Fachhochschule
Lippe und Höxter
University of Applied Sciences

Department of
Environmental Engineering
in cooperation with the

CENTRE FOR WATER & WASTE TECHNOLOGY

DIPLOMA THESIS

Development of an LCA-based Waste Management Model and its Application to optimise Sydney's domestic Waste Management

Gregor Büning
Matriculation No. 16046085

Supervisor: Prof. Dr.-Ing. Karl-Heinz Henne
Co-Supervisor: Prof. Dr.-Ing. Hans-Günter Ramke

Höxter, October 2004

“Of course I care about the future.
I intend to spend the rest
of my remaining life in it.”

MARK TWAIN

Acknowledgement

First of all I would like to thank my supervisor Prof. Dr.-Ing. Karl-Heinz Henne for taking the effort to supervise me during my thesis abroad as well as Prof. Dr.-Ing. Hans-Günter Ramke for the co-supervision.

Many special thanks to Dr. Sven Lundie from the Centre for Water and Waste Technology in Sydney, who gave me the chance to work on this topic in his department. He supported my work with lots of good ideas and most valuable discussions and took time even when he did not have time.

I would like to thank Dr. Andreas Sonnenberg, Patric Peters, Emely Piel, Matt Swan, Ginette and Naomi Carrard, Sebastian Massolle, Jörg Rodehutskors and Christian Leipoldt for their great support.

Further, I am very thankful to Darryl Stuckey from the Department of Environment and Conservation, Nathan Lopez and all the waste management and waste education officers who provided information about waste and waste management in Sydney – without your help the results of my study would never be what they are. Keep it up!

Thanks also to my friends in Sydney of which some are already mentioned above, who gave me a great time. They never got tired to answer linguistic questions. See you back in Sydney.

Summary

In this study the environmental performance of different waste management options have been compared. As a method, Life Cycle Assessment (LCA) was chosen.

The different options to be compared were:

Base Case: Landfilling of garbage, material recycling for recyclables and windrow composting for garden waste (current situation)

Option 1: Landfilling for garbage and garden waste, material recycling for recyclables

Option 2: Landfilling for garbage, material recycling for recyclables with low calorific value (metals and glass), energy recycling (combustion) for recyclables with a high calorific value (papers and plastics) and windrow composting for garden waste

Option 3: Combustion of garbage (Waste-to-Energy), material recycling for recyclables and windrow composting for garden waste.

The main function for all options was the disposal of the yearly amount of domestic waste from the Sydney metropolitan area. In LCA, this amount is called Functional Unit (FU). The FU consists of 1,362,957 tonnes of waste per annum. This includes 884,873 tonnes of garbage, 334,830 tonnes of recyclables (including contamination) and 143,254 of separately collected garden waste.

Several impact categories have been chosen to be evaluated for each option:

- Total energy
- Climate change
- Eutrophication potential (EP)
- Photochemical oxidant formation potential (POCP)
- Human toxicity potential Australia (HTPAU)
- Freshwater aquatic ecotoxicity potential Australia (FAEP)
- Marine aquatic ecotoxicity potential Australia (MAEP) and
- Terrestrial ecotoxicity potential Australia (TEP).

While total energy is a non-environmental impact category measuring the energy intensity of a system all other impact categories are purely environmental. For calculating the results a waste management model was developed within the LCA-Software GaBi 4.

The ranking of options is shown in Table 1 for every impact category. If differences are too small to give recommendations the rankings are the same.

Table 1 Ranking for all options and all impact categories

	Total energy	Climate change	EP	POCP	HTPAU	FAEP	MAEP	TEP
Base Case	2	2	2	2	2	1	2	2
Option 1	2	3	3	3	2	1	2	2
Option 2	4	3	4	4	4	4	4	4
Option 3	1	1	1	1	1	1	1	1

Table 2 shows the differences in %, compared with the current situation, the Base Case. This is equal 0%. A negative result means savings for the impact category, while a positive result means a higher contribution than in the current situation.

Table 2 Comparison of each option to base case [%]

	Base Case	Option 1	Option 2	Option 3
Total energy	0	-3	65	-55
Climate change	0	7	8	-281
EP	0	-6	144	-356
POCP	0	9	30	-262
HTPAU	0	-3	69	-76
FAEP	0	-3	48	1
MAEP	0	-4	43	-92
TEP	0	-4	50	-65

It can be concluded that a combination of material recycling and waste-to-energy as it happens in Option 4 performs better than the options with disposal of garbage at landfill.

Energy recycling as it happens in Option 2 turns out to be no alternative at all, as it comes last for every impact category. This might be surprising for the impact category total energy, but when taking a closer look it turns out to be reasonable as material recycling provides huge savings in energy. This can be either electricity or e.g. oil which is included in total energy as well as coal and other energy carriers. Contributions and savings from windrow composting are so little that they are not decisive. For this technology, benefits occurring after treatment like improved irrigation efficiency and less soil erosion could not be modelled. The improvement of this situation is subject to ongoing research.

As the main reason for the superiority of Option 3 where garbage is combusted the production of energy was identified. This is as it replaces mainly fossil fuel based energy production. The emissions of this process are significant for all impact categories.

The financial assessment, based on a European study, results in the highest operation costs for the treatment of one tonne of waste in an incinerator (181 AUD). The disposal of one tonne of garbage at landfill costs approximately 50 AUD while the treatment of food and garden waste at a composting facility costs about 91 AUD.

Glossary

a	Area of compost application
Al	Aluminium
Ag	Silver
ap	Avoided product
ap_{ha}	Avoided product per hectare
As	Arsenic
Ba	Barium
C	Carbon
$CaCO_3$	Calcium carbonate
cap.	captured
CO_2	Carbon dioxide
Cd	Cadmium
$C_{degr.}$	Degraded carbon
CH_4	Methane
C_{in}	Carbon input
Cl^-	Chloride
Cl_2	Chlorine
CN	Cyanide
CO	Carbon
COD	Chemical Oxygen Demand
C_{org}	Organic Carbon
Cr	Chromium
C_{tot_i}	Total carbon content of substance i
Cu	Copper
DCB	Dichlorobenzene
E_e	Energy (electrical)
eq.	Equivalence factor
EU	European Union
f	factor
F^-	Fluoride
FAEP	Freshwater aquatic ecotoxicity potential
FU	Functional Unit
GaBi 4	Ganzheitliche Bilanzierung (holistic balancing) 4th

	version
G_P	Gas potential
h	Height of compost layer
HCFCs	Hydro chlorofluorocarbons
HCl	Hydrogen chloride
HF	Hydrogen fluoride
HFC	Chlorofluorocarbons
Hg	Mercury
IKP	Institute for Polymer Testing and Polymer Sciences
IPCC	Intergovernmental Panel on Climate Change
ISO	International organization for standardisation
kg	Kilogram
H	Hydrogen content
HDPE	High density polyethylene
HOE	Halogenated organic emissions
HTPAU	Human toxicity potential Australia
K	Kelvin
kPa	Kilopascal
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low density polyethylene
LHV	Lower heating value
LHV_C	Lower heating value of the combustible
LHV_{FW}	Lower heating value food waste
LHV_{GW}	Lower heating value garden waste
LPB	Liquid Paper Board
M	Mole mass
m^3	Cubic metre
MAEP	Marine aquatic ecotoxicity potential
m_{cm}	Mass of composted mulch
MW_i	Molecular weight of i
MJ	Mega Joule
MRF	Material Recycling Facility
MXP	Mixed Paper

N	Nitrogen
N-tot	Total nitrogen
$NaOH_3$	Caustic Soda
NH_3	Ammonia
NH_4^+	Ammonium
Ni	Nickel
NMVOC	Non-methane volatile organic compounds
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_3^-	Nitrate
NO_x	Nitrogen oxides
NPI	National Pollution Inventory
O_2	Oxygen
OCC	Old Cardboard Containers
ONP	Old newsprint
P	Phosphorus
P-tot	Total phosphorus
PAH	Polyaromatic hydrocarbons
Pb	Lead
PET	Ployethylene terephthalate
POCP	Photochemical formation potential
PO_4^{3-}	Phosphate
PVC	Polyvinyl chloride
Q_i	Emission rate of pollutant i
Q_{CH_4}	Methane generation rate
rel.	released
S	Sulphur content
S^{2-}	Sulphide
SAGP	Sensitivity Analysis General Profile
SAHDR	Sensitivity Analysis Higher Diversion Rate
SCR	Selective Catalytic Reduction
SMA	Sydney Metropolitan Area
SN	Tin
SO_2	Sulphur dioxide
SO_3^{2-}	Sulphite

STP	Sewage Treatment Plant
T	Temperature of landfill gas
TC	Transfer Coefficient
TC_c	Transfer Coefficient from C to CO_2
TC_{NO}	Transfer coefficient from N to NO
TEP	Terrestrial ecotoxicity potential
TS	Total solids
TSS	Total suspended solids
UM_i	Uncontrolled mass emissions of pollutant i
UR-3R	Urban resource – reduction, recovery and recycling
URL	Uniform resource locator
V	Volume
W_c	Water content of the combustible
WTE	Waste-to-Energy
Zn	Zinc
α	Degradation yield
α_{tot_i}	total α of substance *i*
θ	Temperature in the landfill
ρ_i	Density of substance *i*
η	Efficiency
V_I	Volume of substance *i*
C_i	*C*oncentration of *i* in landfill gas
$C_{CH_4\%}$	Concentration of CH_4 in the landfill gas
$C_{CO_2\%}$	Concentration of CO_2 and other gas in biogas
Q_i	Emission rate of pollutant i
f_{CaCO_3}	Factor for calculation of $CaCO_3$ demand
M_{CaCO_3}	Mole mass for $CaCO_3$
M_{Cl}	Mole mass for Cl
°C	Degree Celsius

Table of Contents

1 Introduction

1.1 Background of the Study

Sydney is facing an enormous waste problem. Currently approximately 900,000 tonnes of domestic garbage are disposed of at landfill each year. Not just that people in Sydney are unhappy about the way waste is treated instead of using it as a resource. With the current disposal rate Sydney will also have a shortfall of landfill capacity within the next decade [1].

To fix this problem, a new landfill is set up 250 km to the west of Sydney, at Woodlawn. For this, an old mine is used. Once in operation, it should be able to take up to 400,000 tonnes of putrescibles each year [2]. The new landfill, a so-called bioreactor, is meant to solve the capacity problem for 40 – 50 years.

Resource NSW claims the Woodlawn landfill makes efforts to reduce waste by decreasing disposal and increasing diversion of recyclables unnecessary [3]. This is right, as some pressure due to lack in capacity would certainly have done good to reduction and recycling efforts. For sure, Australia does not have a space problem at all like other countries do, e.g. in Europe. Still, environmental problems due to landfilling are the same like anywhere else in the world – emissions to air and water. Biogas from landfills is worldwide one of the biggest contributors of greenhouse gases[4]. Highly contaminated leachate penetrating the base sealing of a landfill is a huge environmental threat to groundwater reservoirs.

So, the introduction of a new mega landfill is not seen as a step forward by the public. But, concerning environmental improvements, what would be a step forward? A consultant was asked to write a report in which he investigates the wide market of disposal technologies and practices. In his letter to the Minister for the Environment he states that the time to 2005 would be good for a change in waste management due to community support and availability of alternatives [5].

But discussions about environmental performance of different technologies continue. Is landfilling combined with energy utilisation from biogas really a bad way to manage waste problems? Should garden waste be landfilled or recycled in windrow composting? Is energy recycling better than material recycling and finally, is garbage better off to be landfilled or should it be combusted in a Waste-to-Energy plant?

Currently, no incinerator for domestic waste is operating in Australia, the last one at Waverley-Woollahra was switched off due to problems with increased emissions of dioxin. Since then, WTE has not really been considered as acceptable method in waste management but as a waste of resources.

