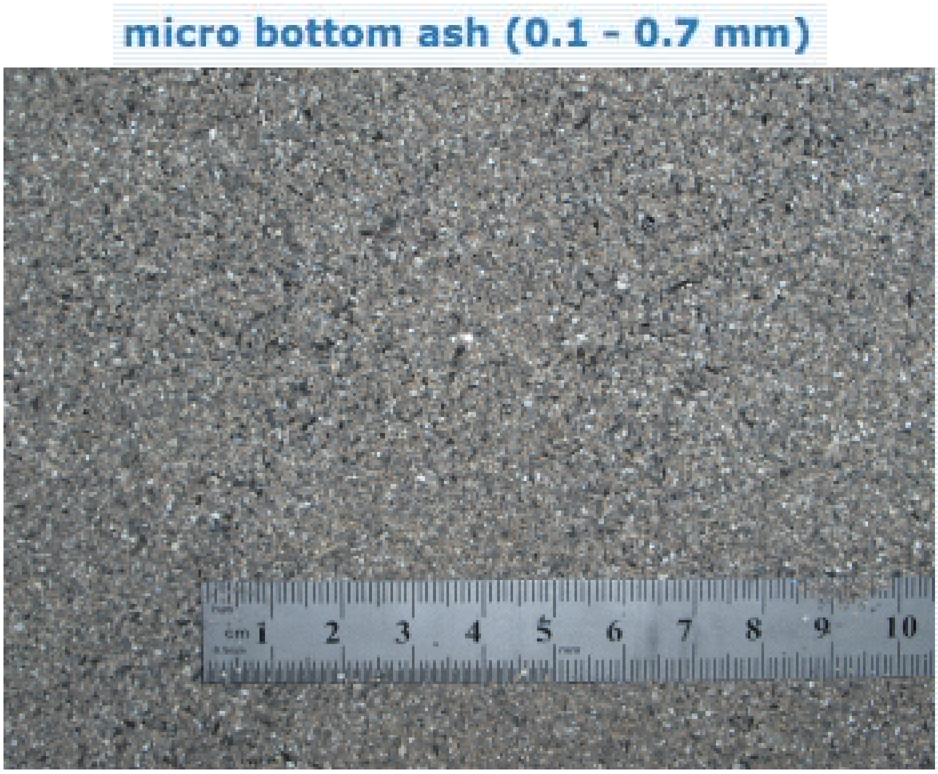
Figure 6. Dry discharge of bottom ash



Source: ZAR, 2012

The bottom ash is discharged continuously via an ash drum, falling down on special baffle plates, on which the bottom ash is crushed again and any glowing embers in agglomerates are torn apart. The vibration conveyor then transports the ash parts to the screening machine. The screening machine separates the bottom ash into three different fractions of diameter size: coarse bottom ash (>5mm), fine bottom ash (0.7mm-5mm) and micro bottom ash (0.1mm-0.7mm) (Figure 7).

Figure 7. Separation of bottom ash into fractions of different sizes



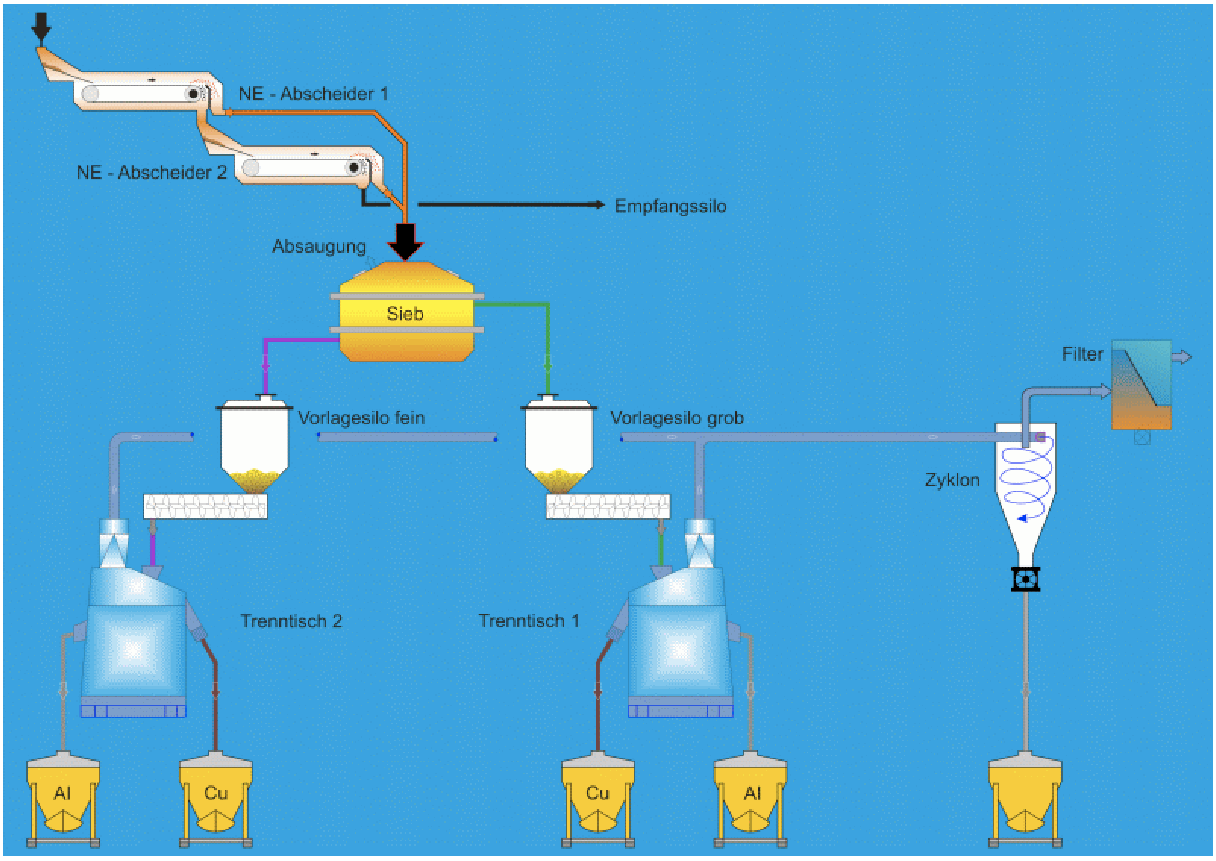
Source: ZAR, 2012

The cost benefit analysis of this study applies the technology that separates the fine bottom ash (0.7 - 5 mm). Operation of the plant was started in September 2008 and its recovery efficiency has been under continuous optimisation. ZAR states that "the central part of the conception are two very strong magnets, connected in series and two following, non ferrous treatment devices, also connected in series. The strong magnets remove all material particles that will disturb the induction field in the next treatment step and reduce the efficiency of the non-ferrous separation" (Figure 8). The non-ferrous separator is a pilot plant, reaching a recovery efficiency over 90% of metals in very high purity and quality (ZAR, 2012).

Eddy Current Principle

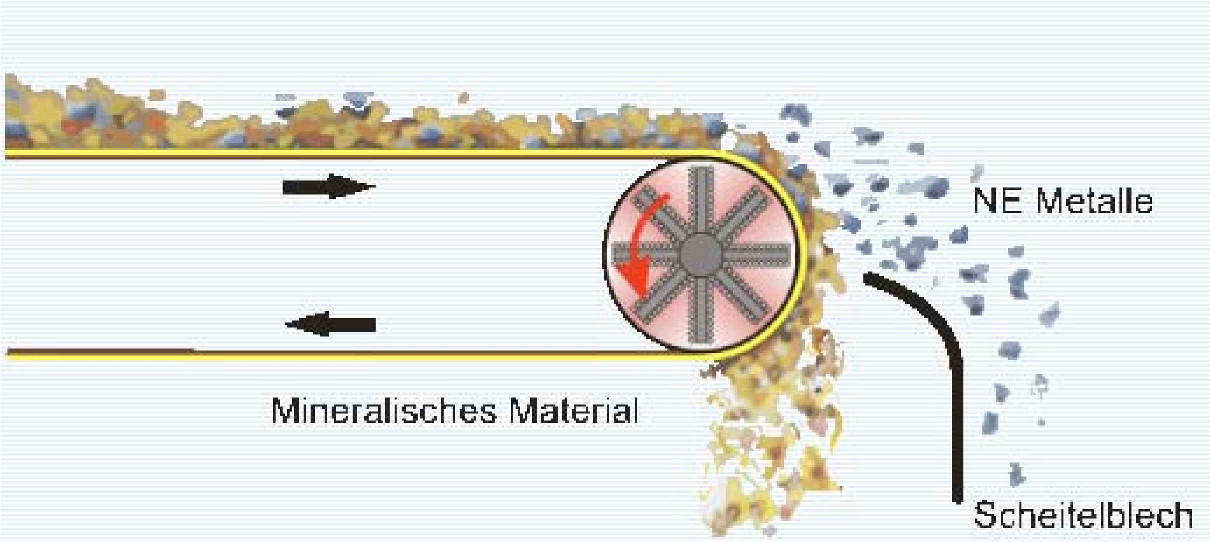
The separation of non-ferrous metal is based on the eddy current principle. A rotating magnetic field in the drum generates an eddy current in each electrically conductive ash part (non-ferrous metal), which will then generate another magnetic field. The magnetic ash part will then be repelled from the drum so that the non-ferrous metals can be separated reliably (Figure 9). The eddy current separator has the potential to reach an efficiency of 96.8% (ZAR, Böni and Di Lorenzo, 2011). Figure 10 shows the actual separator at KEZO incineration plant in Zurich.

Figure 8. Separation of fine bottom ash (0.7mm-5mm)



Source: ZAR, 2012

Figure 9. Eddy current separator



Source: ZAR, 2012

Figure 10. Eddy current separator at KEZO incinerator Zurich

Source: ZAR, Böni and Di Lorenzo, 2011

Part III. Waste Management System in Guanghan

3.1. Development of Waste Management and Environmental Impacts

Guanghan is a second-tier city in the southwest province of Sichuan, with an urban population of 210,000 (Qing[2], 2012). Like many other second-tier cities in China, Guanghan has not developed a holistic municipal solid waste management system. First of all, the definition of municipal solid waste is unclear as to whether it includes informal collection of recyclables by private agents. Secondly, there is no source separation other than those (newspaper, cardboards, metals and furniture) separated by domestic households for selling to informal collectors. As a result, the disposed waste contains a recyclable portion mixed with non-recyclable waste, part of which will then be collected by scavengers at the disposal bins, the waste transfer stations and the final waste dumpsite. Waste has been dumped on an open dumpsite 12km outside the city, where minimum control was applied. In the late 1990s, a pilot waste compost treatment plant went into operation, admitting all municipal solid waste and turning it into organic fertilizer. This waste treatment model was highly praised by the provincial and central government and thereafter was applied in other small to medium cities in Sichuan. Unfortunately, the private operator of the plant went into a legal dispute over intellectual right of the sorting and composting technology with another competitor and eventually lost the case, resulting in the closure of the plant in order to pay the legal fees. Afterwards, waste was again dumped on the open dumpsite with little control, until 2010 when finally a sanitary landfill construction was completed and started its operation.

The current sanitary landfill is built next to the old open dumpsite, which had already accumulated 600,000 tons of wastes (Sichuan Environmental Monitoring Centre, 2011) and was sealed with a grassy field as the top layer when the sanitary landfill was being constructed. The old dumpsite, with no bottom sealing, situated on a hill, had detrimental impacts on the agricultural fields and residing population down the slope. In the past, accidents happened frequently during the stormy season, when the runoff of the rain transported the waste on the open dumpsite to the agricultural fields along the slope,

[2] Qing, G. Z. is an official from the Guanghan Environmental Protection Bureau, who was the main correspondent to provide the local information for this thesis. An interview and a field visit with him were conducted in February 2012; private emails pursued thereafter regarding further data and information.

causing contamination of the soil as well as skin diseases to the farmers who were working on the field. The harvest grown from the contaminated soil thereafter could not be consumed. Besides these accidents, severe environmental impacts associated with open dumpsite persisted until the sanitary landfill was built. These impacts include soil contamination from direct contact with wastes, ground water contamination by the leachate from the waste, odour and green house gas emissions from the site, and pathogenic diseases being carried around by animals and scavengers that scavenged food and recyclable materials from the waste. The new sanitary landfill mitigates the problem of soil and ground water contamination, and the control of entry prevents animals from coming to the waste thereby reducing pathogen contagion. Nevertheless, the old dumpsite without bottom sealing will still pose long-term threat to the environment especially to the soil and groundwater. The new sanitary landfill has a capacity of 180 tons per day and is already admitting a daily intake of 200 tons (Qing, 2012). At the current rate of waste generation growth, the landfill will reach its capacity within 15 years, by then a new landfill has to be constructed.

3.2. Material Flow Analysis of Current Practice

To illustrate the current flow of waste materials in the city, a material flow analysis was conducted using the STAN[3] software for the year 2011. Through the STAN software, a graphical model was built with processes, flows and a system boundary with input data including mass flows, stocks, concentrations and transfer coefficients. Material flow analysis was also conducted on the substance level, for the three substances relevant to the cost benefit analysis, aluminium (Al), copper (Cu) and iron (Fe), in order to illustrate the quantities of their flows within the system. Figure 11 shows the flow of municipal solid waste in Guanghan, from its generation through various channels in the urban area until the final destination.

The official document from the government of Deyang (2009), the upper-level administration above Guanghan, defines municipal solid waste to be the solid waste produced by the urban population from their daily activities and the solid waste produced by entities that supply goods and services to urban life, and other solid waste designated by law and regulations, including wastes from households, offices, restaurants, public facilities such as schools, markets and sport centres, as well as construction waste and special waste, excluding industrial solid waste. Based on this definition, Deyang reported 84,000 tons of waste "generated" in Guanghan in the year 2010. This figure however does not include the recyclables separated by the households and collected by informal collectors before the rest is disregarded as waste (Qing, 2012). This figure hence is in fact formally collected waste. Therefore the actual amount of generated waste should include the amount of recyclables informally collected, which is estimated at about 10% of generated waste in China (Wang and Nie, 2010). The total waste generation of 100,000t into the system is therefore calculated as:

$$W_{r2011} = W_{2010} \ / \ (100\% - 10\%) * (1 + r_g)^1$$

where W_{r2011} is the real total waste generated in the year 2011, W_{2010} the reported total waste generation in the year 2010 (in fact formally collected waste), and r_g the rate of waste generation growth per year. r_g is calculated based on the daily waste generation of

[3] STAN (short for subSTance flow ANalysis) is a freeware that helps to perform material flow analysis according to the Austrian standard ÖNorm S 2096 (Material flow analysis - Application in waste management).