This study is looking for answers to the above questions. It is meant to support the process of optimising the waste management in Sydney towards a more sustainable solution. Its outcomes will enrich the ongoing research of the Centre for Water & Waste Technology in Sydney.

1.2 Tasks of this Thesis

The task of this study is to use the Life Cycle Assessment (LCA) method to compare the environmental performance of different waste management systems. The procedure due to the ISO 14040 series has to be explained. For carrying out this study data have to be collected and a model has to be developed within GaBi 4, an LCA software. Results for different options should be compared and evaluated. Based on this, recommendations to help optimising the waste management in Sydney should be given.

The original terms of the conceptual formulation are:

- describing the demands on the data material and the procedure of life cycle assessment (LCA) due to ISO 14040 series
- Completing the data required to assess the waste management activities of Sydney under ecological and economic aspects
- Developing a data bank system used for computer based LCA (e.g. by means of GaBi software)
- Comparing and valuating the results got from the computer based LCA
- Developing recommendations to optimise the waste management activities of Sydney

2 General LCA Methodology

Life Cycle Assessment (LCA) is used to assess the environmental impacts of products, processes or activities. Energy and material flows are identified and quantified, and the environmental impacts connected with these flows are calculated. In regard to a product this includes “material and energy raw ware acquisition, manufacture, use and waste management” [6]. As the whole life-cycle of a product is considered, it is also called “cradle to grave” (Figure 1).

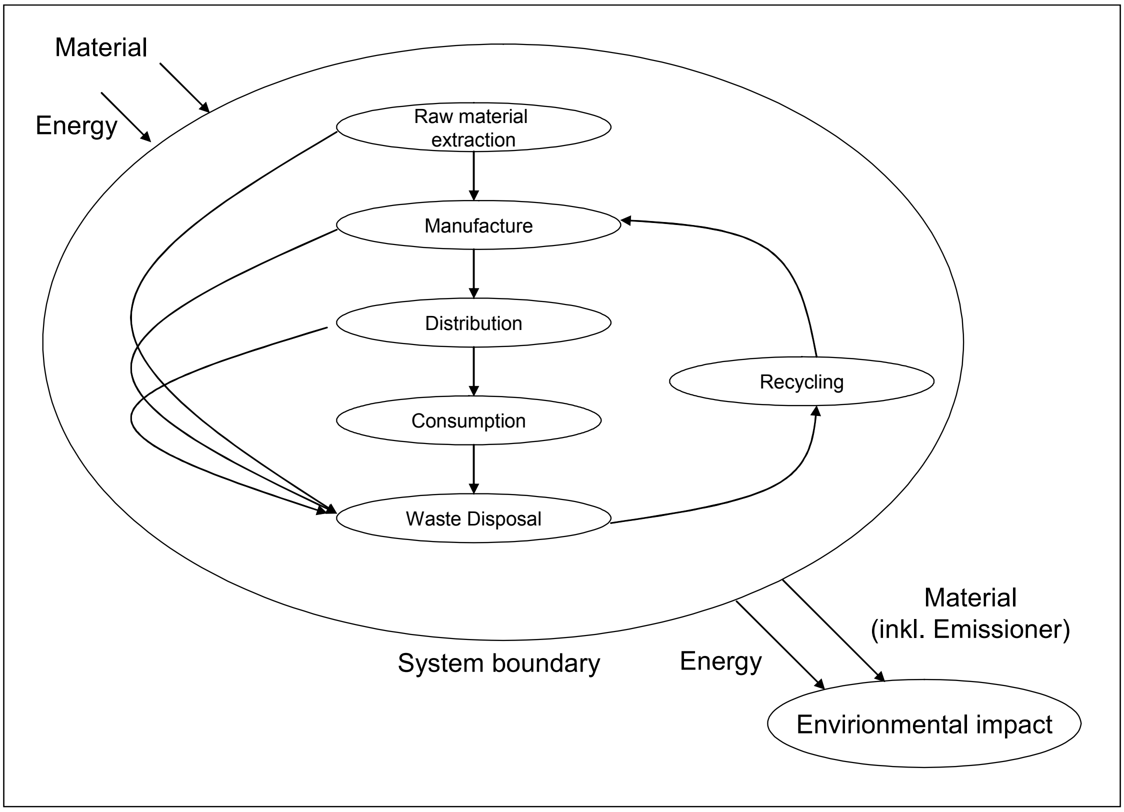


Figure 1 Life cycle assessment for products, from the cradle to the grave [6]

An LCA-study can be used for benchmarking the environmental performance of systems (such as a product or a service) and is therefore of special interest for decision makers. This instrument is of significant importance for the waste management sector, as decisions here are long-lived and environmental burdens are enormous. Therefore, choices have to be taken carefully, and an LCA-study can act as a basis for further investigations, e.g. feasibility studies. LCA-Results do not explain local but continental and/or global effects.

The ISO 14040 series defines a framework for LCA studies which consists out of four phases (Figure 2):

- Goal and Scope Definition
- Inventory Analysis
- Impact Assessment and
- Interpretation.

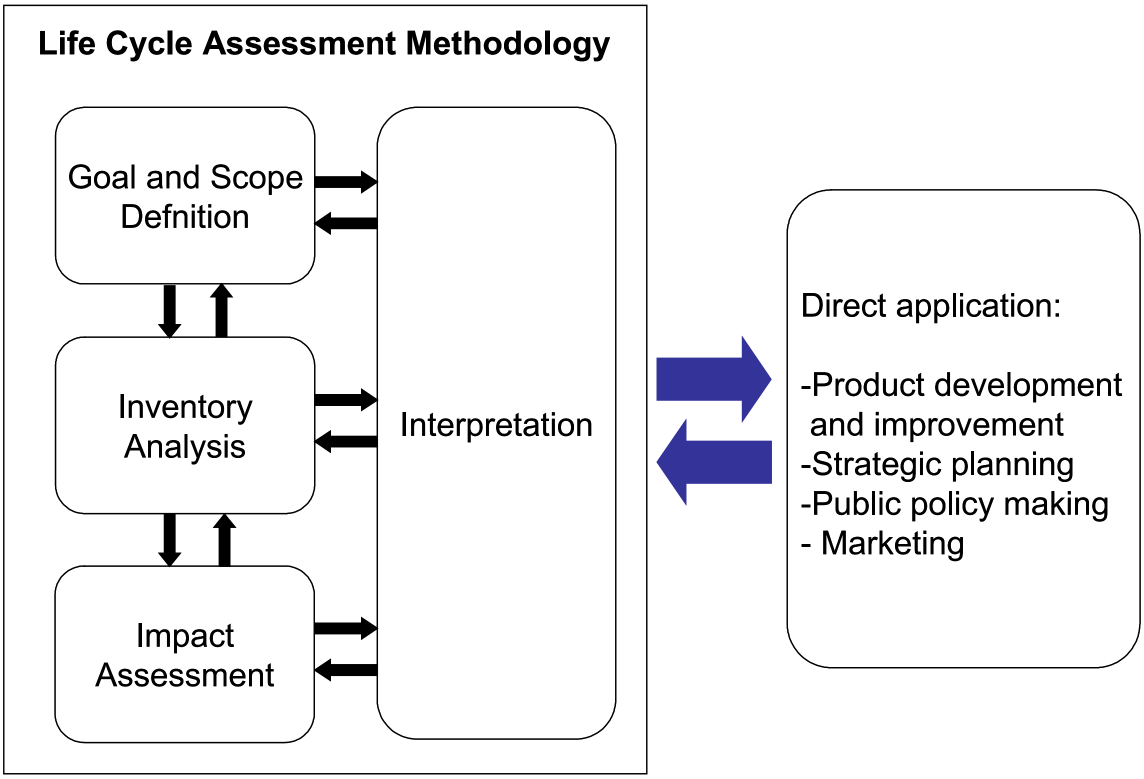


Figure 2 Phases of an LCA and its application[7]

The four phases are explained in the following.

2.1 Goal and Scope Definition

In the *Goal and Scope Definition* one has to take "initial choices which determine the working plan of the entire LCA" [8]. These choices are the question to be answered by the study, the targeted audience and the intended application [8].

The scope defines the functional unit (FU) and the associated system to be studied (function). It describes the primary function of the system and serves as the basis for all calculations in the LCA study. Further, it allows the direct comparison of different systems providing the same FU. As an example, the FU is one tonne of garbage. The function is the disposal of the FU. It can be completely achieved by landfilling. Also, the waste could be combusted. Both systems achieve the main goal, the function. Therefore, all environmental loadings of these two systems can be compared directly and the environmentally preferable system can be identified.

The system, which is to be studied, is defined by the system boundaries. These include upstream and downstream effects. The upstream effects define the start of the system, i.e. raw material acquisition or manufacturing. The downstream effects are the end of the technical system, i.e. the process regarded as the grave for any material flow.

If some processes of the systems to be compared are identical, they can be left out. They have the same emission profile and the same inputs. Therefore they are of no effect for the final results, as they cancel each other out. When comparing waste management options, this could be the manufacturing of a product or its use before disposal. Regardless of the method of disposal, these are the same, therefore have no effect on the balances of the options considered.

2.2 Inventory Analysis

The *Inventory Analysis* concerns the modelling of the processes within the system boundaries. This includes the collection of data and the calculations for specification of relevant inputs and outputs for the product system [9].

The inputs and the outputs, also called environmental interventions, are analysed. Inputs could be raw materials and energy. Outputs could be emissions from production into the air, water and soil as well as the product itself. Byproducts are also taken into account, e.g. the generation of electricity from biogas capture at landfill.

2.3 Impact Assessment

During the *Impact Assessment* (LCIA) the results from the inventory analysis are made more manageable and understandable in relation to the natural environment, human health and availability of resources. Inputs and outputs, identified in the inventory analysis, are characterised and assessed. The LCIA provides the information for the interpretation. In general, the LCIA follows the framework according to the ISO 14042 (Figure 3).

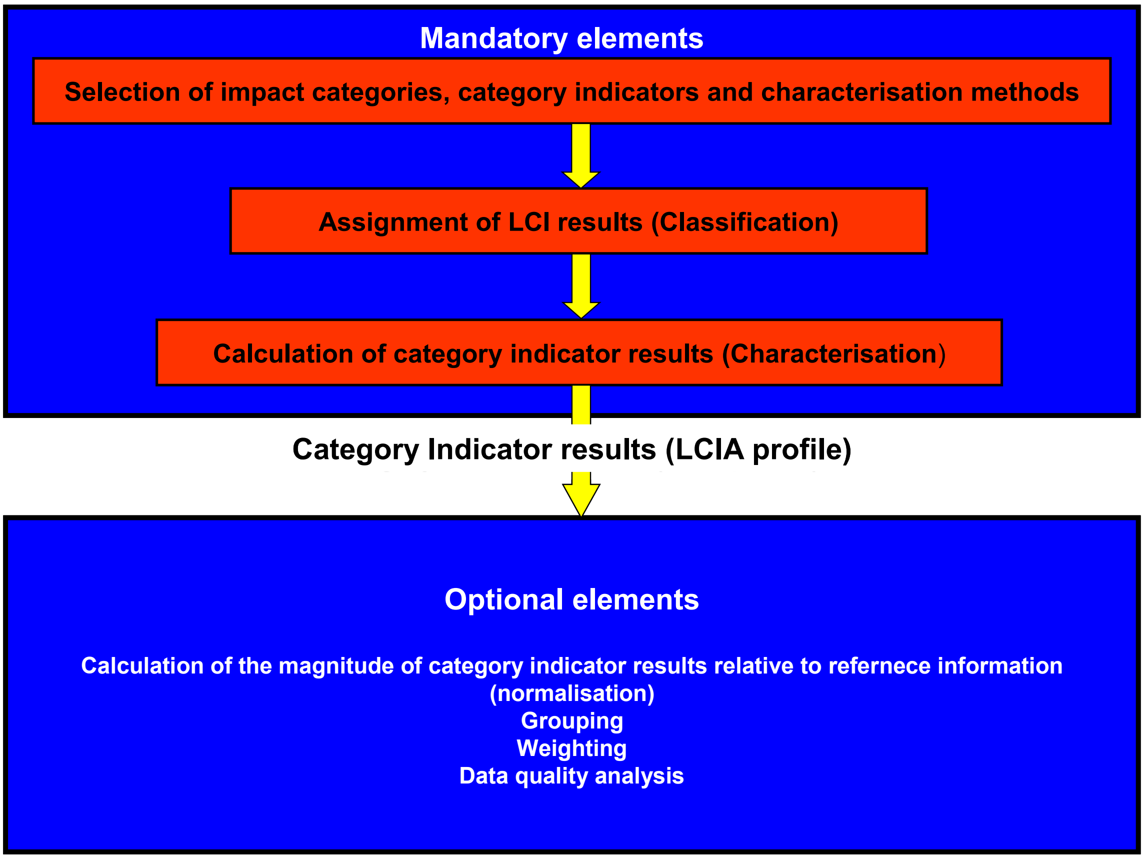


Figure 3 Elements of the LCIA phase [10]

LCIA consists of mandatory and optional elements. The *mandatory elements* are:

- Selection of impact categories, category indicators and models;
- Assignment of LCI results (Classification) to the impact category, and
- Calculation of category indicator results (Characterisation).

Optional elements of LCIA are:

- Calculation of the magnitude of category indicator results relative to reference values (Normalisation);
- Grouping;
- Weighting and
- Data quality analysis.

Depending on the goal and the scope of the study the optional elements can be applied.

This study is limited to the mandatory elements, which will be explained in the following. Further optional elements are not taken into account in this study, as none of them are helpful in reaching the goal. Therefore they are not explained.

2.3.1 Selection of Impact Categories, Category Indicators and Models

The first step in the impact assessment is the choice of impact categories from a list of resource use and environmental impacts. Indicators for those categories and models are determined to quantify the contribution to them. As an example, a category indicator would be “radiative forcing” for the impact category “climate change”. Radiative forcing effects the balance of radiation coming into the atmosphere and radiation going out and has therefore an effect on climate change. This so-called radiative forcing is therefore the category indicator for climate change. Radiative forcing can be caused by reflection of radiation by gases (“greenhouse effect”). The contribution of different emissions to this effect can be modelled. The choice of the model and the calculations had not to be done within this study, as the classification, described in (2.3.2), and the characterisation, described in (2.3.3) were done in several studies before and the results were available within the software GaBi 4. Most models consider Australian conditions. Shows the concept of indicators.

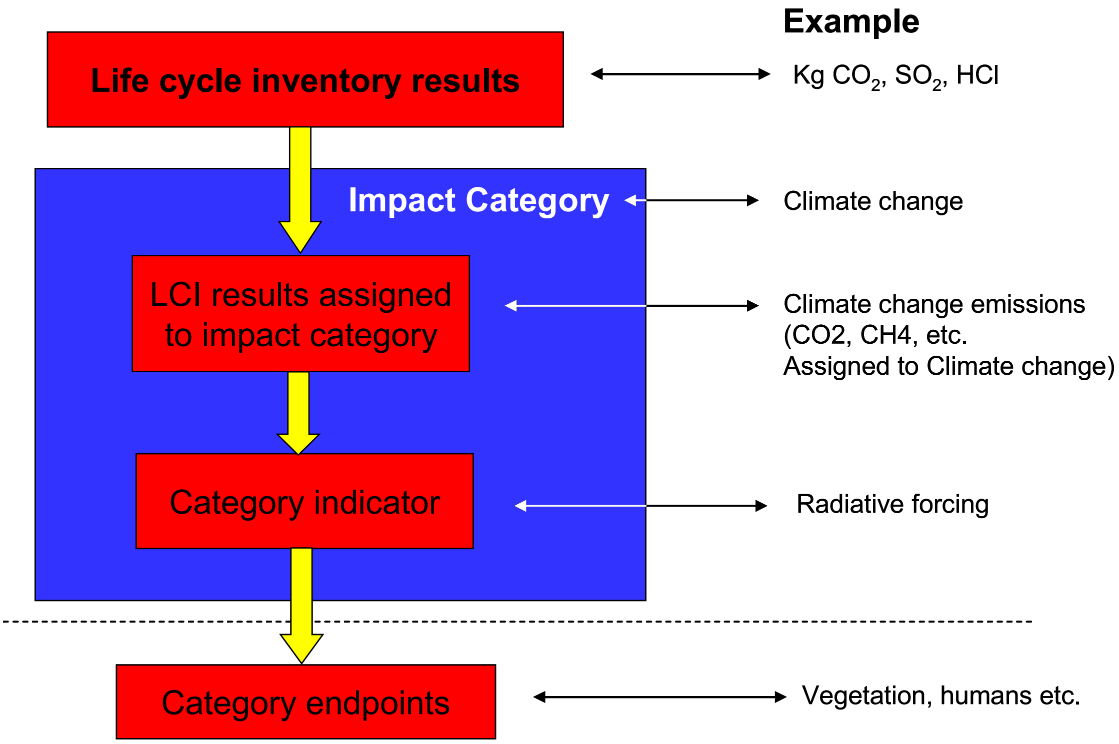


Figure 4 Concept of category indicators [modified from 10]

2.3.2 Assignment of LCI Results (Classification)

The environmental interventions identified in the LCI are assigned to the various selected impact categories [8], e.g. CO_2 is assigned to climate change and SO_2 to terrestrial aquatic ecotoxicity potential.

2.3.3 Calculation of Category Indicator Results (Characterisation)

As lots of different interventions apply to a certain impact category; the estimation of the effect is expressed by so called equivalence factors (eq). So, for example, CO_2 is an intervention having an effect on climate change. It serves as a reference substance to all other gases within this category. Their impacts are therefore calculated as CO_2-equivalence factors ($CO_{2\text{-eq}}$). Methane is supposed to have a 21 times bigger effect on climate change than CO_2 on a 100 year time scale, therefore each kg of emitted CH_4 is taken into account as 21 kg CO_2-eq. Most of these interventions and their equivalence factors are summarized in the [8]. Equivalence factors for climate change are set by the Intergovernmental Panel on Climate Change (IPCC). Based on new research results, these calculations are subject to possible changes.

2.4 Interpretation

The *Interpretation* phase includes the evaluation of the outcomes from the inventory analysis and the impact assessment in relation to the goal of the study, as defined in *Goal and Scope Definition*. A sensitivity analysis is part of the interpretation as well as the quantification of the accuracy of the LCA results by evaluating data quality and data gaps [11].

Based on this, recommendations can be made.

3 LCA Methodology and Solid Waste Management

The methodology used for LCA of products can essentially be used for solid waste management [9]. However, some differences and problems might occur, which are discussed briefly in this chapter.

3.1 System Boundaries

In LCA methodology usually all inputs and outputs from the system are, as mentioned above, based on the “cradle-to-grave” approach. This means that inputs into the system should be flows from the environment “without previous human transformation” and outputs should be “discarded into the environment without subsequent human transformation” [7]. LCA studies in waste management systems take a different approach but the method remains consistent with international standards [9], [12]. Each system starts at the point where domestic solid waste is generated, i.e. at the household. Upstream effects with regard to the extraction of raw materials and the manufacturing of products that finally result in the domestic waste can be disregarded because they are the same for all systems under study.

3.2 Open-loop-Recycling

When comparing different waste management options in LCA studies it is important to ensure parity of the functions provided by the systems. The functional unit can be partially recycled into its original material and, to a varying extent, into other products such as electricity. Both recycling processes are functions. This process is called open-loop recycling.

ISO 14041 recommends system expansion for overcoming this methodological problem.

In this expansion it is asked how the function would “be performed if it was not performed by the system” [13].

As an example, one tonne of garden waste has to be landfilled. The generated biogas is captured and used for energy utilisation. Electricity is produced. The FU is the tonne of garden waste, functions are the disposal of the FU as well as the electricity production. Figure 5 shows how system expansion is performed for this problem.

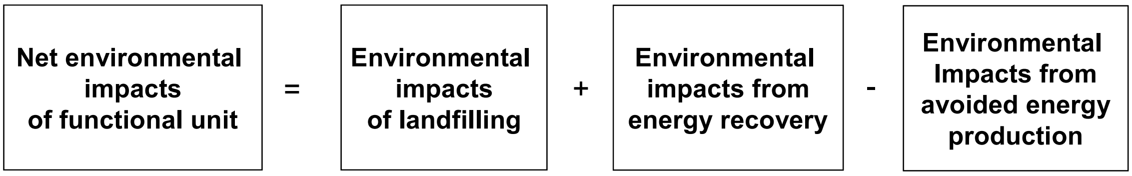


Figure 5 System expansion for open-loop recycling (modified from [12]

A product such as electricity utilised from landfill gas or plastic resin from HDPE recycling is called *avoided product*. Therefore they are products which have to be produced otherwise if no recycling or energy utilisation happens.

3.3 Allocation problems

As waste consists out of many different materials and as there is a huge variety of emissions, it is impossible to allocate precisely certain emissions to a certain waste fraction. Unfortunately, data like these are not available, neither from landfills nor from incinerators, as all emission profiles are for the whole amount of waste [6]. Therefore, calculated emissions in this study are based on so-called “transfer coefficients” (TC), which were derived from models. With these coefficients “responsibility for environmental impacts” [6] can be allocated to different fractions. These coefficients mainly refer to elementary composition.

3.4 Time aspects of Landfilling

While most emissions in an LCA are instantaneous, things are different for landfilling. Here, emissions last for centuries, thousands of years and even more. In order to compare emissions from a landfill with the ones from an incinerator, a time frame needs to be created. Different approaches have been developed, e.g. the period until the next glacial period But another one is a frame which is easy to overview but still long enough to cover the active stage of a landfill, the phase of aftercare and the time range “characterised by high internal activities” [6]. The period is called the surveyable time period and covers 100 years [6]. This, of course, is of importance for landfilled materials considered as inert (glass, metals), hardly degradable (plastics) and materials slowly leaching out (slag), as they are most likely to emit most hazardous substances in the time after this short period. For this study the surveyable time period was chosen for modelling landfill effects, partly due to lack of proven information about long-term-behaviour, but also to make results more “tangible”.

4 The LCA Model

The results of the study are based on a model programmed within the LCA software GaBi 4. (GaBi = Ganzheitliche Bilanzierung = holistic balancing). In the following the software will be introduced and the model will be explained briefly.

4.1 LCA Software GaBi 4

All information about GaBi 4 has been taken from the GaBi 4 Manual [14]. The GaBi 4 Software has been developed by the Institute for Polymer Testing and Polymer Sciences (IKP) of the University of Stuttgart in cooperation with PE Europe GmbH. It is a tool to create life cycle balances and supports the handling of large amounts of data. Balances show the results of a model. Once these balances have been created, they can be analysed within the programme in many different ways.

Each database consists out of objects, which have a certain order according to their hierarchy. These objects are balances, plans, processes, flows, quantities, units, users, projects, quality indicators, weighting and global parameter. The hierarchy is shown in Figure 6.