100t in Guanghan in 1998 (Hu, et al., 1998) and the daily waste generation of 230t[4] in Guanghan in 2010.

10% of the 100,000t of generated waste is sold by households to informal collectors, that is 10,000t, while the remaining 90,000t is disposed in the waste bins at each building or in small communities without separation. They are then collected by small trucks operated by the Urban Appearance and Environmental Hygiene Department and transported to waste transfer stations situated at the periphery of the city. Before the trucks come, scavengers are around the bins to collect recyclables. It is estimated that the amount of recyclables scavenged at this stage is approximately 5% of the disposed waste (Tai, et al., 2011), that is 4,500t, leaving 85,500t of waste to be collected by formal collection trucks. Once the waste is transferred to the transfer stations, it is compacted by a compaction machine to reduce the volume. Bigger trucks then come to the transfer station to collect larger amounts of waste and deliver them to the sanitary landfill 12km (SCEMC, 2011) outside the city. Scavenging also occurs at the transfer stations. The amount of 12,500t is calculated as the difference between the reported amount of waste that is admitted to the landfill and the amount of incoming waste to the transfer stations. On the landfill, an estimated amount of 1% of the admitted waste is collected by scavengers as recyclables, approximately 900t; the rest is stored in the landfill. Scavengers and informal collectors sell their collections to the privately owned recyclable material depots where the materials are sorted, accumulated and delivered to specialised recycling companies.

Figures 12, 13 and 14 illustrate the material flow on the substance level, namely aluminium (Al), copper (Cu) and iron (Fe). While the concentration of Cu in the total formally collected waste, 132g/t, is directly obtained from Qing (2012), the concentration of Al and Fe in the total formally collected waste is not available and therefore their mass is calculated using synthetic data in the following steps: first, the percentage of Al and Fe in the total metal content of the waste, 22%[5] and 67%[6] respectively, is calculated based on the data available in Zhao, et al. (2007) and Giugliano, et al. (2011). Second, the mass of

[4] 230 t/d = 84,000t / 365days

[5] 22% = 0.6% (Aluminium) /(0.6% (Aluminium)+2.1% (metals without Al)), from Fig. 2 of Giugliano, et al. (2011)

[6] 67% = 2% (Fe metal) /(1% (non-Fe metal)+2%(Fe metal)), from Table 1 of Zhao, et al. (2007)

Al and Fe, 100t[7] and 300t[8] respectively, is calculated by applying the above-mentioned percentages to the total metal amount in formally collected waste, 450t[9], which is calculated based on the metal percentage of 0.5% in Guanghan's waste composition (Deyang Urban Appearance and Environmental Hygiene Management Department, 2012). It is assumed that the transfer coefficients remain the same on the substance level as that on the goods level, except for that from the total waste generation because the metal content in it is much higher than in waste formally collected. As direct data is not available on the waste composition of generated waste, 4% of metal content is applied which is the average in Asian countries, resulting in 4,000t of metal generated. The same percentage of Al, Cu and Fe as calculated above is used to calculated the amount of Al, Cu and Fe in the total generated waste, 890t[10], 110t[11] and 2,670t[12]respectively. Then the difference between the amount in the total generated waste and in the total formally collected waste is the amount collected by informal collectors from the households. As a result, the current waste management system leaves approximately 80t of Al, 9t of Cu and 240t of Fe in the sanitary landfill un-recycled.

[7] 100t = 450t * 22%

[8] 300t = 450t * 67%

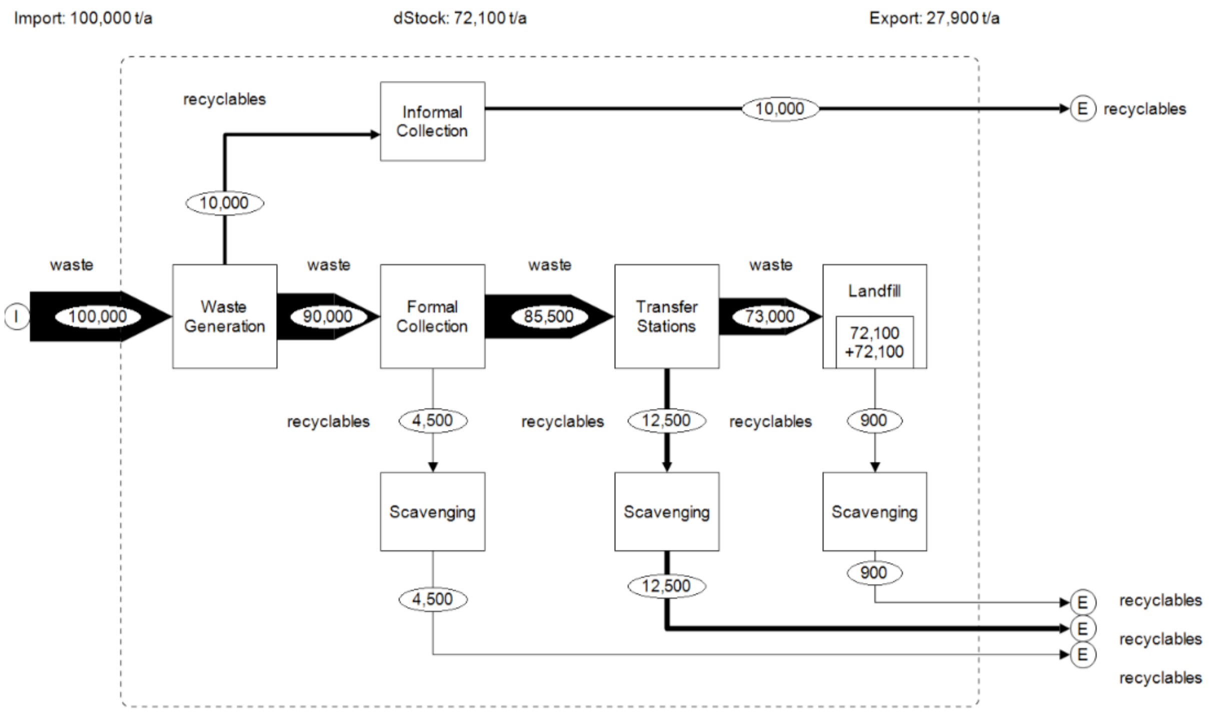
[9] 450t = 90,000 * 0.5%

[10] 890t = 4,000t * 22% (with rounding)

[11] 110t = 4,000t * (12t / 450t) (with rounding)

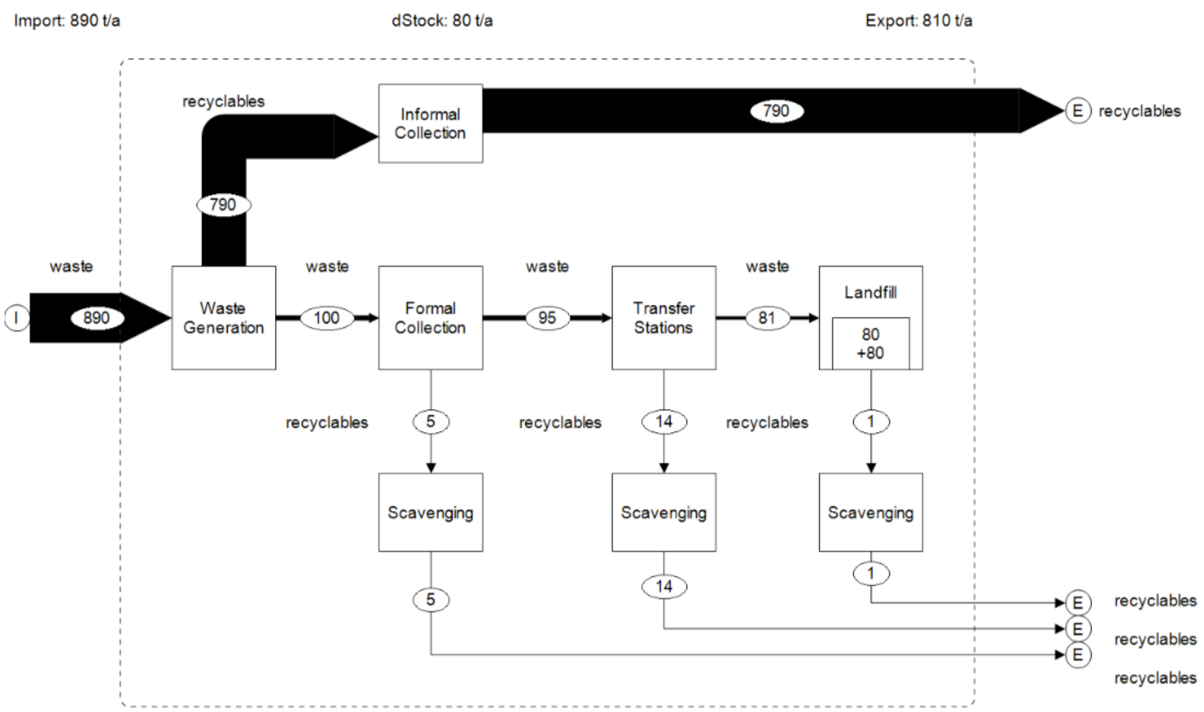
[12] 2,670t = 4,000t * 67% (with rounding)

Figure 11. Current material flow of municipal solid waste in Guanghan



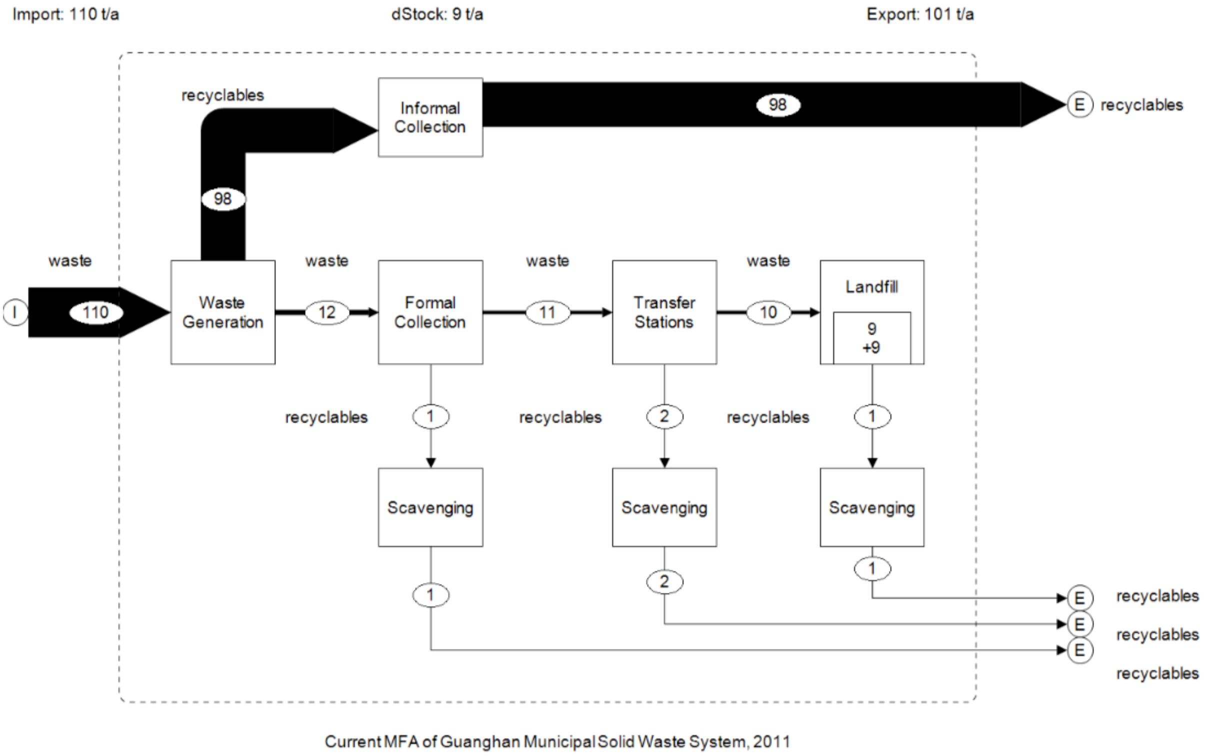
Current MFA of Guanghan Municipal Solid Waste System, 2011

Figure 12. Current material flow of aluminium (Al) in municipal solid waste in Guanghan



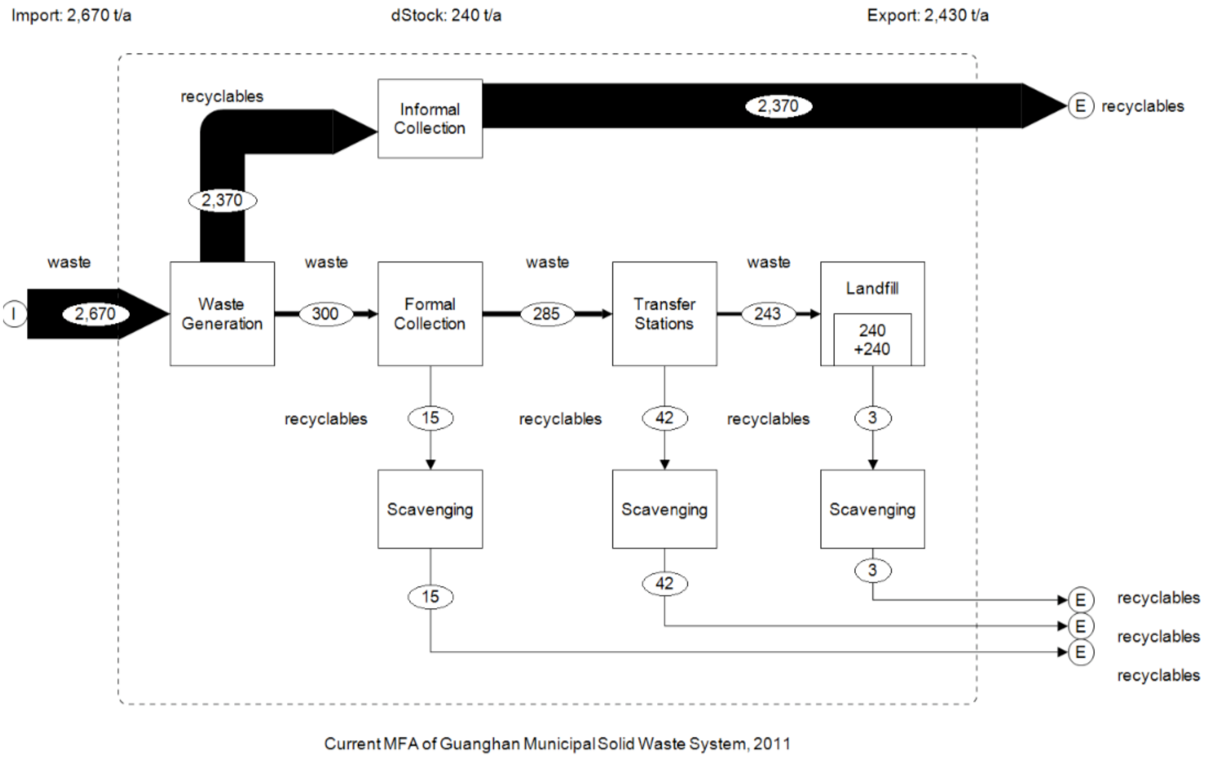
Current MFA of Guanghan Municipal Solid Waste System, 2011

Figure 13. Current material flow of copper (Cu) in municipal solid waste in Guanghan



(Note: The amount of recyclables scavenged from transfer stations is rounded to 2, which creates an insignificant irreconcilable mass equation.)

Figure 14. Current material flow of iron (Fe) in municipal solid waste in Guanghan



3.3. Material Flow Analysis of Two Scenarios for the Cost-benefit Analysis

Since the city of Guanghan is facing the challenge of municipal solid waste management, it is inevitable that a decision has to be made on source separation and separate collection in the future. In order to assist this decision-making, this study compares the costs and benefits of two scenarios:

Scenario I: The city is going to implement source separation, as is the common practice in EU countries, so that recyclable materials are separated at household level and collected separately by specialised collection vehicles, and that informal collection and scavenging is prevented. The rest waste is sent to the landfill as the final disposal without treatment.

Scenario II: The city is going to implement source separation, but excluding separation of metals, which means materials such as batteries and waste electrical electronic equipment are not collected separately. Non-metals are separated at household level and collected by specialised collection vehicles, and informal collection and scavenging is prevented. Instead of being directly buried in the sanitary landfill, the rest waste is incinerated in a waste incinerator, of which only the residual bottom ash will be buried in the sanitary landfill. The incinerator is equipped with state of the art technologies: moving grate, flue gas treatment, energy recovery and material recovery technologies. Al, Cu and Fe are recovered from the bottom ash, using the technology developed by ZAR.

Figure 15 to Figure 18 illustrate the material flow of Scenario I on the goods level and substance level. On the goods level, a recycling rate in households of 27.9%[13] is applied, equivalent to the rate calculated as the total material collected by informal collectors and scavengers over the total waste generated in the current system. This application is based on the assumption that the amount of total recycled materials is the same as that in the current system, and that the difference lies in the elimination of informal collection and scavenging, instead of which households perform source separation and afterwards formally organised vehicles collect recyclables separately. On the substance level, the total Al, Cu and Fe separated and collected from households are 810t[14], 101t[15] and

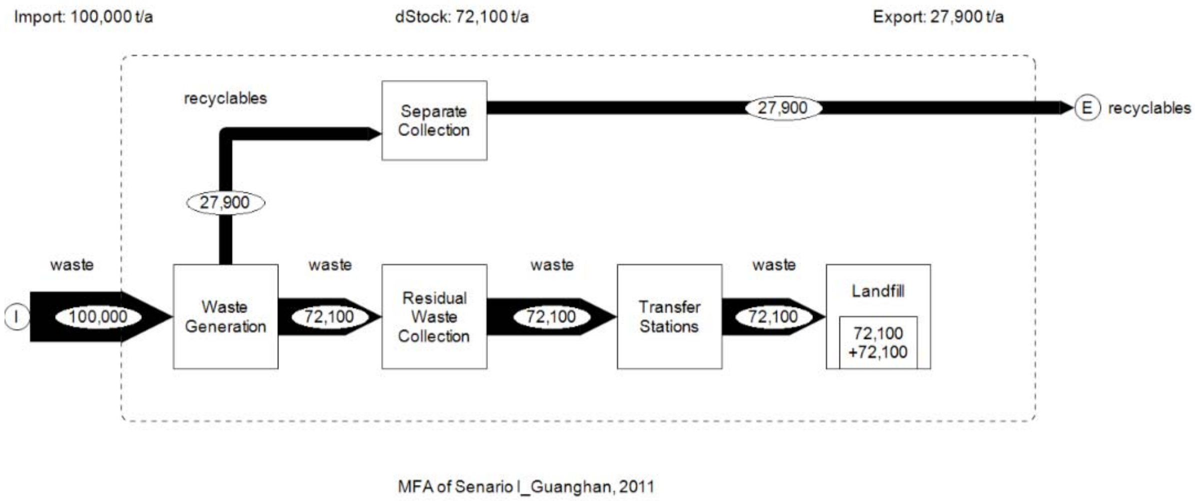
[13] 27.9% = (10,000 + 4.500 + 12,500 + 900) / 100,000, see MFA of current system Figure 11

[14] 810t = 790t + 5t + 14t + 1t. See MFA of current system Figure 12

[15] 101t = 98t + 1t + 2t + 1t, with rounding. See MFA of current system Figure 13

2,430t[16], calculated as the sum of each element collected by informal collectors and scavengers at all points in the current system. In percentage terms, they are 91%, 92% and 91% respectively of the amount in the generated waste. These metal recycling rates seem rather high, when compared to the average metal recycling rates reported by the United Nations Environment Programme (2011) of 70% for Al, 53% for Cu and 90% for Fe. In order to test the robustness of the cost-benefit analysis, these average rates are applied holding other variables unchanged to see if the result of the cost benefit analysis differs substantially from the higher rates used for Scenario II. The result shows only a 325,000 Euro difference.

Figure 15. Scenario I material flow of municipal solid waste in Guanghan



[16] 2,430t = 2,370t + 15t + 43t + 3t, with rounding. See MFA of current system Figure 14

Figure 16. Scenario I material flow of aluminium (Al) in municipal solid waste in Guanghan

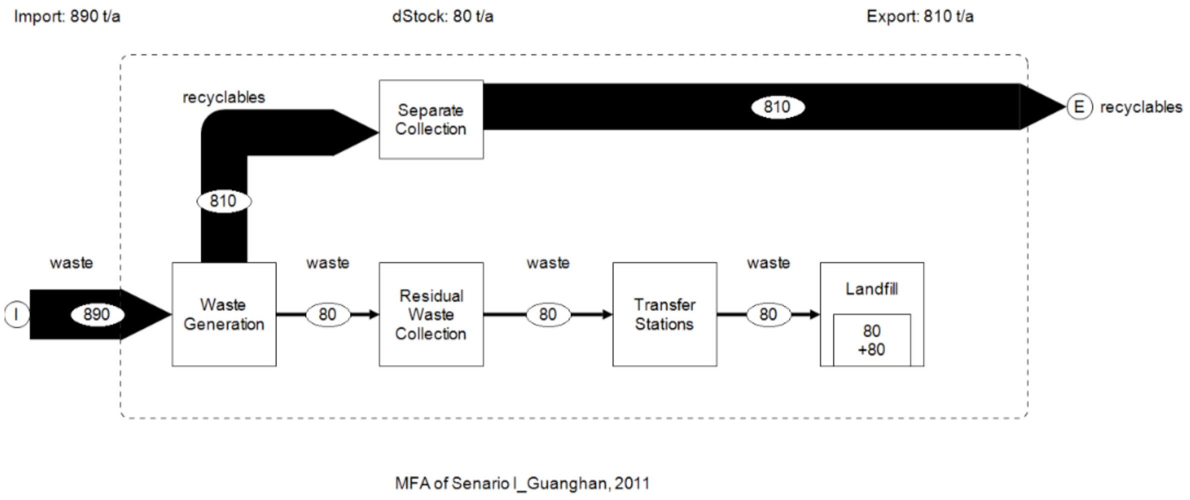


Figure 17. Scenario I material flow of copper (Cu) in municipal solid waste in Guanghan

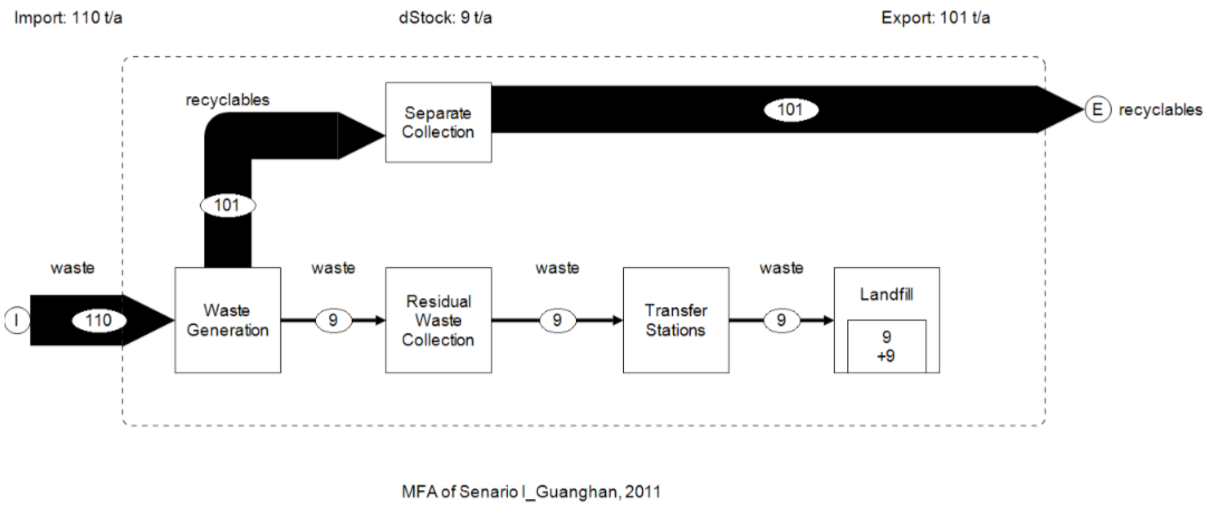


Figure 18. Scenario I material flow of iron (Fe) in municipal solid waste in Guanghan

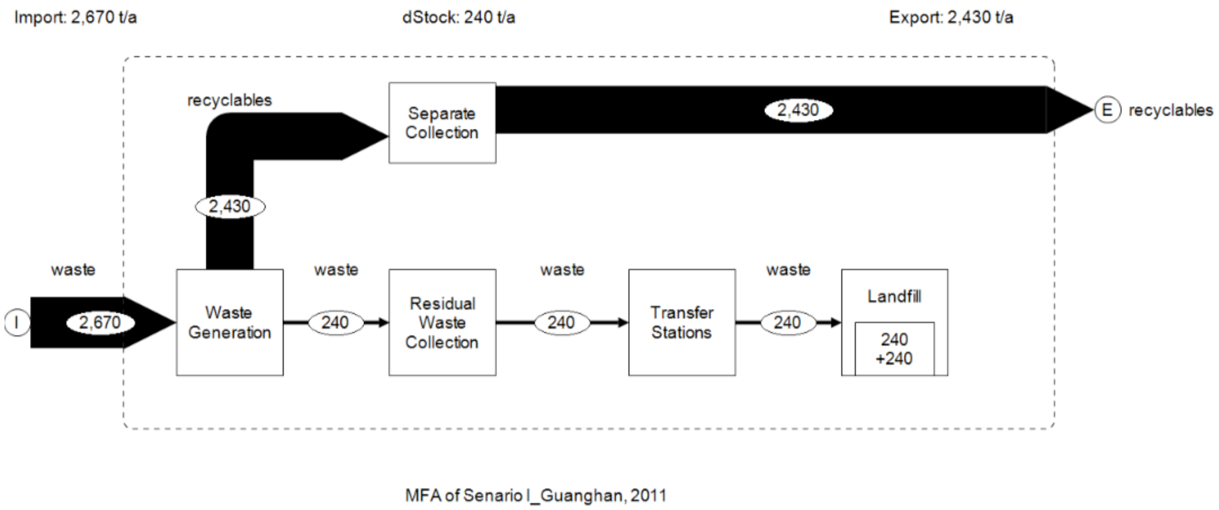


Figure 19 to Figure 22 illustrate the material flow of Scenario II on the goods level and substance level. On the goods level, the recycled amount of 24,600t[17] is calculated by applying the recycling rate of 27.9% less the amount of Al, Cu and Fe that would otherwise have been separately recycled at household level in Scenario I and which is not recycled from households in Scenario II. The amount of bottom ash and raw gas from the incinerator, as well as the amount of recovered Al, Cu and Fe and the residual bottom ash, is calculated based on the data from the KEZO incinerator in Zurich that is operating with the recovery technology. The data shows that 18% of incineration product is bottom ash while the rest 82% is raw gas (including fly ash). The assumption of the same percentage in Guanghan's incinerated waste leads to 13,600t[18] of bottom ash and 61,800t[19] of raw gas. Input of water is 0.34% of input waste, thus 256t[20] of input water is to be used to treat the residual bottom ash that is eventually going to the landfill. Applying the recovery rate of Al, Cu and Fe from KEZO, 95%, 97% and 98% respectively, to the amount of the metals in the waste input into the incinerator, the amount of recoverable metals is calculated: 846t[21], 107t[22] and 2,620t[23] respectively. Consequently, the rest of the amount of bottom ash is residual bottom ash, calculated as the difference between the bottom ash produced plus the water input and the recovered amount of metals: 10,283t[24] to end up in the landfill.

On the substance level, the metals are burnt and they flow into the portion of bottom ash, with none in the raw gas. Then they are separated and recovered in the bottom ash recovery process, resulting in recovered amount of 846t, 107t and 2,617t respectively, as calculated in the previous paragraph, with the unrecovered portion ending in the residual bottom ash, which is then treated to reduce environmentally harmful impacts and sent to the sanitary landfill as the final destination.

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[17] 24,600t = 100,000t * 27.9% - 810t – 101t – 2,430t, with rounding. See Figures 15, 16, 17 and 18.

[18] 13,600t = 75,400t * 18%, with rounding

[19] 61,800t = 75,400t * 82%, with rounding

[20] 256t = 75,400t * 0.34%

[21] 846t = 890t * 95%. See Figure 16.

[22] 107t = 110t * 97%. See Figure 17.

[23] 2,620t = 2,670t * 98%, with rounding. See Figure 18.