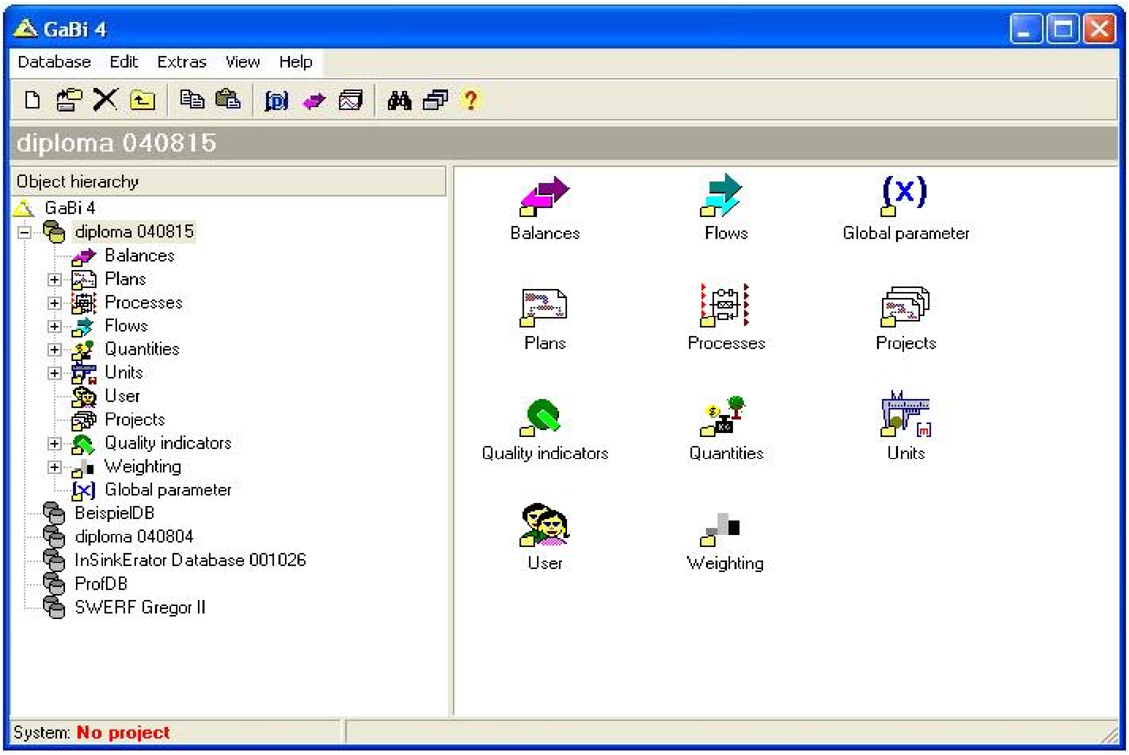


Figure 6 Screenshot of GaBi 4 main menu

As the objects user, projects, quality indicators, weighting and global parameter were not defined for this model they will not be explained.

Balances, as mentioned above, show the results of a model and are used for analysis. They can show the influence of all processes on the results for all impact categories as well as a pure mass balance, where all sorts of material flows are listed.

Plans are the top layer of the model and "can be used to generate life cycle models in the form of flow charts. Here, so-called process instances and sub-plans are linked with one another" [14].

The single steps of a life cycle are modelled within the *processes* and contain all inputs and outputs in form of flows. Concerning the model itself, processes are the bottom layer. Every material and energy *flow* is defined within the flows. Figure 7 shows the main plan for Option 1, containing one process and two subplans.

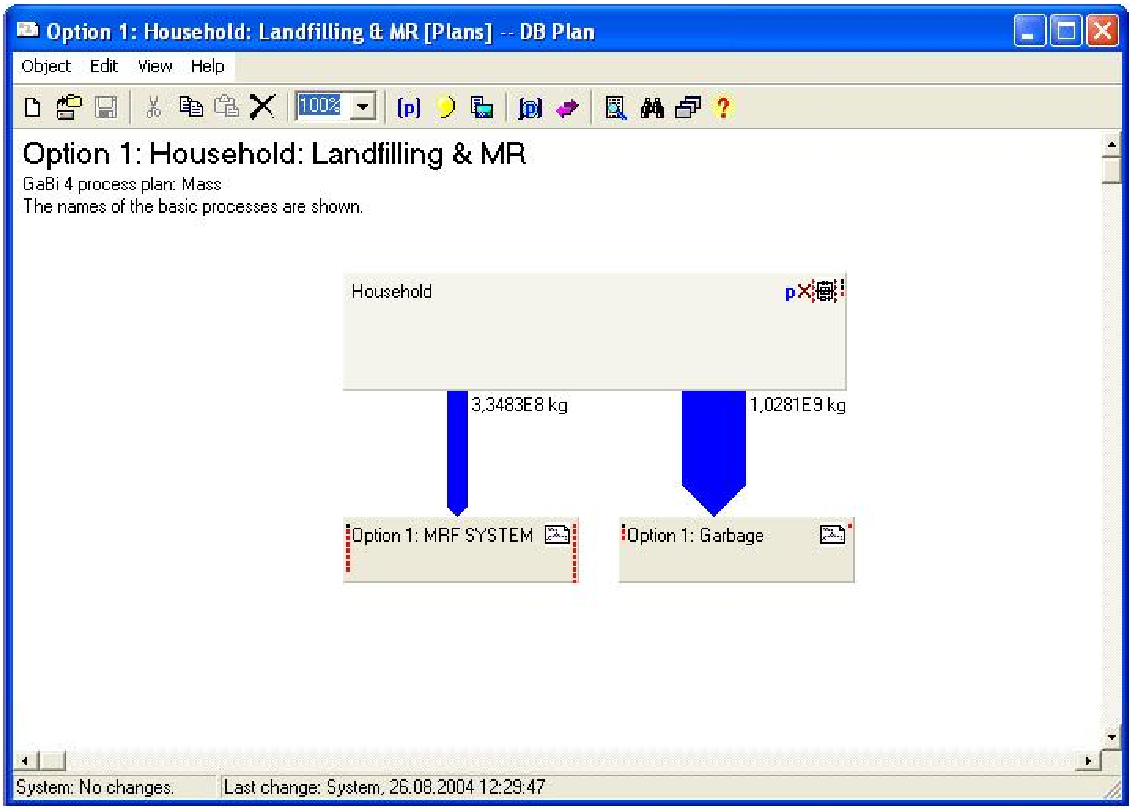


Figure 7 First level of waste management model in Option 1

In this figure, the process called Household is linked with two subplans, Option 1: MRF SYSTEM and Option 1: Garbage. While the process just provides information about the flows in form of materials (amount of recycling material going to MRF and of garbage going to the disposal), each of the subplans provides a system of processes and subplans itself. Some of them will be shown later on.

Within the *quantities* technical material properties like density or calorific values can be defined as well as the impact of flows concerning impact categories such as climate change. A flow can be defined by more than one quantity. So e.g. coal can be referred to kg as well as MJ.

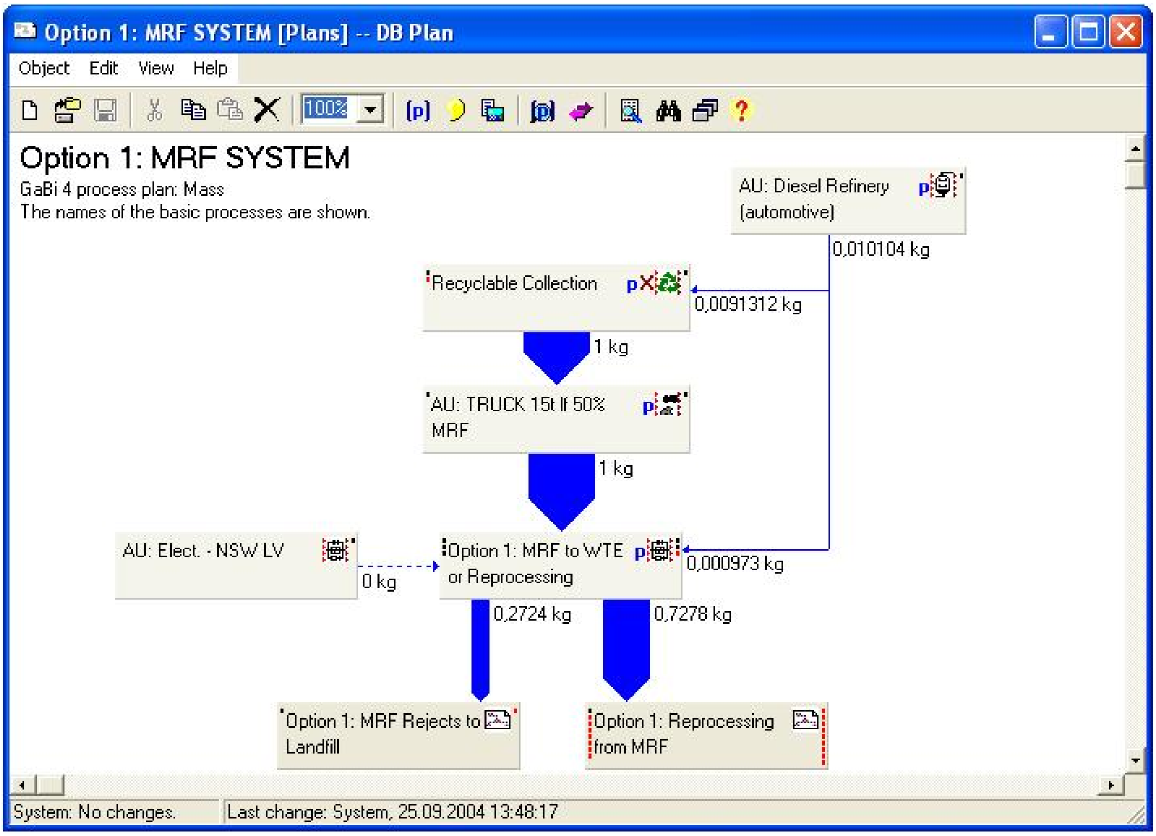
Units contain measuring units like kg or MJ.

4.2 The Waste Management Model

The model is based on a hierarchy of plans and subplans. Two reasons suggested to invent different levels of plans: an uncountable number of processes is involved in the model, which makes it impossible to create a clear plan. Secondly, as the balance shows every process of the plan, a reasonable overview of results and therefore a proper analysis would be impossible.

The complexity of the system will be shown with following the waste fraction paper from the recycling bin to the landfill, as it turns out to be rejected.

The first level (Figure 6) shows how much of the waste is diverted to the recycling system and how much of it is going to be finally disposed. The material flows are entering the next level. From there on, mass calculations are based on 1 kg, so that percentages have to be given, e.g. how much of the recyclables are rejects. When asked for a balance, the system calculates the handling of the complete FU by multiplying the MRF System with the amount of recyclables entering (Figure 8).