[24] 10,283t = 13,600t + 256t – 846t – 107t – 2,620t

Figure 19. Scenario II material flow of municipal solid waste in Guanghan

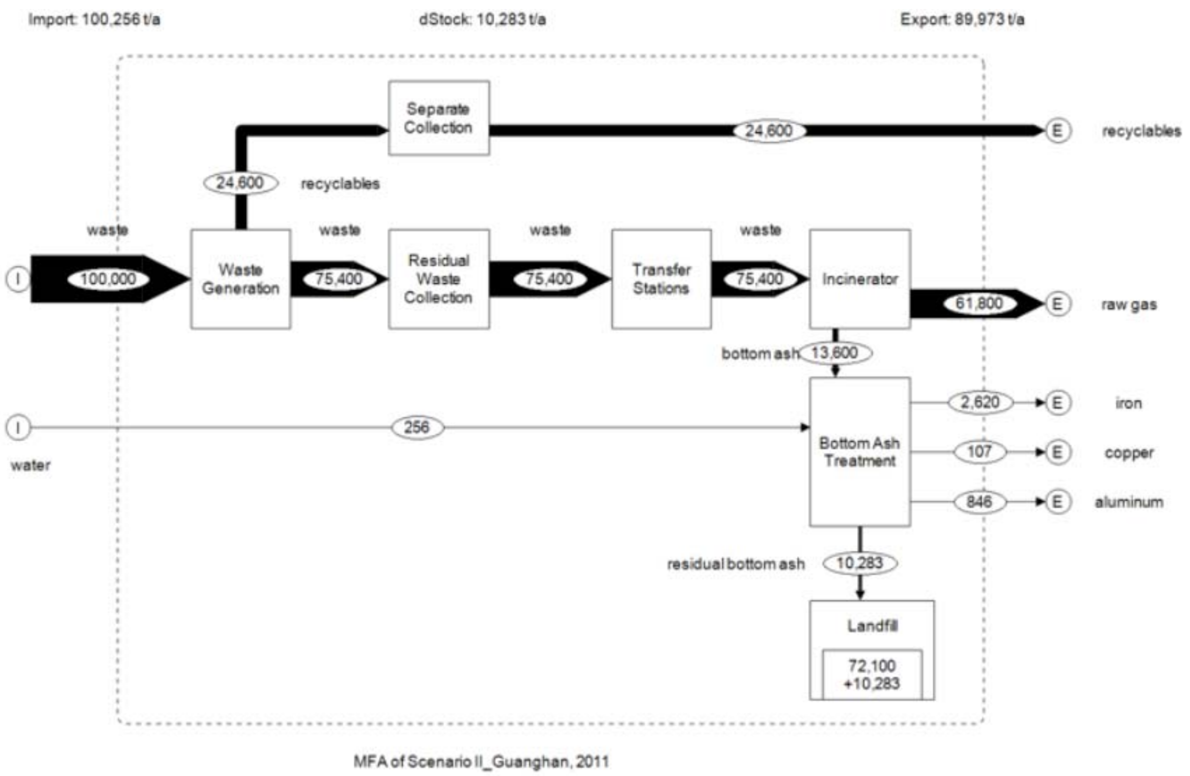


Figure 20. Scenario II material flow of aluminium (Al) in municipal solid waste in Guanghan

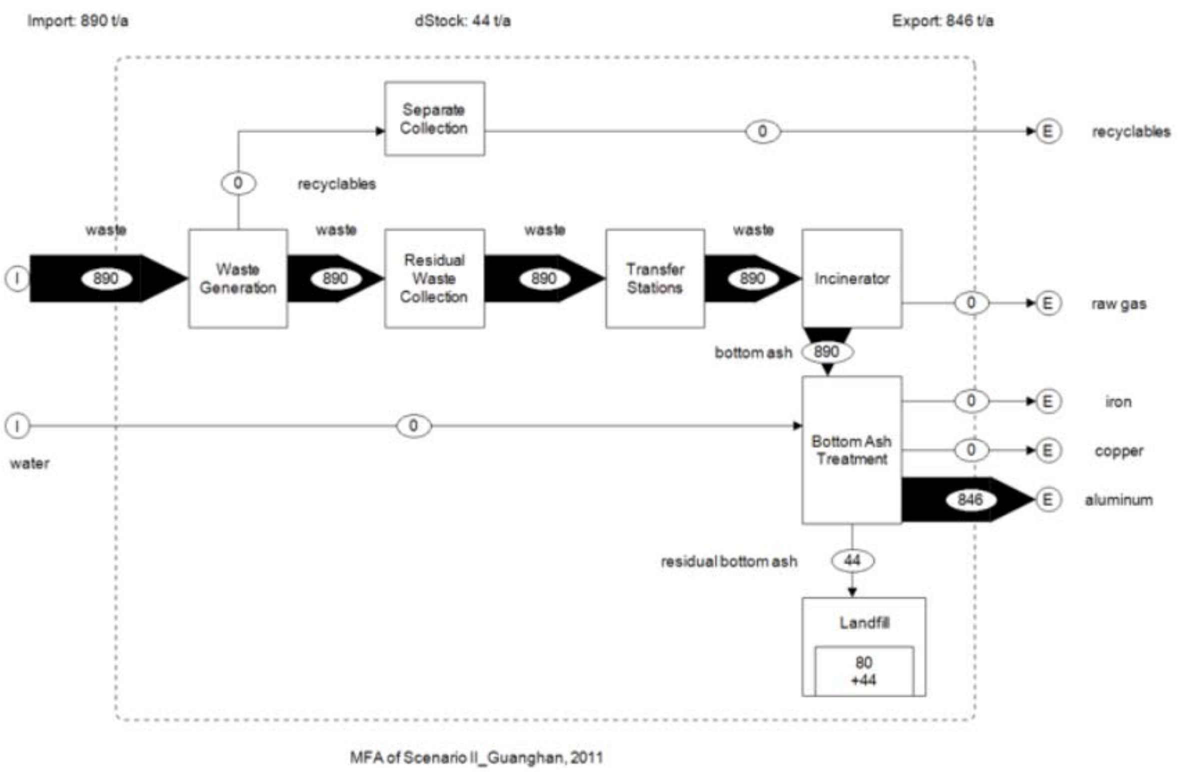


Figure 21. Scenario II material flow of copper (Cu) in municipal solid waste in Guanghan

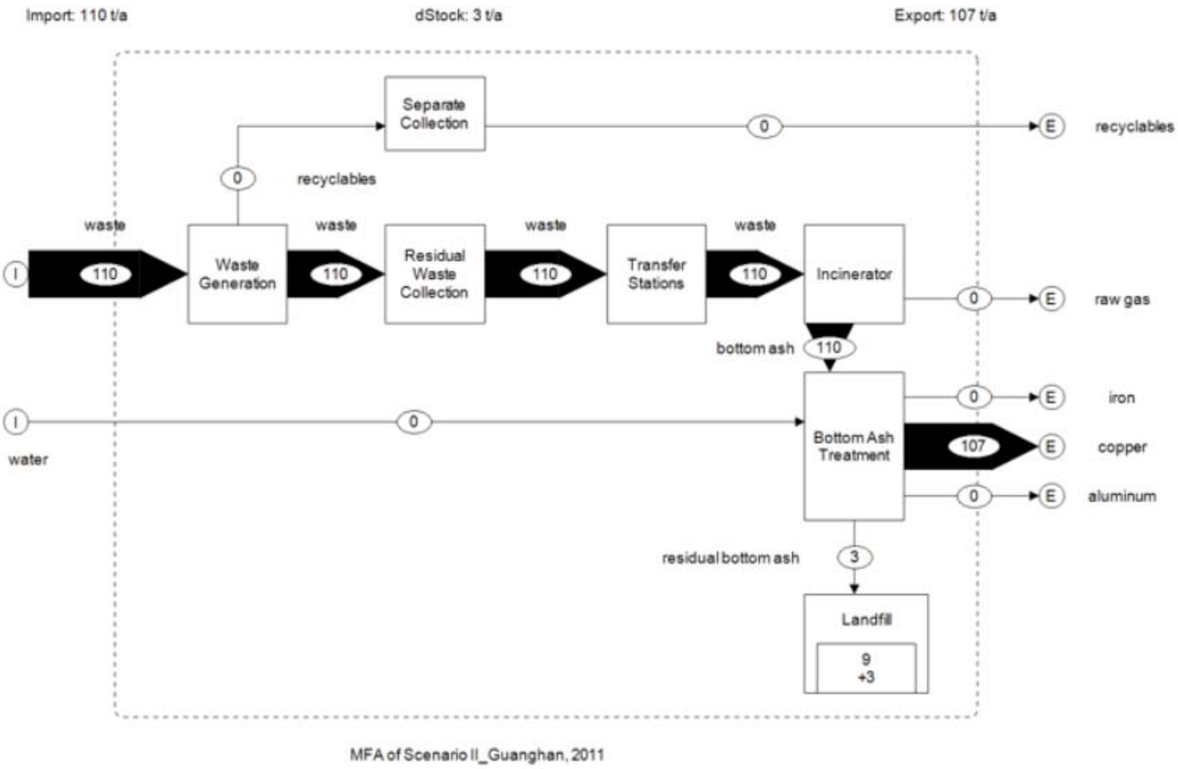
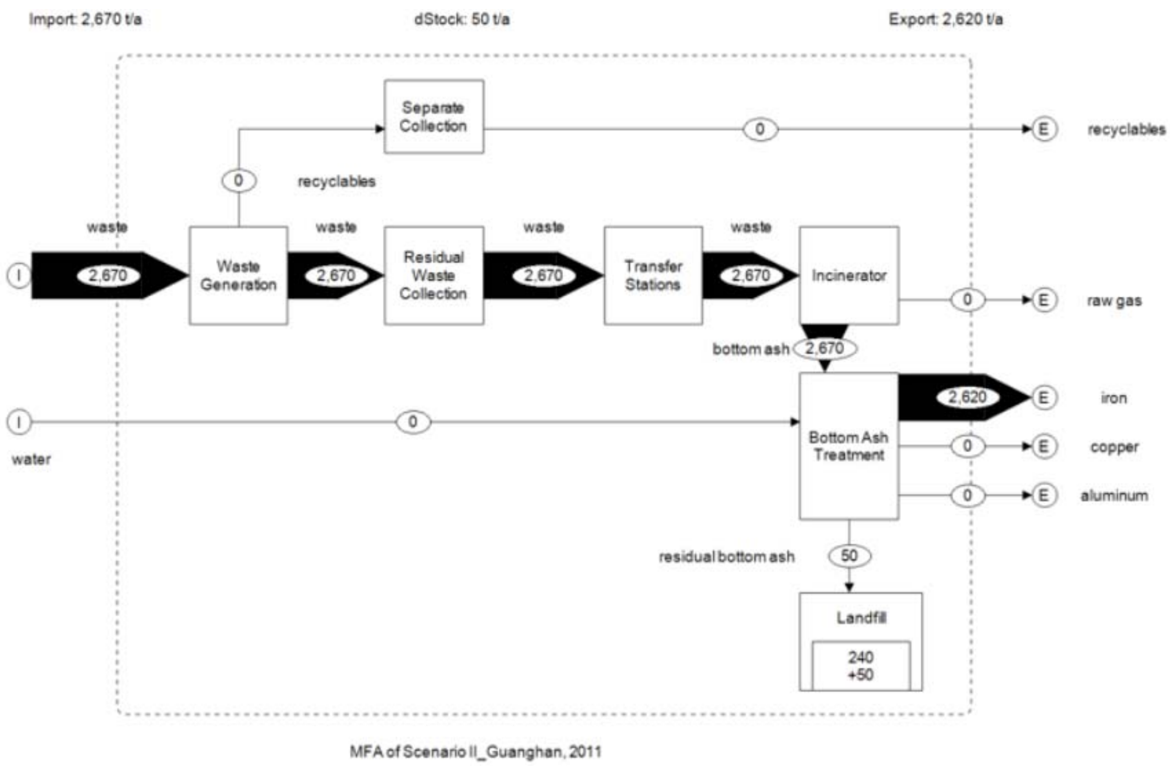


Figure 22. Scenario II material flow of iron (Fe) in municipal solid waste in Guanghan



Part IV. Cost-Benefit Analysis

4.1. Cost-benefit Analysis: Assumptions and Scope

When undertaking a project, goods and services are consumed as well as produced, while social, economic and environmental impacts occur. Economic efficiency is a fundamental criterion for public investment, which means that the benefits must outweigh the costs of using scarce resources, benefits being the total positive effects while costs the total negative effects measured in economic terms. The purpose of cost-benefit analysis therefore is to help decision-makers choose the option among alternatives that is efficient in its use of resources. In the case of Guanghan, since the city is facing the challenge of improving its municipal solid waste management system, it is inevitable that a decision has to be made on source separation, separate collection and waste treatment options. In order to assist the decision-making, this study analyses the cost benefit of Scenario II in comparison to the baseline of Scenario I. Note that Scenario I is also a hypothetical situation, which differs from the current waste management system in that informal collection and scavenging are replaced by source separation and formal separate collection of different types of waste. The reason for using Scenario I as the baseline instead of the current situation is based on the assumption that source separation will inevitable happen in the future for the efficient recycling of materials. The cost-benefit analysis therefore is to examine whether the exclusion of metal separation at source together with the implementation of a waste incinerator with advanced metal recovery technology before landfilling is economically more efficient than separating metals at source without incineration before landfilling. Based on this result, together with considerations of other non-economic factors, the municipal government will be able to make an informed decision on whether to implement the proposed Scenario II for the city of Guanghan, with the goal of improving resource use efficiency and eventually managing the city's municipal solid waste sustainably.

The system under examination includes the flow of waste from its generation to its final disposal and the processes in between, excluding the processes of recycling after collection at source and after recovery from the incinerator. It should be recognised that not all impacts can be known, and that not all known impacts can reliably be assigned a quantitative value, even less a monetary value. For this study, the economic impacts will be quantified in the cost benefit analysis, while the social and environmental impacts will be discussed in the next chapter in a qualitative context. It is assumed that the lifetime of the proposed incinerator is 20 years with 1 year of construction in addition, and that it has two individual lines (one as backup for when the other's capacity is exceeded) with a capacity of 400t/d[25] each. It is also assumed that the plant is located within 1km distance to the current sanitary landfill, and that it is near to the existing electricity grid, so that no extra cost is incurred through a costly new transmission system. Furthermore, revenue from electricity sale is assumed to flow throughout the lifetime of the plant. Finally, it is assumed that the level of waste flow increases by 7.19% per year, which is the growth rate of waste generation during the past thirteen years (Table 1 below shows the predicted waste flows based on this growth rate); and that the tipping fee of the incinerator is equal to that of the current landfill: 90 Yuan. The calorific value of the waste is assumed to increase by 3% per annum, a trend observed in Europe from year 1980 to 2000.

Table 1. Predicted waste generation and waste flows

Year	Waste Generation (t/y)	Waste Input to Incinerator(t/y)	Waste Input to Incinerator (t/d)	Waste flow from source to landfill(t/y) (Scenario I)	Waste sent to landfill (t/y) (Scenario II)	Metal recovered by separate collection(t/y) (Scenario I)	Reduction in landfilled waste(t/y)
2011	100,000	75,400	207	72,100	10,283	3,340	61,817
2012	107,192	80,823	221	77,286	11,023	3,581	66,263
2013	114,902	86,637	237	82,845	11,815	3,838	71,030
2014	123,167	92,868	254	88,804	12,665	4,114	76,139
2015	132,026	99,548	273	95,191	13,576	4,410	81,615
2016	141,523	106,709	292	102,038	14,553	4,727	87,485
2017	151,702	114,384	313	109,378	15,600	5,067	93,778
2018	162,614	122,611	336	117,245	16,722	5,432	100,523
2019	174,310	131,430	360	125,678	17,924	5,823	107,754
2020	186,848	140,884	386	134,718	19,214	6,241	115,504
2021	200,287	151,017	414	144,408	20,596	6,690	123,812
2022	214,694	161,880	444	154,795	22,077	7,171	132,718
2023	230,136	173,523	475	165,929	23,665	7,687	142,264
2024	246,689	186,004	510	177,864	25,367	8,240	152,497
2025	264,433	199,383	546	190,657	27,192	8,833	163,465
2026	283,453	213,725	586	204,371	29,148	9,468	175,223
2027	303,841	229,097	628	219,070	31,244	10,149	187,826
2028	325,696	245,576	673	234,828	33,491	10,879	201,336
2029	349,123	263,239	721	251,718	35,900	11,662	215,818
2030	374,234	282,174	773	269,824	38,483	12,501	231,341
2031	401,152	302,470	829	289,232	41,251	13,400	247,981

[25] Close to the waste flow into the incinerator at the end of lifetime: 829t/d = 75,400t/y / 365d * (1+7.19%)^20y

In order to identify the economic impacts of Scenario II, assessment of the net changes compared to the baseline scenario is needed. Firstly, there is additional input of water into the system that is needed in the incinerator; however the amount (256t/y) is so insignificant that the additional cost (only a few hundred euros per year) will not be included in the cost-benefit analysis. Secondly, the amount of recycled materials at source is reduced because of the exclusion of metal separation, hence the cost of source separation is reduced. Thirdly, as a consequence of reduced need to separate metals, there is a higher amount of residual waste flowing through the rest waste collection and transfer stations, which means higher collection cost. Fourthly, the incinerator induces a variety of economic impacts: fixed costs on capital investment, variable cost of operation and maintenance, revenue from the waste treatment fee, electricity sale and recovered metal sale. Lastly, the reduced amount of waste that is sent to the landfill means a reduced cost of landfilling, and more significantly it means there is no need to construct a new landfill that would have otherwise been needed in 15 years under Scenario I. Table 2 below lists the impact parameters of the cost benefit analysis.

Table 2. Economic impact parameters for the cost-benefit analysis

Economic Impact Parameters	
Costs:	**Type**
increased collection cost from source to landfill	variable
Incinerator land acquisition	fixed
Incinerator equipment and technology acquisition	fixed
Incinerator construction cost	fixed
Incinerator operational cost	variable
Incinerator maintenance cost	variable
Benefits:	
saved cost of acquiring and constructing additional landfill area	fixed
saved cost on source separation and separate collection of metals	variable
saved cost on landfilling	variable
revenue from incinerator tipping fee	variable
revenue from electricity sale	variable
revenue from sale of recovered aluminum from incinerator	variable
revenue from sale of recovered copper from incinerator	variable
revenue from sale of recovered iron from incinerator	variable

Physical quantification of these parameters and monetary evaluation is described in the following sections. The result of the cost benefit analysis is the Net Present Value (NPV), the difference between the sum of discounted benefits and the sum of discounted costs. If the NPV is greater than zero, the proposed scenario represents an efficient change in the allocation of resources. The NPV is calculated as:

$$NPV = \Sigma B_t(1+i)^{-t} - \Sigma C_t(1+i)^{-t}$$

Where B denotes benefit, C denotes cost, i the discount rate, and the summation runs from t=0 (the first year of the project) to t=T (the last year of the project). A five-year averaged bank-lending rate from the year 2008 to 2012 of 6.73% per annum (Bank of China, 2012) is used as the discount rate.

The functional unit of the cost benefit analysis is the Euro. Three-month averaged currency exchange rates (as of 10 August 2012 from ECB) are applied to convert other currencies to Euro. Most data are obtained through currently operating incinerators in China, particularly those with a similar capacity. Since data used are subject to variation, as the future flow of physical impacts and prices are predicted rather than known, a sensitivity analysis is conducted at the end to identify which factors the outcome of the cost-benefit analysis is most sensitive to.

It should be noted that the cost-benefit analysis provides a general guideline on the waste management system level. A feasibility study is required for a specific investment to investigate detailed investment cost and to take consideration of local factors such as waste transport distance, land use, and environmental and social impacts on the local population.

4.2. Costs

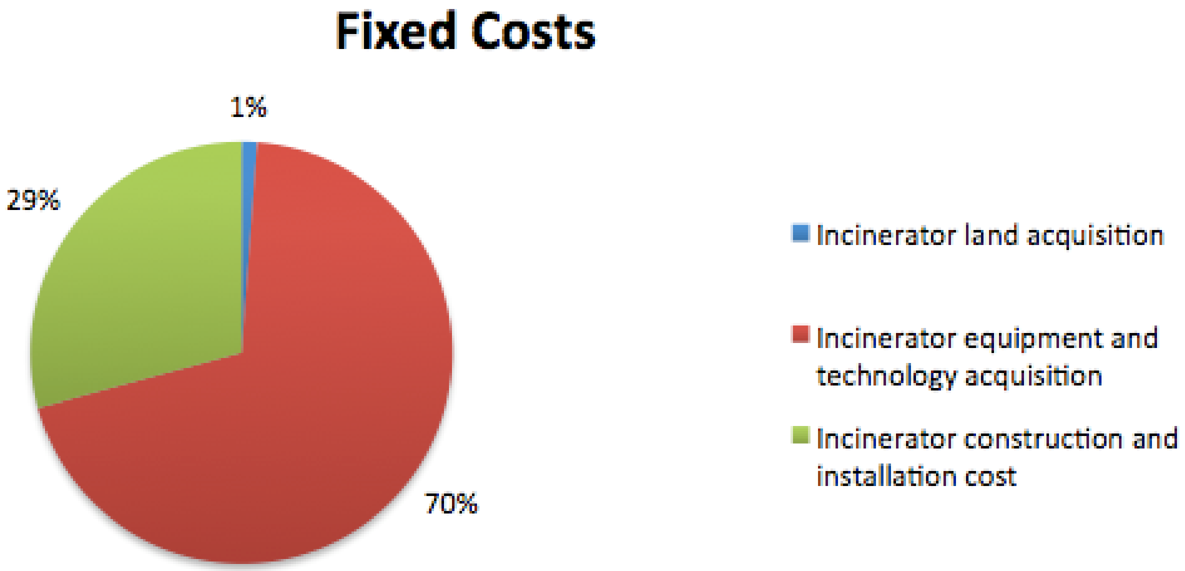
4.2.1. Fixed Costs

Fixed costs are associated with the capital investment in the first year of the proposed incinerator, including three categories of cost: land acquisition cost, equipment and technology acquisition cost, and construction and installation cost. Land acquisition cost is calculated based on the size of the land area needed and the current price of the type of land needed. The size of the land needed is estimated to be 52,800m^2, similar to that of the KEZO plant in Zurich; while the current price of the type of land needed in Guanghan is equivalent to €23/m^2 (Land and Resources Department of Sichuan Province, 2012). The equipment and technology acquisition cost estimation is based on the cost of the state of the art technologies applied in a Viennese waste incinerator (Federal Ministry for Soil and Forestry, Environment and Water Management2002) adjusted with the cost of the most advanced incinerators in China (Anon, 2012?). The construction and installation cost is obtained from a feasibility study of an advanced waste incinerator in Tonghua in China (Wuzhou Engineering Design and Research Centre, 2010), since the capacity of the incinerator is similar to the proposed incinerator in Guanghan. Table 3 lists the fixed costs and Figure 23 shows their corresponding percentages of total fixed costs. The incinerator equipment cost and the construction cost are by far the majority of the total fixed costs.

Table 3. Fixed cost

Year	Category	Fixed Cost (€)
2011	Incinerator land acquisition	1,230,000
2011	Incinerator equipment and technology acquisition	71,700,000
2011	Incinerator construction and installation cost	30,100,000

Figure 23. Percentages of different types of fixed cost out of total fixed costs



4.2.2. Variable Costs

1). Increased collection cost from source to landfill

Because metals are not separated from the rest waste in Scenario II, and also because the incinerator is assumed to be within 1km distance to the current landfill, the amount of waste to be collected from the source and to be transported to the incinerator is higher by the amount of metals that would have been separated in Scenario I. Additionally, based on the assumption that the distance between the incinerator and the landfill is 1km, the cost of collecting and transporting the residual bottom ash from the incinerator to the landfill is accounted for. The increased collection cost from source to landfill every year is therefore calculated as:

$$C_c = (Q_{wfII} - Q_{wfI})*P_{c1} + Q_{wl}*D_l*P_{c2}$$

where C_c is the total increased collection cost from source to landfill, Q_{wfII} the quantity of waste flow from source to the incineration plant in Scenario II, Q_{wfI} the quantity of waste flow from source to the landfill in Scenario I, P_{c1} the unit cost of collection per ton of waste from source to the incineration plant, Q_{wl} the quantity of residual bottom ash that is sent to the landfill, D_1 the distance between the incinerator and the landfill, and P_{c2} the unit cost of collection per ton per km of bottom ash from the incinerator to the landfill.

The unit cost per ton of waste from source to the incineration plant is obtained from a study done for the city of Shenzhen on municipal solid waste collection cost (Li and Kong, 2011), while the unit cost per ton of waste per km is obtained from a study done for the municipality of Heping in the city of Tianjin (Research Office of Tianjing City Heping Municipal People's Government, 2007). Furthermore, the price of collection cost increases every year by 6.17% per annum, calculated as:

$$R_{cr} = r_{dn}*p_{d/c} + r_{wn}*p_{w/c}$$

where R_{cr} is the rate of collection cost increase per year, r_{dn} the rate of diesel price increase per year, $p_{d/c}$ the percentage of diesel cost as a component of collection cost, r_{wn} the rate of wage increase per year, and $p_{w/c}$ the percentage of wage cost as a component of collection cost.

r_{dn} is calculated based on the diesel price in China between 2000 and 2012, while r_{wn} is calculated based on the average wage level in Guanghan between 2004 and 2011 (Statistic Bureau of Deyang, 2012). The percentage of diesel cost and wage cost as two major components of collection cost, 52.7% and 15.5% respectively, is obtained from a study by Wang (2009). Table 4 below lists the increased collection cost from source to landfill.

Table 4. Increased collection cost from source to landfill

Year	Physicial quantity(t) b/w source and incinerator	Price per unit (€/t)	Cost(€)	Physicial quantity(t) b/w incinerator and landfill	Price per unit (€/t.km)	Cost(€)	Total collection cost (€)
2012	3,537	11.11	39,295	11,023	0.15	1,694	40,988
2013	3,792	11.79	44,718	11,815	0.16	1,928	46,646
2014	4,065	12.52	50,890	12,665	0.17	2,194	53,084
2015	4,357	13.29	57,914	13,576	0.18	2,497	60,411
2016	4,670	14.11	65,907	14,553	0.20	2,841	68,748
2017	5,006	14.98	75,004	15,600	0.21	3,233	78,237
2018	5,366	15.91	85,356	16,722	0.22	3,679	89,036
2019	5,752	16.89	97,137	17,924	0.23	4,187	101,324
2020	6,166	17.93	110,544	19,214	0.25	4,765	115,309
2021	6,610	19.03	125,801	20,596	0.26	5,423	131,224
2022	7,085	20.21	143,165	22,077	0.28	6,171	149,336
2023	7,595	21.45	162,924	23,665	0.30	7,023	169,948
2024	8,141	22.78	185,411	25,367	0.32	7,993	193,404
2025	8,726	24.18	211,002	27,192	0.33	9,096	220,098
2026	9,354	25.67	240,125	29,148	0.36	10,351	250,476
2027	10,027	27.25	273,267	31,244	0.38	11,780	285,047
2028	10,748	28.93	310,983	33,491	0.40	13,406	324,389
2029	11,521	30.72	353,906	35,900	0.42	15,256	369,162
2030	12,350	32.61	402,752	38,483	0.45	17,362	420,114
2031	13,238	34.62	458,340	41,251	0.48	19,758	478,098

2) Incinerator maintenance cost

Incinerator maintenance cost is the cost of maintaining and repairing the equipment at the incineration plant. According to a study on waste incineration enterprise information system (Anon, 2011), the annual cost of maintenance is approximately 3% of capital investment on the equipment. Therefore 3% is applied to the incinerator technology and equipment acquisition cost (€71.7Mil from Table 3) to calculate the yearly maintenance cost (see Table 5): €2,146,000 per annum.

Table 5. Incinerator maintenance cost

Year	Maintenance Cost(€)
2012	2,146,000
2013	2,146,000
2014	2,146,000
2015	2,146,000
2016	2,146,000
2017	2,146,000
2018	2,146,000
2019	2,146,000
2020	2,146,000
2021	2,146,000
2022	2,146,000
2023	2,146,000
2024	2,146,000
2025	2,146,000
2026	2,146,000
2027	2,146,000
2028	2,146,000
2029	2,146,000
2030	2,146,000
2031	2,146,000

3) Incinerator operational cost

The yearly operational cost of the incineration plant includes utility costs (water, electricity, gas), human resource costs, cost of chemical materials needed for air pollution control, cost of auxiliary fuel when needed, cost of materials for amenity and office maintenance, and other administrative costs, excluding equipment maintenance cost. An average cost equivalent to €13.9/ton of admitted waste is calculated as an average value based on the data available in a recent feasibility study of a waste incinerator investment in the city of Baoji (Anon, 2004?) and the study on waste incineration enterprise information system (Anon, 2011). The operational cost every year is calculated as:

$$C_o = Q_{wi} * P_o$$

where C_o is the operational cost, Q_{wi} the waste input into the incinerator, and P_o the unit cost of operation. Table 6 below lists the operational cost every year.