Option 1: MRF SYSTEM

GaBi 4 process plan: Mass

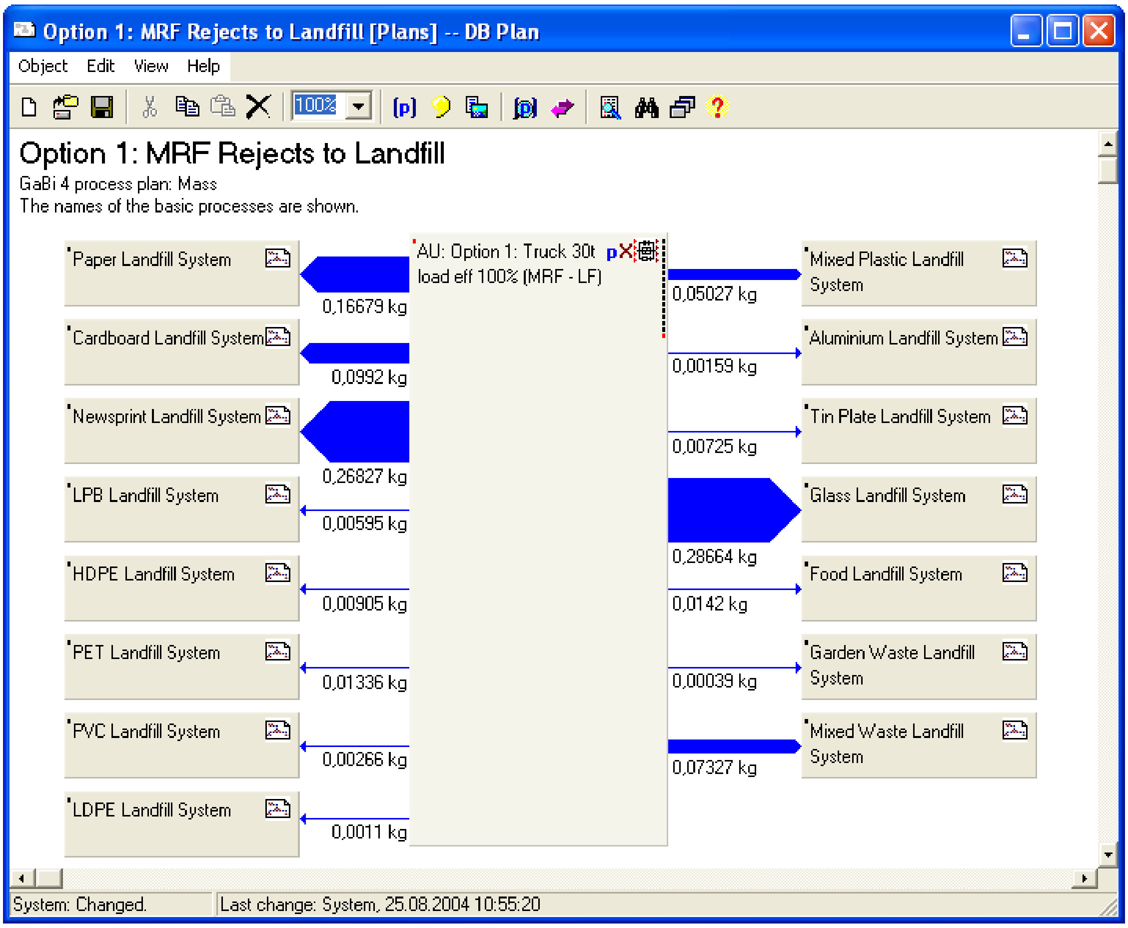
The names of the basic processes are shown.

System: No changes.

Last change: System, 25.09.2004 13:48:17

Figure 8 MRF system

The second level models the collection of the recyclables and the energy use for the sorting process. It shows also how much of the recyclables have to be landfilled and how much is going to be reprocessed. It contains two new subplans, the landfilling of the rejects and the reprocessing. The transport of the rejects is shown in Figure 9.


Option 1: MRF Rejects to Landfill [Plans] -- DB Plan

Option 1: MRF Rejects to Landfill

GaBi 4 process plan: Mass

The names of the basic processes are shown.

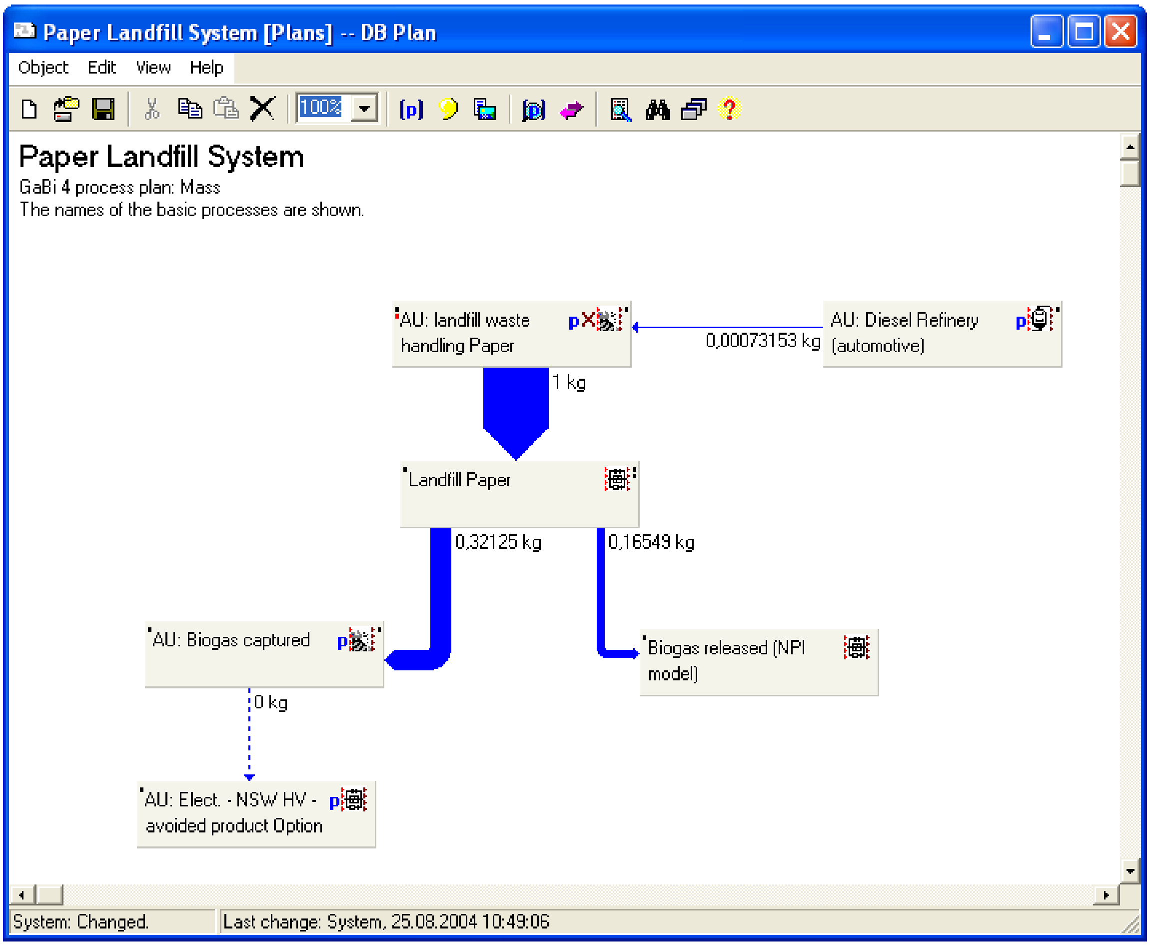
System: Changed.

Last change: System, 25.08.2004 10:55:20

Figure 9 Transport of rejects to landfill

So far an “anonymous” mixture of recyclables was handled. On this level the composition of the recycling rejects is shown, entering the fraction specific landfill subplans. The Paper Landfill System is the final level, as no further subplans are involved. It gives information about the handling of the fraction and the biogas production.

While on the landfill level mass flows occur as well as energy flows, in Figure 10 only mass flows are shown.



Paper Landfill System

GaBi 4 process plan: Mass

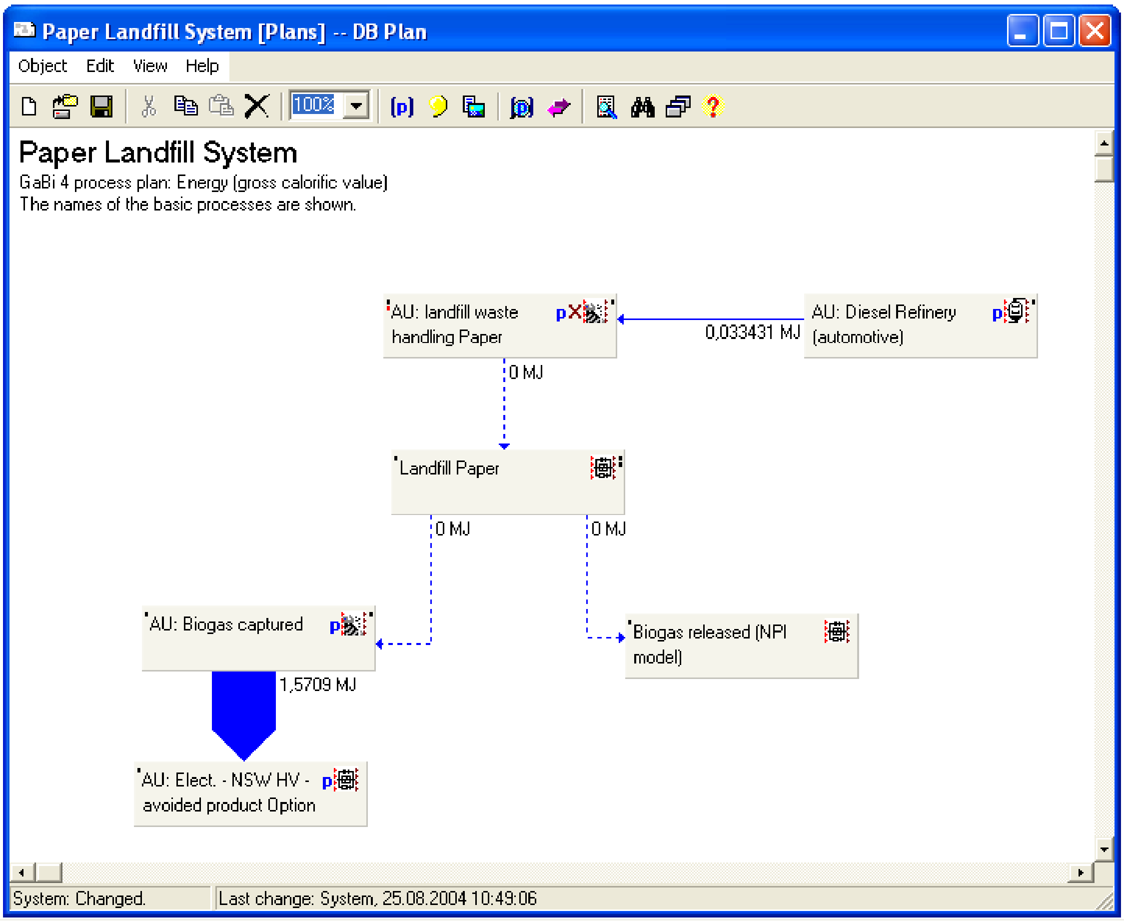
The names of the basic processes are shown.

System: Changed.

Last change: System, 25.08.2004 10:49:06

Figure 10 Paper landfill process (mass flows)

Figure 11 shows the energy flows for the same process. Diesel as an energy carrier can be shown both ways, as a mass flow as well as an energy flow.



Paper Landfill System

GaBi 4 process plan: Energy (gross calorific value)
The names of the basic processes are shown.

System: Changed.
Last change: System, 25.08.2004 10:49:06

Figure 11 Paper landfill process (energy flows)

5 Goal and Scope of the Study

In this chapter the intention and the framework of the study are described.

5.1 Goal of the Study

The primary goal of this study is to evaluate the environmental performance of different waste management options. Environmental impacts of the domestic waste stream of Sydney metropolitan area (SMA) were quantified to assist in this comparative waste management assessment. The SMA is the Sydney local government area, consisting of 39 councils.

In addition to a comparative analysis of waste management impacts, a detailed investigation of the superiorities and inferiorities of each option defined according to environmental impact categories was obtained.

Three different options were compared with the current situation in Sydney, the Base Case. The potential impacts of a change in waste management strategy are shown. Further, the choice of options allows a direct comparison of windrow composting and landfilling of garden waste, energy recycling and material recycling and landfilling and combustion of garbage.

Waste consists of

- garbage that is currently disposed of at landfills
- recyclables that is defined as materials being treated in the recycling system and
- garden waste which is collected separately by some councils and brought to windrow composting and otherwise disposed of at landfill.