Table 6. Incinerator operational cost

Year	Physical quantity(t)	Price per unit(€)	Operational cost (€)
2012	80,823	13.9	1,122,277
2013	86,637	13.9	1,203,000
2014	92,868	13.9	1,289,529
2015	99,548	13.9	1,382,283
2016	106,709	13.9	1,481,707
2017	114,384	13.9	1,588,283
2018	122,611	13.9	1,702,525
2019	131,430	13.9	1,824,984
2020	140,884	13.9	1,956,251
2021	151,017	13.9	2,096,959
2022	161,880	13.9	2,247,789
2023	173,523	13.9	2,409,468
2024	186,004	13.9	2,582,775
2025	199,383	13.9	2,768,549
2026	213,725	13.9	2,967,684
2027	229,097	13.9	3,181,143
2028	245,576	13.9	3,409,956
2029	263,239	13.9	3,655,227
2030	282,174	13.9	3,918,139
2031	302,470	13.9	4,199,962

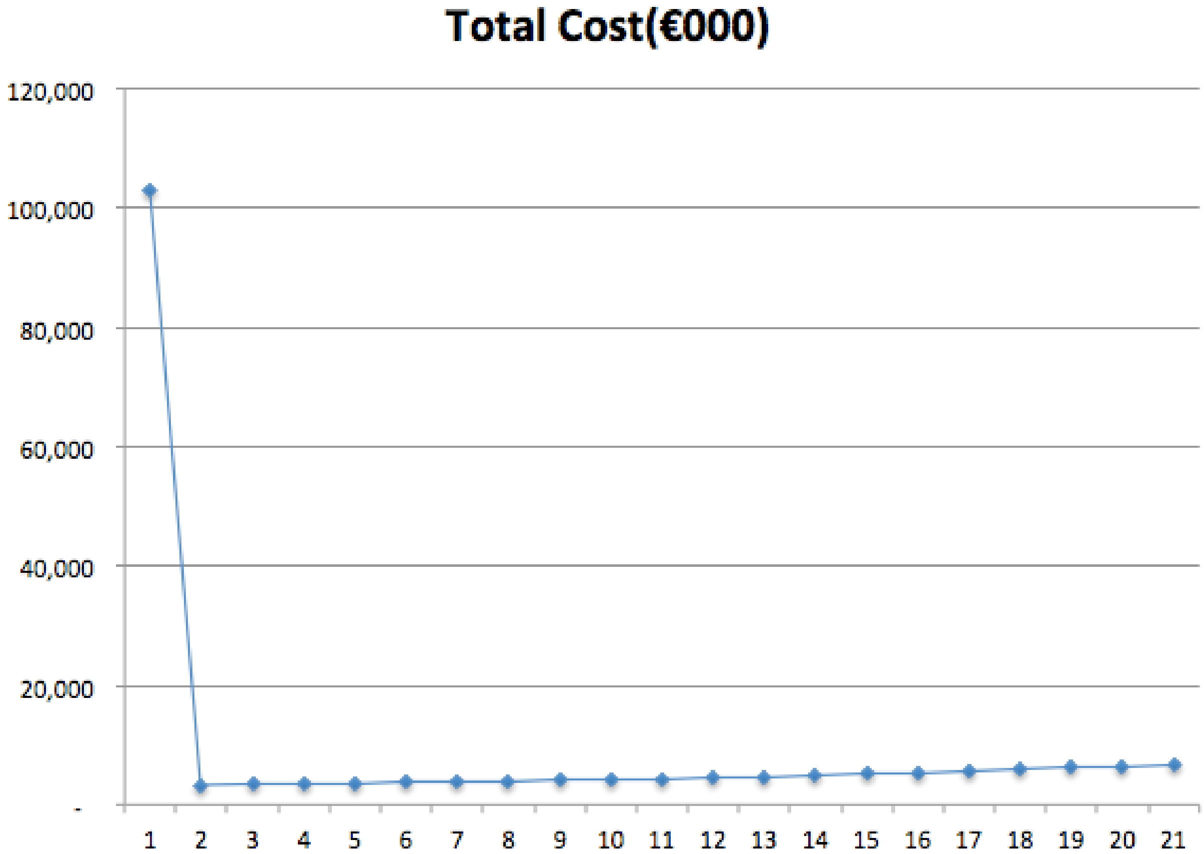
4.2.3. Summary of Costs

Table 7 below gives an overview of cost parameters during the 21-year project period at nominal value. Figure 24 shows that the initial investment cost is very high, while from the year of operation on annual costs rise steadily because of the increase in waste volume. To even out cash flow, financing is needed. The financing cost, namely the borrowing cost, assumed to be the averaged bank-lending rate, which is used as the discount rate, affects the result of the cost-benefit analysis by influencing the present value of future cash flows. The higher the borrowing cost, the lower is the present value of future cash flows.

Table 7. Summary of costs

Year	Incinerator land acquisition (€)	Incinerator equipment and technology acquisition(€)	Incinerator construction and installation cost(€)	Increased collection cost from source to landfill(€)	Incinerator operational cost(€)	Incinerator maintenance cost(€)	Total Cost(€)
2011	1,230,000	71,700,000	30,100,000	0	0	0	103,030,000
2012	0	0	0	40,988	1,122,277	2,146,000	3,309,266
2013	0	0	0	46,646	1,203,000	2,146,000	3,395,646
2014	0	0	0	53,084	1,289,529	2,146,000	3,488,613
2015	0	0	0	60,411	1,382,283	2,146,000	3,588,693
2016	0	0	0	68,748	1,481,707	2,146,000	3,696,456
2017	0	0	0	78,237	1,588,283	2,146,000	3,812,520
2018	0	0	0	89,036	1,702,525	2,146,000	3,937,560
2019	0	0	0	101,324	1,824,984	2,146,000	4,072,308
2020	0	0	0	115,309	1,956,251	2,146,000	4,217,560
2021	0	0	0	131,224	2,096,959	2,146,000	4,374,184
2022	0	0	0	149,336	2,247,789	2,146,000	4,543,125
2023	0	0	0	169,948	2,409,468	2,146,000	4,725,415
2024	0	0	0	193,404	2,582,775	2,146,000	4,922,179
2025	0	0	0	220,098	2,768,549	2,146,000	5,134,646
2026	0	0	0	250,476	2,967,684	2,146,000	5,364,160
2027	0	0	0	285,047	3,181,143	2,146,000	5,612,190
2028	0	0	0	324,389	3,409,956	2,146,000	5,880,345
2029	0	0	0	369,162	3,655,227	2,146,000	6,170,388
2030	0	0	0	420,114	3,918,139	2,146,000	6,484,253
2031	0	0	0	478,098	4,199,962	2,146,000	6,824,060

Figure 24. Trend of cost



4.3. Benefits

4.3.1. Fixed Benefits

One impact parameter is identified as a fixed benefit: the saved cost of acquiring and constructing additional landfill area. In the baseline Scenario, the current landfill will reach its capacity in the year 2025, by then a new landfill area needs to be acquired and a new landfill constructed; while Scenario II will sustain the current landfill until the end of the 21-year project. It is assumed that the new landfill to be constructed will have the same capacity and technical requirement as the current landfill, hence the cost of the current landfill is applied, equivalent to €5,680,000 (SCEMC, 2011). This is the present value of the cost. To present the value of the cost in the year 2024, which is when the construction actually should take place, the future value of the cost is calculated as:

$$FV_l = PV_1 * (1+i)^{(2024-2011)}$$

where FV_1 is the future value of the cost of acquiring and constructing a new landfill, PV_1 the present value of the cost of acquiring and constructing a new landfill, i the discount rate, and (2024-2011) the number of years to account for.

The future value is needed to show the correct year when the cost occurs, even though at the end it will be discounted back to present value to obtain the NPV of the scenario. Table 8 shows the cost of acquiring and constructing a new landfill in 2024:

Table 8. Saved cost of acquiring and constructing additional landfill area

Year	Fixed Benefit	Saved cost (€)
2024	Saved cost of acquiring and constructing additional landfill area	13,252,365

4.3.2. Variable Benefits

1). Saved cost on source separation and separate collection of metals

Source separation and separate collection is costly. According to a study on the cost of source separation of household waste in China (Zhuang et al., 2008), it costs an equivalent of €10.7 per ton of waste materials for source separation. Applying this unit cost to the quantity of metals that otherwise would have been recovered by separate collection in the baseline scenario, the saved cost on source separation and separate collection of metals every year is calculated (Table 9).

Table 9. Saved cost on source separation and separate collection of metals

Year	Physical quantity(t)	Cost per unit (€/t)	Saved cost on separation(€)
2012	3,581	10.7	38,328
2013	3,838	10.7	41,085
2014	4,114	10.7	44,040
2015	4,410	10.7	47,208
2016	4,727	10.7	50,604
2017	5,067	10.7	54,243
2018	5,432	10.7	58,145
2019	5,823	10.7	62,327
2020	6,241	10.7	66,810
2021	6,690	10.7	71,616
2022	7,171	10.7	76,767
2023	7,687	10.7	82,289
2024	8,240	10.7	88,207
2025	8,833	10.7	94,552
2026	9,468	10.7	101,353
2027	10,149	10.7	108,643
2028	10,879	10.7	116,458
2029	11,662	10.7	124,834
2030	12,501	10.7	133,813
2031	13,400	10.7	143,438

2). Saved cost on landfilling

Incineration reduces the mass and the volume of waste significantly. When comparing the amount of waste sent to the landfill, shown by the MFA, the amount in Scenario II is merely 14%[26] of that in Scenario I. The reduced amount to be admitted by the landfill means a reduced landfill treatment fee (the tipping fee). The current tipping fee of the landfill is equivalent to €11.4/ton. Applying this tipping fee to the quantity of waste reduced going to the landfill, the saved cost is calculated for every year (Table 10).

Table 10. Saved cost on landfilling

Year	Physical quantity(t)	Cost per unit(€/t)	Saved cost on landfilling(€)
2012	66,263	11.4	752,812
2013	71,030	11.4	806,960
2014	76,139	11.4	865,003
2015	81,615	11.4	927,221
2016	87,485	11.4	993,914
2017	93,778	11.4	1,065,404
2018	100,523	11.4	1,142,036
2019	107,754	11.4	1,224,180
2020	115,504	11.4	1,312,233
2021	123,812	11.4	1,406,619
2022	132,718	11.4	1,507,794
2023	142,264	11.4	1,616,246
2024	152,497	11.4	1,732,499
2025	163,465	11.4	1,857,114
2026	175,223	11.4	1,990,692
2027	187,826	11.4	2,133,878
2028	201,336	11.4	2,287,363
2029	215,818	11.4	2,451,888
2030	231,341	11.4	2,628,247
2031	247,981	11.4	2,817,291

[26] 14% = 10,283 /72,100, see Figure 15 and Figure 19.

3). Revenue from incinerator tipping fee

Assuming the tipping fee of the incinerator to be the same as that of the current landfill, the revenue from incinerator tipping fee is then calculated by applying the tipping fee to the quantity of waste that is admitted into the waste incinerator. Table 11 lists the revenue from incinerator tipping fee every year.

Table 11. Revenue from incinerator tipping fee

Year	Physical quantity(t)	Price per unit(€/t)	Revenue from incinerator tipping fee(€)
2012	80,823	11.4	918,227
2013	86,637	11.4	984,273
2014	92,868	11.4	1,055,070
2015	99,548	11.4	1,130,958
2016	106,709	11.4	1,212,306
2017	114,384	11.4	1,299,504
2018	122,611	11.4	1,392,975
2019	131,430	11.4	1,493,168
2020	140,884	11.4	1,600,569
2021	151,017	11.4	1,715,694
2022	161,880	11.4	1,839,100
2023	173,523	11.4	1,971,383
2024	186,004	11.4	2,113,180
2025	199,383	11.4	2,265,176
2026	213,725	11.4	2,428,105
2027	229,097	11.4	2,602,754
2028	245,576	11.4	2,789,964
2029	263,239	11.4	2,990,640
2030	282,174	11.4	3,205,750
2031	302,470	11.4	3,436,333

4). Revenue from electricity sale

Electricity sale from waste incinerators is strictly regulated by the Chinese government. The amended regulation on waste to energy projects (National Development and Reform Commission, 2012) mandates the price of electricity sold from waste incinerators to be 0.65 yuan per kilowatt-hour, equivalent to €0.08/kwh (Article 1). Article 1 also mandates 280 kwh of electricity transmission to the power grid per ton of waste incinerated for the baseline calculation of total electricity transmitted by an incineration plant. Article 3.2 states that, when the total baseline transmission is lower than 50% of the actual total transmission, the electricity is regarded as conventional electricity that does not fall under this regulation; when the baseline transmission is higher than 50% of the actual total transmission but lower than the actual total transmission, the baseline calculation applies for receiving the revenue; and when the total baseline transmission is lower than the actual total transmission, the actual amount is applied for receiving the revenue. The municipal solid waste in Guanghan has a low heat value of 1,291 kcal/kg, which according to a statistical study on incinerators operating during 2006-2010 in China (Anon, 2012?) will be able to transmit approximately 200 kwh of electricity to the grid per ton of waste incinerated. Since this level of transmission falls under the third situation in Article 3.2, the actual total transmission is used for calculating the revenue. In addition, it is assumed that the heating value of the waste will increase by 3% per annum. If the energy capacity of the incineration plant is assumed to be planned at the level of full capacity in 21 years, the 3% increase per annum could be reasonably applied to the quantity of electricity transmitted as well. Thus the calculation of the revenue from the electricity sale is:

$$R_e = Q_{wi} * 200kwh/t *(100\%+3\%)^\wedge(t_n - t_1) * P_e$$

Where R_e is the revenue from the electricity produced at the incinerator, Q_{wi} the waste input into the incinerator, t_n any referred year, t_1 the first year of the project (2011), and P_e the price of electricity sold by the waste incinerator. Table 12 lists the revenue flow from electricity sale every year.

Table 12. Revenue from electricity sale

Year	Quantity of waste incinerated(t)	Quantity of electricity transmitted (kwh)	Price per unit(€/kwh)	Revenue from electricity sale(€)
2012	80,823	16,649,611	0.08	1,366,118
2013	86,637	18,382,597	0.08	1,508,311
2014	92,868	20,295,961	0.08	1,665,304
2015	99,548	22,408,479	0.08	1,838,639
2016	106,709	24,740,880	0.08	2,030,015
2017	114,384	27,316,050	0.08	2,241,310
2018	122,611	30,159,259	0.08	2,474,598
2019	131,430	33,298,404	0.08	2,732,168
2020	140,884	36,764,290	0.08	3,016,548
2021	151,017	40,590,924	0.08	3,330,527
2022	161,880	44,815,856	0.08	3,677,187
2023	173,523	49,480,543	0.08	4,059,929
2024	186,004	54,630,757	0.08	4,482,510
2025	199,383	60,317,034	0.08	4,949,074
2026	213,725	66,595,171	0.08	5,464,202
2027	229,097	73,526,772	0.08	6,032,947
2028	245,576	81,179,853	0.08	6,660,890
2029	263,239	89,629,509	0.08	7,354,193
2030	282,174	98,958,654	0.08	8,119,659
2031	302,470	109,258,828	0.08	8,964,799

5). Revenue from the sale of recovered aluminium from the incinerator

From the MFA of Scenario II on the element level, the quantity of aluminium recovered from the bottom ash is obtained, 846t for the year 2011. The waste generation growth rate of 7.19% per annum is applied as the growth rate of the recovered amount of metals to calculate the quantity of aluminium recovered every year. The current price of scrap aluminium in the province of Sichuan is approximately 12,400 yuan per ton (China Waste Products, 2012), equivalent to €1,570/ton. Though metal prices are usually volatile, the trend from the past 20 years can be observed and used as a base for future price prediction. The revenue every year is then calculated by multiplying the price with the quantity, adjusted for an annual price increase of 1.12%[27] (Trading Economics, 2012) during the lifespan of the incinerator, shown in Table 13.