The four different waste management strategies are:

Base Case: Garbage to landfill and material recycling (Paper, ONP, Cardboard, LPB, Tin Plate, Aluminium, HDPE, PET) and windrow composting for garden waste (current situation);

Option 1: Garbage including garden waste to landfill and material recycling (Paper, Old Newsprint (ONP), Cardboard, Liquid Paper Board (LPB) Tin Plate, Aluminium, HDPE, PET)

Option 2: Garbage to landfill, material recycling for fractions with a low calorific value (tin plate, aluminium and glass), energy recycling for fractions with a high calorific value (paper and plastics) and windrow composting for garden waste;

Option 3: Garbage to Waste-to-Energy (WTE), material recycling (Paper, ONP, Cardboard, LPB, Tin Plate, Aluminium, HDPE, PET) and windrow composting for garden waste.

5.2 Intended Application

This study is intended to compare environmental profiles of several options of waste treatment. The results will serve as a base to ongoing, extended studies where modern technologies will be added to cover all disposal options that are technically and economically feasible. The results will go into current discussions about finding a more sustainable solution to Sydney's waste problem.

5.3 Target Audience

The target audience is the Centre for Water & Waste Technology, Sydney. The study will support their ongoing research of LCA on waste management. Decision makers in local, regional and national authorities who showed a keen interest in this (in a context where several councils are considering alternative treatment technologies) will also find this study useful as students and researchers with an interest in LCA and waste management.

5.4 Scope of the Study

In this part of the chapter the framework of the study, what is examined, is defined.

5.4.1 Functional Unit of the Study

The *functional unit* (FU) of this LCA study is the yearly amount of waste generated in households in the SMA.

Getting a detailed picture of the FU was a problem in this study as public data on waste are hardly available. During the `90s a database was established but as waste composition is subject to significant changes more recent data were important. For this, all councils in the SMA had to be contacted. In the end, 15 councils provided detailed information on their garbage stream and 17 on their recycling stream. All audits from these councils were undertaken by the same consultant and could therefore be compared. A few other councils provided data as well, but they were based on completely different type of audits, as they obviously tried to achieve another goal with their studies. These statistics could not be taken into account. Furthermore, the majority of councils providing proper data just had percentages for each fraction, so that in the end average percentages had to be calculated. This method might lead to a distorted picture about the waste composition. But in the current situation this is the only possible way to gain a database about what is in the bins.

The overall amount of garbage, recyclables and green waste, provided by NSW resource, is from the financial year 2002/03, while the audits were mainly undertaken in 2001; the most recent is from 2003. Table 1 provides the composition of the garbage and recycling stream.

Table 1 Composition of garbage and recycling stream [%] based on [15]

	Garbage	Recyclables
Paper	9.72	19.33
Cardboard	3.23	11.50
ONP	2.92	31.10
LPB	0.49	0.41
HDPE	0.64	1.70
PET	0.70	2.51
PVC	0.03	0.07
LDPE	0.02	0.03
Mixed Plastics	9.03	1.37
Aluminium	0.39	0.36
Tin Plate	2.62	1.36
Glass	4.49	27.89
Food	38.14	0.39
Vegetation	8.97	0.01
Mixed Waste	18.59	2.00

Although these councils have a different population density and socio-demographic characteristics, the FU can be considered as representative as the councils are spread over the whole SMA; councils from the business district and inner suburban areas are included as well as outer areas in the south, west and north. However, as most of the audits are not public it was agreed to allow no link between a council and its statistic, therefore all councils received a number.

The FU consists of 1,362,957 tonnes of waste per annum. This includes 884,873 tonnes of garbage, 334,830 tonnes of recyclables (including contamination) and 143,254 of separately collected garden waste [16]. Some councils reported of contamination in the garden waste as well, but the amount was of minor importance and therefore not modelled separately. For the tables showing the composition of the garbage and the recyclables please refer to Appendix B.

5.4.2 Function of the Study

The *main function* in this study is the treatment of the amount of waste generated each year in the households of the SMA, the FU. The production of electricity and materials are supplementary functions, the so-called avoided products.

Each option under view fulfils these functions up to a varying extent (Table 2).

Table 2 Functions of each waste management option

Function	Base Case	Option 1	Option 2	Option 3
Treatment of solid waste	Yes	Yes	Yes	Yes
Electricity production based on	Biogas from degraded garbage and MRF rejects	Biogas from degraded garbage and MRF rejects	Biogas from degraded garbage and MRF rejects, energy recycling from paper, cardboard, ONP, LPB, plastics	Combustion of garbage
Material recovery from	Paper, cardboard, ONP, LPB, HDPE, PET, aluminium, tin plate, glass	Paper, cardboard, ONP, LPB, HDPE, PET, aluminium, tin plate, glass	Aluminium, tin plate, glass	Paper, cardboard, ONP, LPB, HDPE, PET, aluminium, tin plate, glass
Windrow Composting	Yes	No	Yes	Yes

5.4.3 System Boundaries of the Options

Base Case – MRF, landfilling and windrow composting

The Base Case shows the current situation of Sydney’s domestic waste management. Garbage and recyclables are disposed in separate 240L garbage bins. The garbage is collected and trucked from the council to the Transfer Station. At the Transfer Station the garbage is compacted and reloaded into a larger landfill truck. These trucks transport the garbage to landfill. At the landfill the garbage is unloaded, placed and compacted. The organic fraction degrades to various extents and contributes to biogas and leachate generation. The biogas is partly captured and utilised for electricity production (avoided electricity production).

The recyclables are transported to a Material Recycling Facility (MRF). At the MRF the material is unloaded and separated into eight different material streams: paper, cardboard, ONP, LPB, PET, HDPE, aluminium and tin plate. Rejects and inappropriate material are also landfilled. After separation each recycling stream is transported to different locations where material reprocessing takes place. Each material replaces primary materials of different quality:

- Paper and ONP are reprocessed into newsprint (avoided product newsprint)
- Cardboard is reprocessed into cardboard (avoided product unbleached kraft pulp);
- Glass replaces primary glass melt;
- Reprocessed steel substitutes for pig iron;
- Aluminium replaces primary material; and
- PET and HDPE replace the same virgin plastic resin.

Garden waste is collected separately in some councils and transported to a windrow composting facility. The compost product replaces N-, P- and K-fertilisers. Figure 12 shows the system diagram.

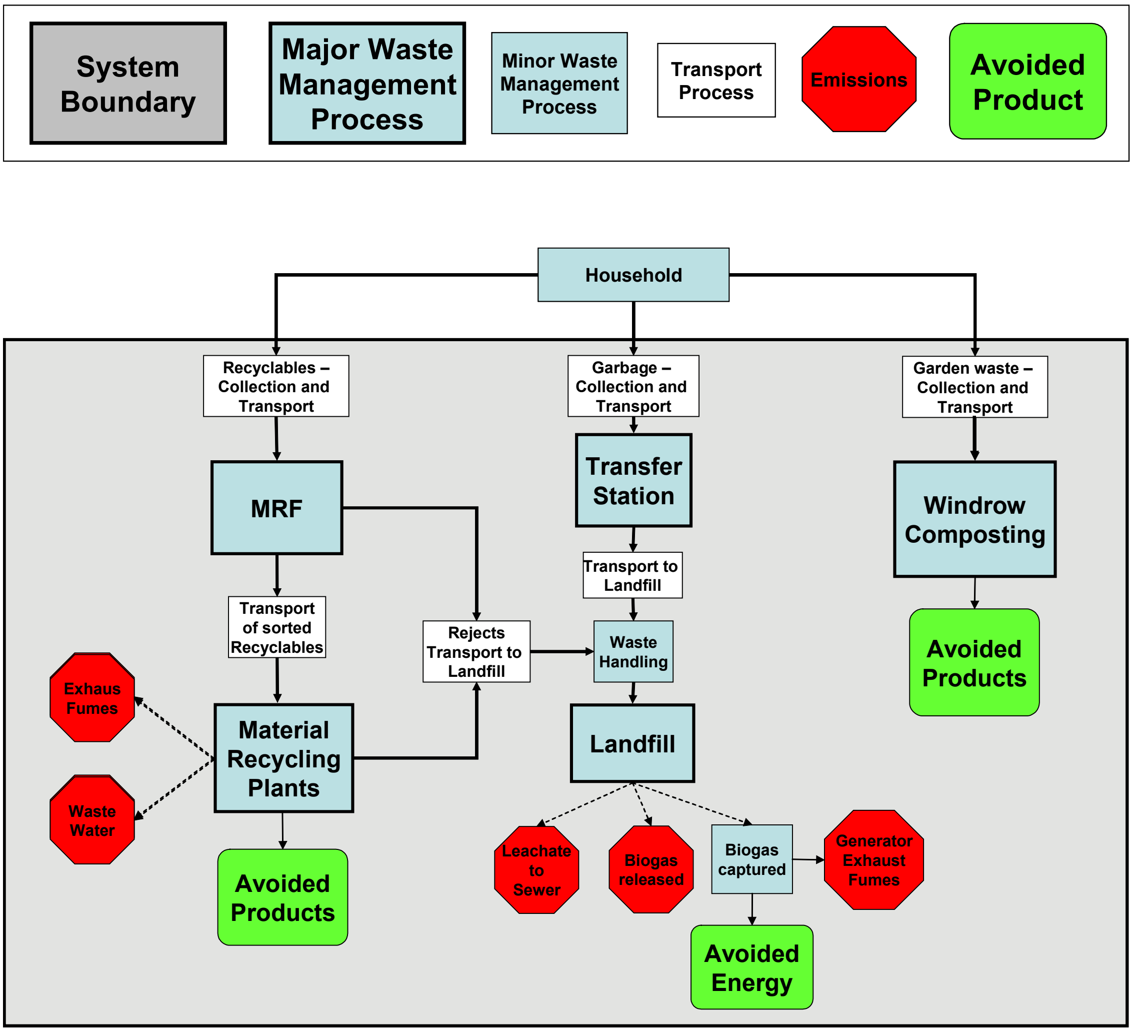


Figure 12 System diagram for the Base Case (landfill, MR and windrow composting)

Option 1 MRF and Landfill

Garbage and recyclables are treated as in the Base Case. Garden waste is collected with garbage and disposed of at landfill. A system diagram is shown in Figure 13.

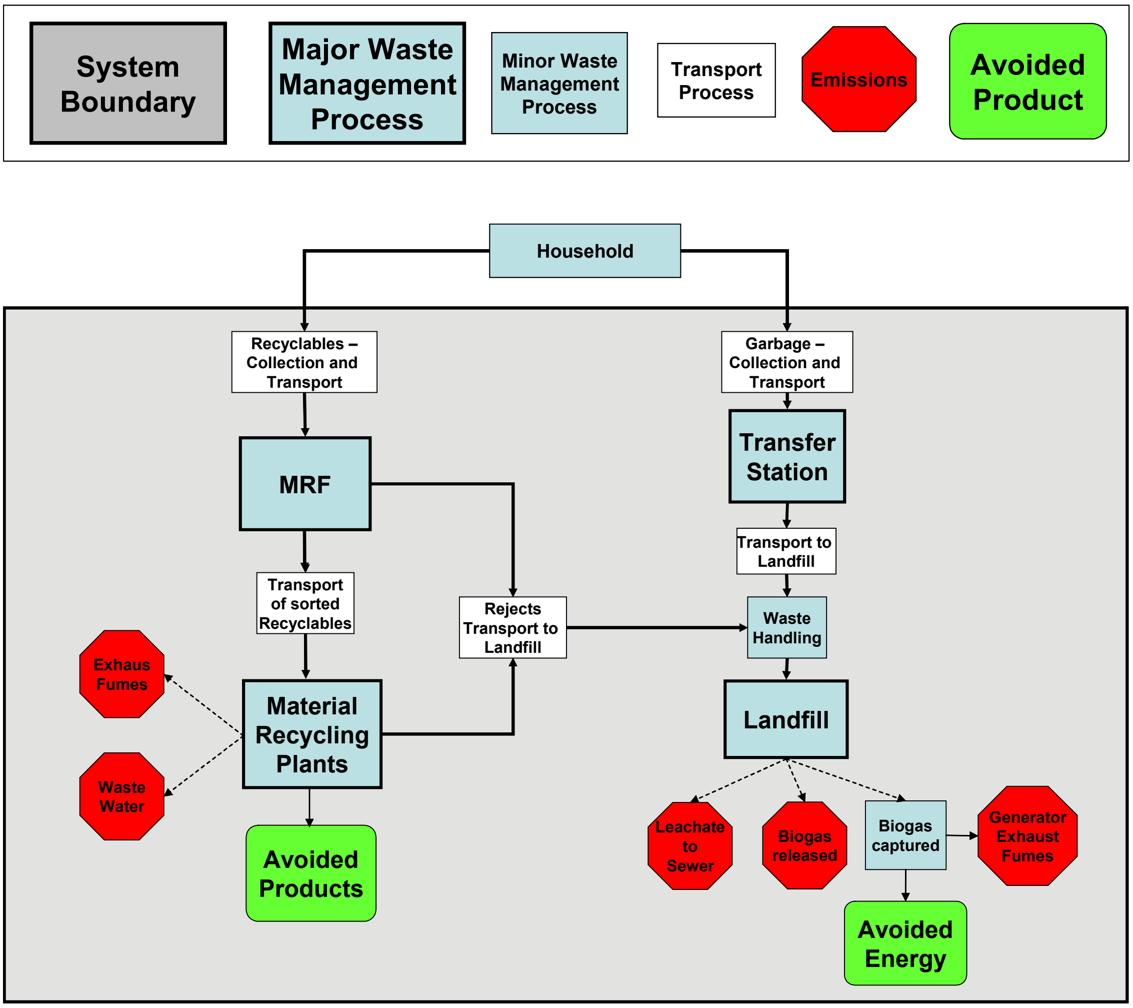


Figure 13 System diagram for Option 1 (landfill and MR)

Option 2 MRF, Energy Recycling, Landfill and Windrow Composting

Garbage and recyclables are collected and transported as in the Base Case and Option 1. While Garbage is landfilled again, recyclables are separated into fractions appropriate for energy recycling and for material recycling. Residues from the combustion process are disposed of at landfill. Garden waste is brought to windrow composting. A system diagram is shown in Figure 14.

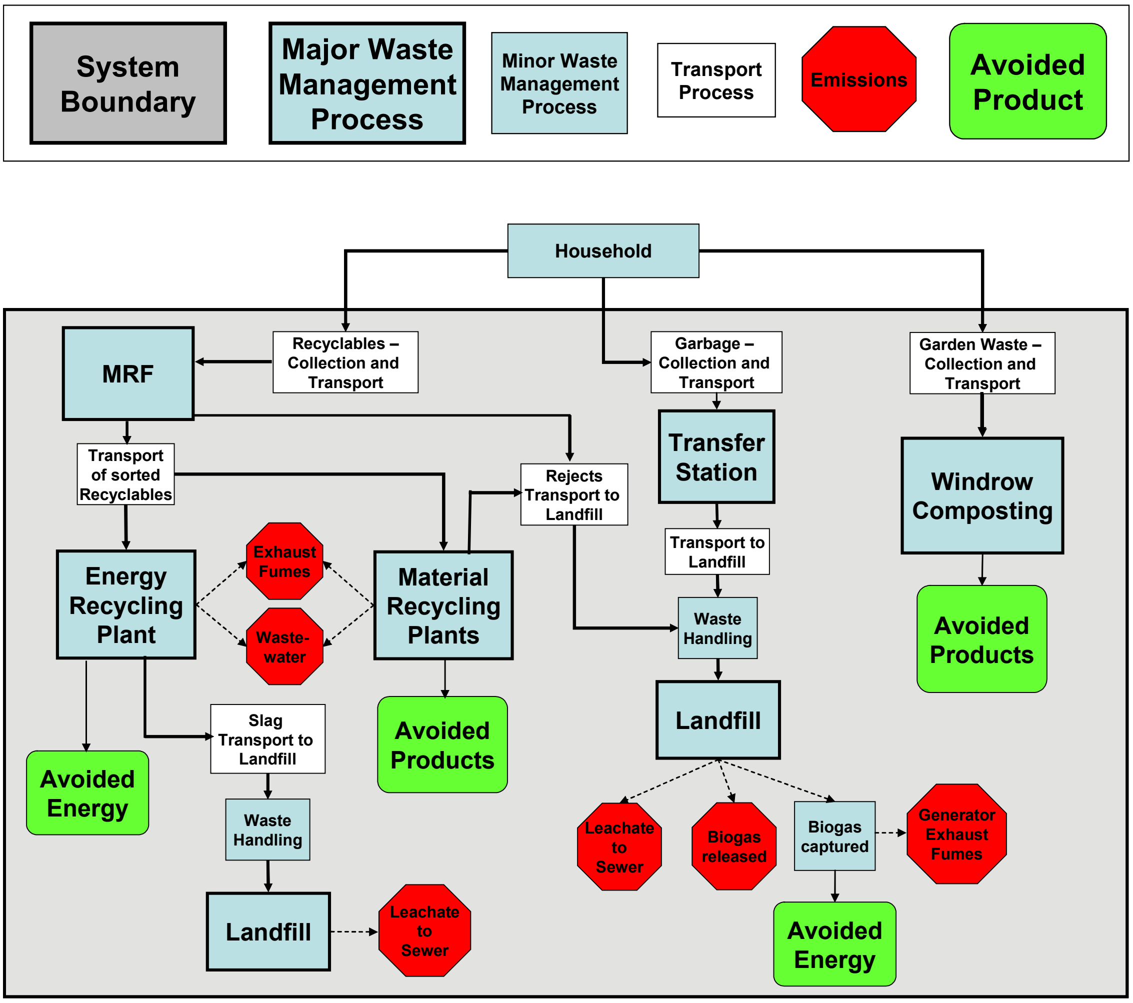


Figure 14 System diagram Option 2 (landfill, ER, MR and windrow composting)

Option 3 MRF, Combustion and Windrow Composting

Garbage is transferred to a WTE-plant instead to a landfill. The residues from this combustion process is disposed of at landfill. Recyclables including green waste will be treated as in the Base Case. The system diagram is shown in

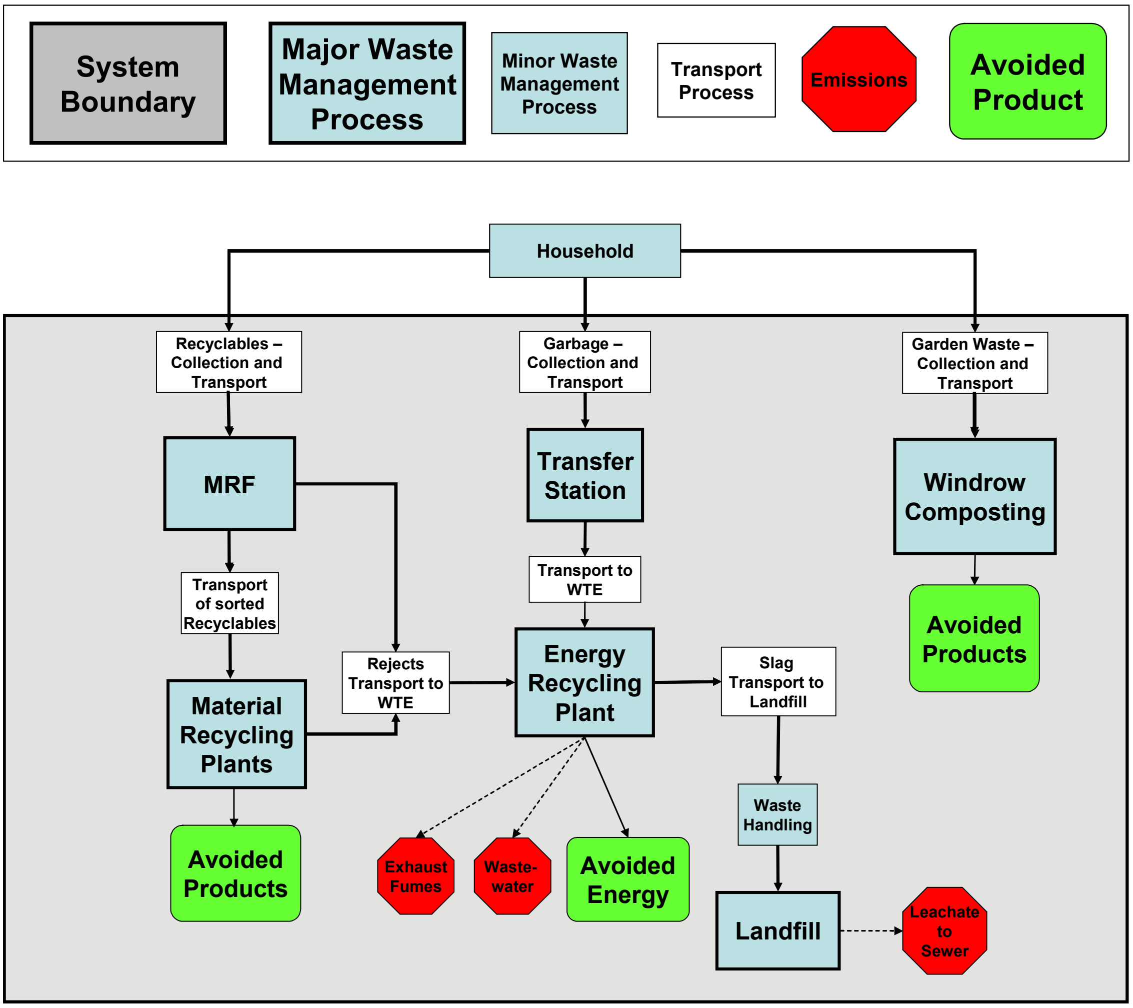


Figure 15 System diagram Option 3 (WTE, MR and windrow composting)

5.4.4 Data Quality Requirement

The quality of data has a big influence on the outcome of an LCA study. Therefore achieving a high level of data quality is a pre-condition for achieving the goal. A focus was certainly on the composition of the FU and the allocation of emissions. Transfer coefficients for allocating these emissions are mainly based on long-term-research projects (Sundqvist et al., (1999) [6]) and research underdone within a PhD project at the ETH Zurich about modelling the combustion of waste (Hellweg, 2000 [17]) The calculation of biogas is based on a scientific approach and its composition was calculated according the National Pollution Inventory of Australia [18].

Data for collection and transport, electricity and reprocessing incl. avoided products are almost taken from Lundie et al. (2001) [12].

Predominantly, data which were not calculated are Australian. Where necessary, they were complemented by international data.

All data represent current technology.

6 Life Cycle Inventory

This section provides a technical description of the systems under review with focus on relevant data for the model. A more detailed description of the waste management techniques can be found in Appendix A.

6.1 Collection and Transportation

Due to the high tonnages, transportation is a significant contributor to emissions and energy use.

In Table 3 key connections, distances, truck types and load efficiencies are identified. All data were taken from [12], except the transports connected with combustion and windrow composting. For the location of the incinerator it is assumed to be next to a landfill, therefore it has the same distance from the transfer station. This results in quite short transport distances for the slag as well. The windrow composting facility is supposed to be next to the landfill, but after collection the truck goes straight to the facility without stopping at the transfer station.

Table 3 Trucking logistics

Connections	Distances [km]	Distances from reprocessing to final Landfill / WTE [km]	Truck Types	Efficiency Loads [%]
Council – Transfer station	6.3		15t	50
Transfer Station – Landfill	27.5		22t	75
Council - MRF	17.3		15t	50
MRF - Landfill	23		30t	100
MRF - Reprocessing				
- Paper	24		22t	75
- Glass	24,6	28	15t	50
	then 50km to Penrith	19,5	15t	50
- Steel	80	10	28t	rural
- Aluminium	11	30	30t	100
- HDPE	1		7.5t	25
- LPB	160		28t	rural
Transfer Station - WTE	27.5		22t	75
WTE - Landfill	3		30t	100
Council – Windrow Comp.	30		15t	50

Fuel consumption for collection and transport is based on calculations from Lundie et al. (2001) [12]. As the collection of recyclables is more time consuming for each tonne collected, due to its lower weight per bin, more fuel is consumed.