Table 13. Revenue from the sale of recovered aluminium from the incinerator

Year	Physical quantity(t)	Price per unit(€/t)	Revenue from Al (€)
2012	907	1,570	1,424,669
2013	973	1,588	1,544,276
2014	1,042	1,606	1,673,925
2015	1,117	1,624	1,814,459
2016	1,198	1,642	1,966,791
2017	1,284	1,660	2,131,911
2018	1,376	1,679	2,310,895
2019	1,475	1,698	2,504,905
2020	1,581	1,717	2,715,203
2021	1,695	1,736	2,943,156
2022	1,817	1,756	3,190,247
2023	1,948	1,775	3,458,083
2024	2,088	1,795	3,748,404
2025	2,238	1,815	4,063,099
2026	2,399	1,836	4,404,215
2027	2,572	1,856	4,773,968
2028	2,757	1,877	5,174,764
2029	2,955	1,898	5,609,209
2030	3,167	1,920	6,080,127
2031	3,395	1,941	6,590,580

27 1.12% = (2000/1600)^(1/20) – 1. 2000USD/LB was the price at the end of 2011, 1600USD/LB was the price at the end of 1991.

6). Revenue from the sale of recovered copper from the incinerator

From the MFA of Scenario II on the element level, the quantity of copper recovered from the bottom ash is obtained, 107t for the year 2011. The waste generation growth rate of 7.19% per annum is applied as the growth rate of the recovered amount of metals to calculate the quantity of copper recovered every year. The current price of scrap copper in the city of Chengdu (the capital city of the province of Sichuan) is approximately 46,100 yuan per ton (China Waste Products, 2012), equivalent to €5,820/ton. The trend of the last 20 years shows an annual increase in the price of copper of 5.65%[28] (Trading Economics, 2012). The revenue every year is then calculated by multiplying the price with the quantity, adjusted for the annual price increase, shown in Table 14.

Table 14. Revenue from the sale of recovered copper from the incinerator

Year	Physical quantity(t)	Price per unit(€/t)	Revenue from Cu(€)
2012	115	5,820	669,706
2013	123	6,149	758,413
2014	132	6,496	858,869
2015	142	6,863	972,632
2016	152	7,251	1,101,464
2017	163	7,660	1,247,360
2018	175	8,092	1,412,582
2019	187	8,549	1,599,687
2020	201	9,032	1,811,577
2021	215	9,542	2,051,532
2022	230	10,081	2,323,271
2023	247	10,650	2,631,004
2024	265	11,252	2,979,498
2025	284	11,887	3,374,153
2026	304	12,558	3,821,082
2027	326	13,267	4,327,209
2028	350	14,017	4,900,377
2029	375	14,808	5,549,465
2030	402	15,644	6,284,529
2031	431	16,528	7,116,956

[28] 5.65% = (330/110)^(1/20) -1. 330 USD/LB was the price at the end of 2011, 110USD/LB was the price at the end of 1991.

7). Revenue from the sale of recovered iron from the incinerator

From the MFA of Scenario II on the element level, the quantity of iron recovered from the bottom ash is obtained, 2,620t for the year 2011. The waste generation growth rate of 7.19% per annum is applied as the growth rate of the recovered amount of metals to calculate the quantity of iron recovered every year. The current price of scrap iron in the province of Sichuan is approximately 1,820 yuan per ton (China Waste Products, 2012), equivalent to €230/ton. The trend of the last 20 years shows an annual price increase of iron of 5.66%[29] (U.S. Geological Survey, 2011). The revenue every year is then calculated by multiplying the price with the quantity, adjusted for the annual price increase, shown in Table 15.

Table 15. Revenue from the sale of recovered iron from the incinerator

Year	Physical quantity(t)	Price per unit(€/t)	Revenue from Fe(€)
2012	2,809	230	645,286
2013	3,011	243	730,873
2014	3,227	257	827,812
2015	3,459	271	937,609
2016	3,708	286	1,061,968
2017	3,975	303	1,202,822
2018	4,261	320	1,362,357
2019	4,567	338	1,543,053
2020	4,896	357	1,747,715
2021	5,248	377	1,979,522
2022	5,626	399	2,242,075
2023	6,030	421	2,539,452
2024	6,464	445	2,876,270
2025	6,929	470	3,257,763
2026	7,427	497	3,689,855
2027	7,961	525	4,179,257
2028	8,534	555	4,733,570
2029	9,148	586	5,361,405
2030	9,806	619	6,072,512
2031	10,511	654	6,877,936

29 5.66% = (319/106)^(1/20) -1. 319USD/t was the average price of scrap iron in 2010, 106USD/t was the average price of scrap iron in 1990.

4.3.3. Summary of Benefits

Table 16 below gives an overview of benefit parameters during the 21-year period at nominal value. Figure 25 shows that from year 2 of the project, which is the year when operation starts, benefits flow in steadily throughout the entire project because of the steady increase of waste generated leading to an increasing amount of the revenue source, except for the 14th year (2024). In 2024, the benefits rise steeply because of the saving of the cost of constructing the landfill that would otherwise have been required under the baseline scenario.

Table 16. Summary of benefits (part 1)

Year	Saved cost of acquiring and constructing additional landfill area(€)	Saved cost on source separation and separate collection of metals(€)	Saved cost on landfilling(€)
2011	0	0	0
2012	0	38,328	752,812
2013	0	41,085	806,960
2014	0	44,040	865,003
2015	0	47,208	927,221
2016	0	50,604	993,914
2017	0	54,243	1,065,404
2018	0	58,145	1,142,036
2019	0	62,327	1,224,180
2020	0	66,810	1,312,233
2021	0	71,616	1,406,619
2022	0	76,767	1,507,794
2023	0	82,289	1,616,246
2024	13,252,365	88,207	1,732,499
2025	0	94,552	1,857,114
2026	0	101,353	1,990,692
2027	0	108,643	2,133,878
2028	0	116,458	2,287,363
2029	0	124,834	2,451,888
2030	0	133,813	2,628,247
2031	0	143,438	2,817,291

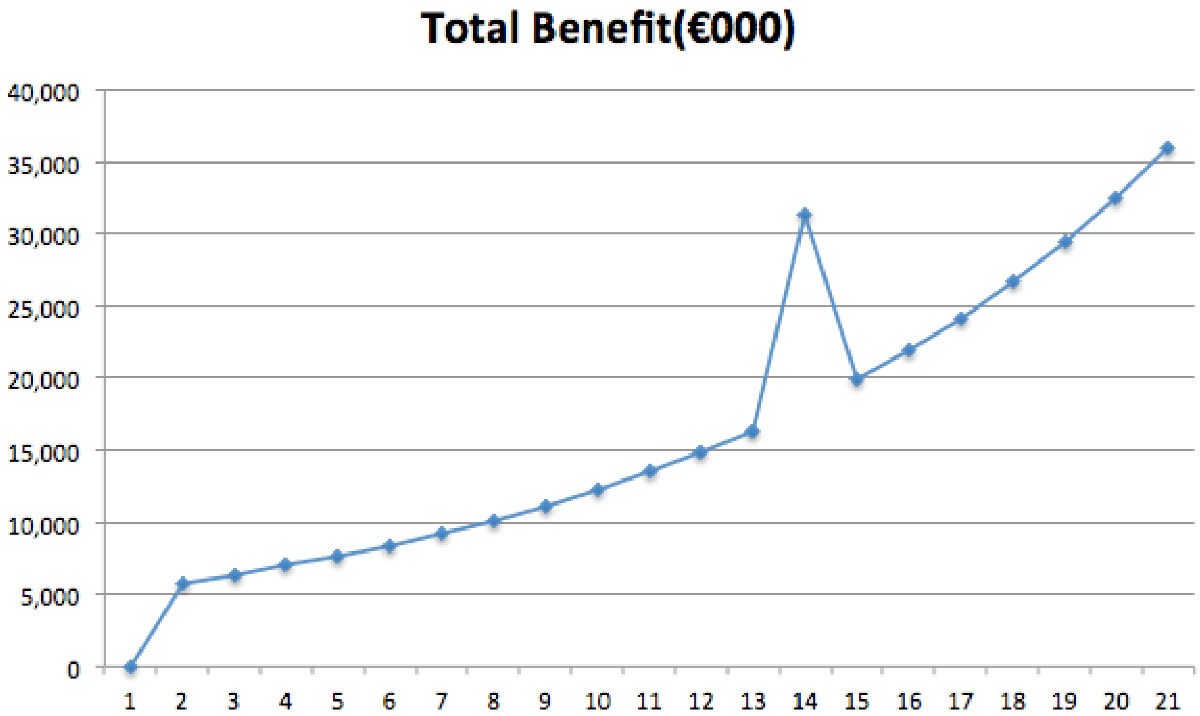
Table 16. Summary of benefits (part 2)

Year	Revenue from tipping fee(€)	Revenue from electricity sale(€)	Revenue from sale of recovered Al from incinerator(€)
2011	0	0	0
2012	918,227	1,366,118	1,424,669
2013	984,273	1,508,311	1,544,276
2014	1,055,070	1,665,304	1,673,925
2015	1,130,958	1,838,639	1,814,459
2016	1,212,306	2,030,015	1,966,791
2017	1,299,504	2,241,310	2,131,911
2018	1,392,975	2,474,598	2,310,895
2019	1,493,168	2,732,168	2,504,905
2020	1,600,569	3,016,548	2,715,203
2021	1,715,694	3,330,527	2,943,156
2022	1,839,100	3,677,187	3,190,247
2023	1,971,383	4,059,929	3,458,083
2024	2,113,180	4,482,510	3,748,404
2025	2,265,176	4,949,074	4,063,099
2026	2,428,105	5,464,202	4,404,215
2027	2,602,754	6,032,947	4,773,968
2028	2,789,964	6,660,890	5,174,764
2029	2,990,640	7,354,193	5,609,209
2030	3,205,750	8,119,659	6,080,127
2031	3,436,333	8,964,799	6,590,580

Table 16. Summary of benefits (part 3)

Year	Revenue from sale of recovered Cu from incinerator(€)	Revenue from sale of recovered Fe from incinerator(€)	Total Benefit(€)
2011	0	0	-
2012	669,706	645,286	5,815,146
2013	758,413	730,873	6,374,192
2014	858,869	827,812	6,990,024
2015	972,632	937,609	7,668,726
2016	1,101,464	1,061,968	8,417,061
2017	1,247,360	1,202,822	9,242,555
2018	1,412,582	1,362,357	10,153,588
2019	1,599,687	1,543,053	11,159,489
2020	1,811,577	1,747,715	12,270,654
2021	2,051,532	1,979,522	13,498,666
2022	2,323,271	2,242,075	14,856,441
2023	2,631,004	2,539,452	16,358,385
2024	2,979,498	2,876,270	31,272,934
2025	3,374,153	3,257,763	19,860,932
2026	3,821,082	3,689,855	21,899,503
2027	4,327,209	4,179,257	24,158,656
2028	4,900,377	4,733,570	26,663,386
2029	5,549,465	5,361,405	29,441,634
2030	6,284,529	6,072,512	32,524,636
2031	7,116,956	6,877,936	35,947,334

Figure 25. Trend of benefits



4.4. Cost-benefit Analysis Result and Sensitivity Analysis

Result

In order to calculate the NPV, the difference between the sum of discounted benefits and the sum of discounted costs, the present value of each year's costs and benefits is at first calculated then summed up for comparison:

$$NPV = \Sigma B_t(1+i)^{-t} - \Sigma C_t(1+i)^{-t}$$

Where B denotes benefit, C denotes cost, i the discount rate, and the summation runs from t=0 (the first year of the project: 2011) to t=T (the last year of the project: 2031). A five-year averaged bank-lending rate of 6.73% is used as the discount rate.

Table 17 shows the present value of each year's total costs and the present value of each year's total benefits, and at the end the NPV as the difference between the total present value of total benefits and the total present value of total costs. An alternative way of calculating the NPV is to sum up the total present value of each impact parameter, as presented in Table 18. The impact of each parameter's total present value is then clearly shown in Figure 26: the cost of equipment and technology is the parameter most influential on the final result, followed by revenue from electricity sale, revenue from the sale of aluminium and the construction cost of the incinerator.

The resulting NPV is a positive €2.3 million, meaning the proposed Scenario II is more efficient in its allocation of resources in comparison to the baseline scenario within the waste management system of Guanghan. Such a positive result shows that waste incineration is worth being taken into consideration by the municipal government of Guanghan when planning its municipal solid waste management in the coming decade.

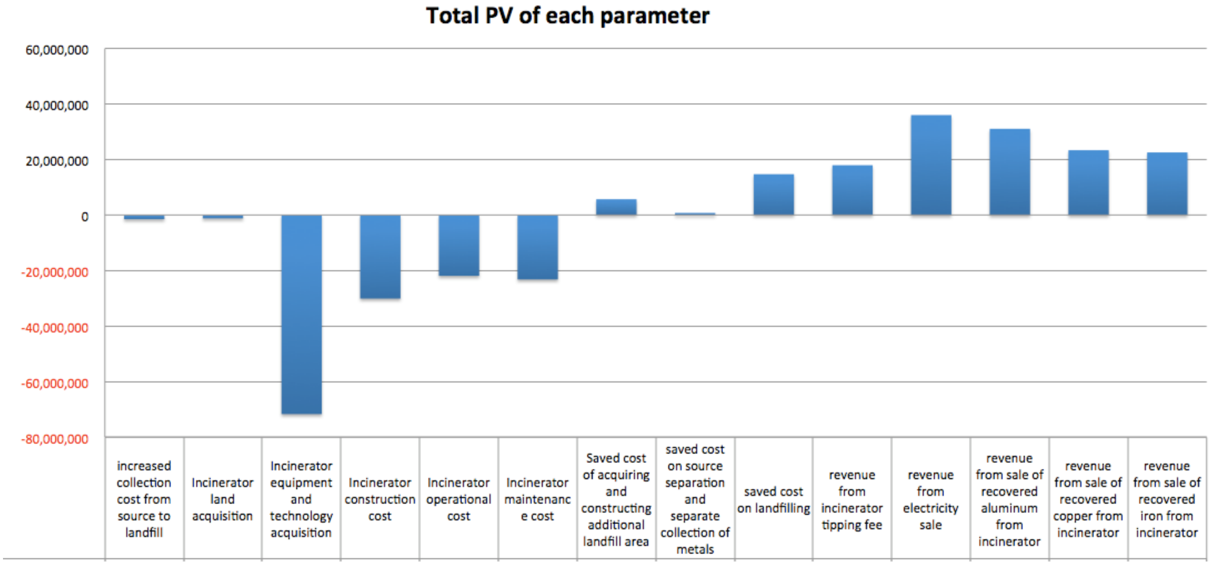
Table 17. Result of the cost-benefit analysis

Year	Total Cost	PV of toal cost	Total Benefit	PV of total benefit	NPV
2011	103,030,000	103,030,000	0	0	-103,030,000
2012	3,309,266	3,100,475	5,815,146	5,448,252	2,347,777
2013	3,395,646	2,980,681	6,374,192	5,595,233	2,614,552
2014	3,488,613	2,869,079	6,990,024	5,748,682	2,879,604
2015	3,588,693	2,765,174	7,668,726	5,908,937	3,143,763
2016	3,696,456	2,668,506	8,417,061	6,076,355	3,407,849
2017	3,812,520	2,578,644	9,242,555	6,251,313	3,672,669
2018	3,937,560	2,495,186	10,153,588	6,434,211	3,939,024
2019	4,072,308	2,417,758	11,159,489	6,625,469	4,207,710
2020	4,217,560	2,346,011	12,270,654	6,825,532	4,479,521
2021	4,374,184	2,279,620	13,498,666	7,034,872	4,755,253
2022	4,543,125	2,218,281	14,856,441	7,253,986	5,035,705
2023	4,725,415	2,161,715	16,358,385	7,483,398	5,321,683
2024	4,922,179	2,109,660	31,272,934	13,403,666	11,294,006
2025	5,134,646	2,061,874	19,860,932	7,975,375	5,913,502
2026	5,364,160	2,018,133	21,899,503	8,239,148	6,221,015
2027	5,612,190	1,978,231	24,158,656	8,515,641	6,537,410
2028	5,880,345	1,941,976	26,663,386	8,805,549	6,863,572
2029	6,170,388	1,909,194	29,441,634	9,109,605	7,200,411
2030	6,484,253	1,879,724	32,524,636	9,428,588	7,548,863
2031	6,824,060	1,853,419	35,947,334	9,763,317	7,909,899
Total		**149,663,340**		**151,927,130**	**2,263,789**

Table 18. Total present value of each impact parameter

Impact Parameters	Total PV of each parameter
increased collection cost from source to landfill	-1,510,845
Incinerator land acquisition	-1,230,000
Incinerator equipment and technology acquisition	-71,700,000
Incinerator construction cost	-30,100,000
Incinerator operational cost	-21,910,341
Incinerator maintenance cost	-23,212,153
Saved cost of acquiring and constructing additional landfill area	5,680,000
saved cost on source separation and separate collection of metals	748,286
saved cost on landfilling	14,697,232
revenue from incinerator tipping fee	17,926,643
revenue from electricity sale	35,983,031
revenue from sale of recovered aluminum from incinerator	31,037,260
revenue from sale of recovered copper from incinerator	23,332,541
revenue from sale of recovered iron from incinerator	22,522,136
NPV	**2,263,789**

Figure 26. Comparison of total PV of each impact parameter



Sensitivity Analysis

The NPV result is calculated based on various input parameters, some of which are estimated, and some of which are predicted in the case of future values. Changes in these input parameters will inevitably alter the NPV result. The reason why they should change is because of uncertainty in the estimated and predicted data. In order to find out to which input parameters the NPV result is most sensitive to, sensitivity analysis is conducted, by recalculating NPV when certain key input parameters change. The key input parameters identified for the sensitivity analysis are the following independent variables:

P1: discount rate

P2: waste generation growth rate

P3: incinerator equipment and technology acquisition cost

P4: incinerator construction and installation cost

P5: operational cost per unit of waste incinerated

P6: percentage of maintenance cost per annum per incinerator equipment and technology acquisition cost

P7: saved cost on acquiring and constructing additional landfill area

P8: quantity of electricity transmitted to the grid per ton of waste incinerated

P9: price per kwh of electricity uploaded to the grid from the incinerator

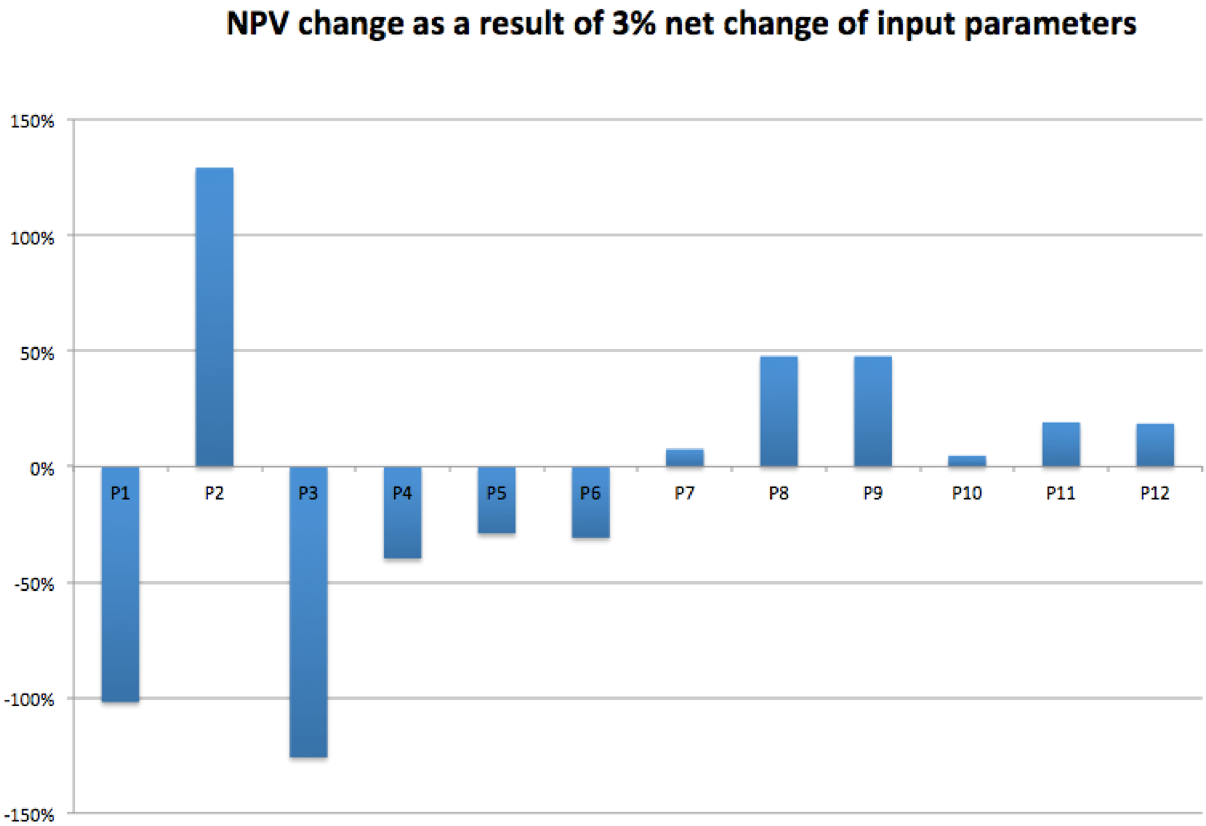
P10: rate of price increase of aluminium

P11: rate of price increase of copper

P12: rate of price increase of iron

By applying a 3% increase in each of the key input parameters one at a time, the percentage change of the NPV is observed for each of the 3% increases per input parameter, holding other input parameters constant. As shown in Figure 27, the NPV result is most sensitive to a change in P2: waste generation growth rate; secondly to P3: incinerator equipment and technology acquisition cost; and thirdly to P3: discount rate; followed by P8: quantity of electricity transmitted to the grid per ton of waste incinerated, and P9: price per kwh of electricity uploaded to the grid from the incinerator. As evidenced in reality, the capital cost of incineration plant, i.e. the equipment and construction costs, are critical to the economic feasibility of such project. In addition, the discount rate is usually an influential parameter for the NPV, and a 3% increase will already bring the NPV to negative. Finally, the project lifespan is positively correlated to the NPV. To be specific, the NPV starts to become positive only in the last year 2031. In China, a license is usually given to waste incineration projects for 25 years, in which case the NPV would be even higher than the current result.

Figure 27. Sensitivity analysis graph



P1: discount rate

P2: waste generation growth rate

P3: incinerator equipment and technology acquisition cost

P4: incinerator construction and installation cost

P5: operational cost per unit of waste incinerated

P6: percentage of maintenance cost per annum per incinerator equipment and technology acquisition cost

P7: saved cost on acquiring and constructing additional landfill area

P8: quantity of electricity transmitted to the grid per ton of waste incinerated

P9: price per kwh of electricity uploaded to the grid from the incinerator

P10: rate of price increase of aluminium

P11: rate of price increase of copper

P12: rate of price increase of iron

The result of the sensitivity analysis means that when considering the proposed scenario, the municipal government should look into the input parameters that the NPV is most sensitive to, namely the waste generation growth rate and the equipment cost, so that more efforts are made to improve the accuracy of the input parameters when conducting a feasibility study and to manage the risk associated with these parameters carefully during project implementation, although many of them are out of the control of the decision-maker.

Part V. Other Considerations Out of the Scope of the Cost-Benefit Analysis

The social and environmental costs and benefits that arise in Scenario II mainly lie in the difference in the impact between landfilling and incineration. In addition to the general discussion on landfilling and incineration, a specific focus is put on the social impacts brought by Scenario II in comparison with Scenario I. First of all, the existence of an incinerator as an additional process in the system boundary of the waste flow in the city of Guanghan means an additional demand for labour. Employment opportunity will not only rise because of the demand by the incinerator (estimated to be between 60 to 70 permanent employees), but also because of the demand by the associated services, such as separate collection, logistics design, etc. Secondly, by reducing the amount of landfilled waste, the living environment of the farmers downstream of the landfill will improve; additionally, as the farmland becomes less vulnerable to accidents from the landfill, healthy crops and fewer health risks will follow. Since the landfill will only bury treated residual bottom ash, the problem of disease contagion and bad smell will disappear.

On the other hand, since metals are not separated at source and no separate collection of them is needed, the metal collectors will not easily accept the fact that their business is taken away and taken over by the incineration plant. To solve this issue, employment as well as a partnership opportunity could be offered in a way that the benefit of recovering metals at the incinerator is fairly shared. The biggest issue in fact lies in the pollution control of the incineration plant. In China, as the number of waste incinerators rises, the civil environmental movement is also progressing to the extent that community opposition to a few waste incineration proposals has pressured local governments to halt these projects. For new waste incineration projects to proceed, the general public needs on one hand objective environmental education and on the other hand certainty over emission control. Current public opposition to incineration is partly due to ill-informed and popular media coverage on the level of toxic emissions from waste incinerators, particularly about dioxins. Some of the information does not reflect the reality of state of the art pollution control technologies. Nevertheless, the concerns of the population should be addressed, best by real-time or close to real-time emission monitoring on site and public display of the results of on-going monitoring.

Social and environmental impacts are not quantified because of the lack of empirical data in this respect for the region under consideration. Moreover, these impacts are strongly influenced by the political and legal environment in China, entailing high uncertainty. A cooperative effort with the local and regional government is essential in carrying out the quantification and the valuation of social and environmental impacts.

Part VI. Conclusion

Waste incineration is a common waste treatment method in large parts of Europe, where the municipal solid waste system is integrated to a high extent, while in China waste incineration is still in its infant stage of development: an average 22% of the waste in EU countries is incinerated, compared to 13% in China. Incineration reduces the waste mass and volume by 70% and 90% respectively; it also reduces the chemical reactivity of waste to a large extent, reducing the burden on landfills significantly. In addition, incineration utilises the energy in the waste, turning it into useful heat and electricity during the incineration process. Recovery of iron also commonly takes place at waste incinerators. Despite these advantages, China still relies primarily on landfilling to treat municipal solid waste. The main reason lies in the economic factor: investment and operational costs of waste incineration plants is high, as a new incinerator needs capital investment exceeding 100 million euros. Such a high cost can not be compensated by revenue from energy recovery.

A break-through technology was developed by ZAR in Switzerland, Development Centre for Sustainable Management of Recyclable Waste and Resources of the Canton of Zurich, which runs its operation in the incineration plant KEZO in Hinwil and which is proven to be consistently successful. This technology incorporates dry bottom ash discharge from the combustion furnace, separation of bottom ash into different size fractions, magnetic devices and eddy current method with smart engineering design, in order to recover precious metals from the bottom ash, namely aluminium, copper and iron. With soaring metal prices, this technology sheds new light on investing in waste incineration plants for low-income countries.

In order to find out if this technology provides sufficient economic benefits, a cost-benefit analysis was conducted, based on the case of a mid-sized Chinese municipality, Guanghan, with a population of 210,000. Material Flow Analysis of the current municipal solid waste system in Guanghan was conducted to identify the flow of waste on the mass level and the metals on the substance level. Then a baseline scenario was assumed for the purpose of the cost benefit analysis, which differs from the current system in that source separation and separate collection from source is in place instead of informal collectors and scavengers collecting recyclables at all spots within the system. The assumption of such a baseline scenario is based on a long-term view that source separation is inevitable in the future. The question with the cost benefit analysis of Scenario II is that whether by not separating the metals at source and instead recovering them from the bottom ash of the incinerator is an economically more efficient way than the baseline scenario.

The result of the cost-benefit analysis, a positive NPV of 2 million Euros, indicates that Scenario II is more efficient in resource allocation than the baseline scenario within the waste management system of Guanghan. The result provides critical information for the decision-makers of the municipal government in assisting them to plan the city's waste management system, particularly in considering whether to incorporate a waste incineration plant with resource recovery technology and advanced air pollution control equipment, and if so, whether metals need to be separated at source. The result means, even if the metal content in the municipal solid waste in Guanghan becomes the same level as that in Switzerland (three times its the current level), the new metal recovery technology would not make the investment, operational and maintenance cost less critical for the economic feasibility of waste incineration investment. In fact, it is still the most critical factor, and must be reduced for the investment to be economically feasible.

A sensitivity analysis identified certain key input parameters, the variation of which the result of the cost-benefit analysis is sensitive to. Among the identified input parameters, the municipal government should look into those input parameters that the NPV is most sensitive to: the waste generation growth rate, the investment cost on equipment and technology and the discount rate, so that more efforts are made to improve the accuracy of these input parameters when conducting a feasibility study and to manage the risk associated with these parameters carefully during project implementation.

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