6.2 Landfill

Landfill is relevant for all options, although disposed quantities vary significantly. In the Base Case most of the functional unit is disposed. This includes garbage, rejects from MRF and from recycling facilities. Garden waste is collected separately and composted. Option 1 differs for the amount of garden waste which is landfilled. In Option 2 the amount of waste to be disposed is smaller as less rejects occur at energy recycling for the calorific valuable fraction. Combustion residues are of much smaller volume. In Option 3 only combustion residues are landfilled. The emissions of landfilled slag are described in chapter 6.4.3.

6.2.1 Waste Handling

Once delivered, the waste has to be placed where it should be built in the landfill body. Then it is compacted.

The consumption of diesel for rolling stock is 0,7 kg per tonne waste deposited [12]. It is assumed that there are no differences in handling garbage or combustion residues.

6.2.2 Leachate

Leachate has its origin in liquid already contained in Waste and rain that enters the landfill body. Although a good compaction of waste prevents some of the water going through, it can't be completely avoided without a coverage.

In this study leachate generated at landfill is assumed to be collected and discarded into the sewer. Therefore it is treated off-site in a sewage water treatment plant (STP). This meets current practice in Sydney, although Lucas Heights in Southern Sydney recently set up a treatment facility for its leachate. During this study it was still under test conditions and results were not available.

Leachate is calculated for each waste fraction separately. Calculations are based on elementary compositions from [9,19,21], shown in Appendix C. With a known elementary composition, the effects of each fraction on leachate can be calculated by using transfer coefficients. [1]

Leachate emissions result in emissions to water and emissions to soil. This is due to the treatment in an STP, where the treated water is discharged to the sea (effluent) and the biosolids are applied in agriculture, composting and land rehabilitation [20]. Table 4 shows transfer coefficients and rates for treatment reduction. Emissions to soil are equal to the reduction rate at the STP except for total nitrogen (N-tot). The emissions for each fraction can be seen in Appendix C.

---

[1] Please note that a good prognosis on leachate emissions is extremely difficult, therefore the coefficients can only be seen as a rule of thumb

Table 4 Transfer Coefficients (TC) and treatment reduction for leachate

	TC	Treatment Reduction	Effluent emission as
N-tot	1 [a]	0.82 [b,d]	NH_3/NH_4^+
		0.5 [b]	NO_3^-
P-tot	0.02 [a]	0.834 [b]	PO_4^{3-}
Pb	$6 \cdot 10^{-5}$ [a]	0.8 [b]	
Cd	$7.13 \cdot 10^{-11}$ [a]	0.5 [b]	
Hg	$9.24 \cdot 10^{-13}$ [a]	0.8 [b]	
Cu	$2.53 \cdot 10^{-9}$ [a]	0.5 [b]	
Cr	$4.5 \cdot 10^{-9}$ [a]	0.6 [b]	
Ni	$2.38 \cdot 10^{-8}$ [a]	0.4 [b]	
Zn	$9.86 \cdot 10^{-9}$ [a]	0.9 [c]	
TSS	Waste specific [c]	0.9 [c]	

a taken from [6]

b taken from [9]

c taken from [11]

d 80% oxidation to Nitrate then a further 50% reduction to nitrogen gas [9]

Another important parameter for measuring environmental impacts from leachate is the Chemical Oxygen Demand (COD). It was calculated according (1) [6]. The reduction rate at the STP is 0.944 [12]. The results are shown in Table 5.

$$COD \approx 3 \times \alpha \times 0.01 \qquad (1)$$

where:

α = Degradation yield [kg degr. C/kg C_{in}]

C_{in} = Carbon input [kg]

COD = Chemical Oxygen Demand [kg O_2/kg waste]

Table 5 COD calculation

	C_{in} [kg/kg]	α	COD [kg O_2/kg]
Paper	0.414 [a]	0.90 [e]	$6.25 \cdot 10^{-4}$
Cardboard	0.502 [b]	0.80 [e]	$6.74 \cdot 10^{-4}$
ONP	0.394 [b]	0.80 [e]	$5.30 \cdot 10^{-4}$
LPB	0.537 [c]	0.71 [e]	$6.38 \cdot 10^{-4}$
HDPE	0.813 [b]	0.03 [e]	$4.10 \cdot 10^{-5}$
PET	0.608 [b]	0.02 [e]	$2.04 \cdot 10^{-5}$
PVC	0.381 [b]	0.03 [e]	$1.92 \cdot 10^{-5}$
LDPE	0.813 [b]	0.03 [e]	$4.10 \cdot 10^{-5}$
Mixed Plastic	0.694 [a]	0.03 [e]	$3.20 \cdot 10^{-5}$
Aluminium	0 [a]	0	0
Tin Plate	0 [a]	0	0
Glass	0 [a]	0	0
Food	0.13 [b]	0.86 [f]	$1.88 \cdot 10^{-4}$
Garden Waste	0.278 [a]	0.52 [f]	$2.41 \cdot 10^{-4}$
Mixed Waste	0.20 [d]	0.10 [d]	$3.36 \cdot 10^{-5}$

a taken from [6]

b taken from [9]

c based on estimated figure where LPB consists out of 12% LDPE and 88% cardboard

d estimated

e taken from [21]

f calculated (see Appendix C)

6.2.3 Biogas

All waste fractions except for inert ones (Glass, Aluminium and Tin Plate) contribute in a varying extent to the production of biogas. In general, the biogas potential of waste can be calculated with the equation invented by RETTENBERGER/TABASARAN [22]:

$$G_P = 1.868 \times C_{org} \times \left(0.014 \times \theta + 0.28\right) \tag{2}$$

where:

G_p = gas potential [m^3/t]

θ = temperature in the landfill [°C]

$C_{org.}$ = organic Carbon [kg/t]

This equation had to be modified for two reasons: 1st the content of organic carbon was unknown and 2nd landfill effects were examined for the surveyable time period of 100 years. As biogas production continues after that time, the production during the first 100 years must be smaller than the potential. Therefore, $C_{org.}$ was replaced by degraded Carbon $C_{degr.}$[kg]:

$$C_{\deg r} = C_{in} \times \alpha \tag{3}$$

The temperature in the landfill body is assumed to be 30°C. The modified equation is:

$$G_p = 1.868 \times C_{\deg r} \times (0.014 \times 30 + 0.28) \tag{4}$$

Once the gas volume was calculated, it had to be converted into weight as the software model can not handle volumes. For the biogas, a CO_2-content of 45% and a CH_4-content of 55% is assumed. The following equation is used to calculate the density of mixed gases [23]:

$$\rho_m = \frac{\rho_1 V_1 + \rho_2 V_2}{V_1 + V_2} \tag{5}$$

ρ_m = density of gas mixture	[kg/m^3]
ρ_1 = density of gas no. 1	[kg/m^3]
ρ_2 = density of gas no. 2	[kg/m^3]
V_1 = volume of gas no. 1	[m^3]
V_2 = volume of gas no. 2	[m^3]

As the density of gases differ with varying temperatures, the densities of CO_2 and CH_4 in the biogas had to be calculated. Within this calculation, which is shown in Appendix C, trace elements were neglected.

Once these two values were derived, the density of the biogas (ρ_{BG}) could be calculated according to (5):

$$\rho_{BG} = \frac{\rho_{CO2} V_{CO2} + \rho_{CH4} V_{CH4}}{V_{CO2} + V_{CH4}} \tag{6}$$

$$\rho_{BG} = \frac{1.811053\frac{kg}{m^3}\times 0.45m^3 + 0.656666\frac{kg}{m^3}\times 0.55m^3}{0.45m^3 + 0.55m^3} = 1.17614\frac{kg}{m^3} \quad (7)$$

This resulted in an overall density of the studied biogas of 1.17614 kg/m^3. Now the production of biogas for each waste fraction and, based on the capture rate of 66%, the released biogas could be calculated [12].

Table 6 Biogas production

	$C_{degr.}$ [kg/kg]	Biogas [m^3/kg]	Biogas cap. [kg/kg]	Biogas rel. [kg/kg]
Paper	0.372	0.487	0.321249	0.165492
Cardboard	0.401	0.525	0.346311	0.178403
ONP	0.315	0.412	0.272188	0.140218
LPB	0.380	0.497	0.327855	0.168895
HDPE	0.024	0.032	0.021054	0.010846
PET	0.012	0.016	0.010494	0.005406
PVC	0.011	0.015	0.009863	0.005081
LDPE	0.024	0.032	0.021054	0.010846
Mixed Plastic	0.019	0.025	0.016459	0.008479
Aluminium	0	0	0	0
Tin Plate	0	0	0	0
Glass	0	0	0	0
Food	0.112	0.146	0.096546	0.049736
Garden Waste	0.144	0.019	0.123860	0.063807
Mixed Waste	0,200	0.026	0.01726	0.008892

The captured biogas is used for energy production. The generator which converts biogas into electricity produces 4.89 MJ/kg [12]. The emission profile of the engine exhaust is shown in Appendix C.

The profile of 1 kg of biogas needs to be more detailed. As mentioned above, it contains trace elements of other gases. Further, not all carbon dioxide produced within the landfill can be considered, as some of it is emitted from biogenic sources. Biogenic sources can be e.g. paper, food and garden waste. In an LCA, this is considered as being neutral and therefore not balanced. CO_2 arising from fossil sources, e.g. plastics, is counted. What kind of carbon is in the different waste fractions is shown in the elementary composition in Appendix C. Last but not least, some of the methane oxidises on its way to the surface through the soil cover (which is applied regularly on a landfill). The chemical reaction of this process is:

$$CH_4 + 2O_2 \rightleftharpoons CO_2 + 2\,H_2O \qquad (8)$$

It is assumed that 15% of the methane is oxidised [6].

The trace elements of biogas were calculated according the manual of the National Pollution Inventory, although the equations had to be modified slightly. This is because the manual refers to emissions of a landfill for 1 year and not to 1 kg of biogas. The release rate of 34% had to be considered as well. First, the volume of 1 kg of biogas had to be calculated, based on the density of 1.17613 kg/m^3:

$$V_{1kgBG} = \frac{1kg}{1.17614\frac{kg}{m^3}} = 0.850238917m^3 \qquad (9)$$

The next two equations served to estimate the volume terms of certain gases listed in Table 7 and convert them into kg.

$$Q_i = \left(1 + \left(\frac{C_{CO2\%}}{C_{CH4\%}}\right)\right) \times Q_{CH4} \times \left(\frac{C_i}{10^6}\right) \qquad (10)$$

where:

Q_i = emission rate of pollutant i [m^3]

Q_{CH_4} = methane generation rate [m^3]

C_i = concentration of i in landfill gas [ppmv]

$C_{CH_4\%}$ = concentration of CH_4 in the landfill gas (55% assumed)

$C_{CO_2\%}$ = concentration of CO_2 and other gas in the landfill gas (45% assumed)

10^6 = conversion from ppmv

$$UM_i = Q_i \times \left(\frac{MW_i \times 1atm}{8.205 \times 10^{-5} \times 1000 \times 273 + T}\right) \times 0.34 \qquad (11)$$

where:

UM_i = uncontrolled mass emissions of pollutant i [kg]

Q_i = emission rate of pollutant i [m^3]

MW_i = molecular weight of i [g/mol]

T = temperature of landfill gas [°C]

$8.205 \cdot 10^{-5}$ = constant to convert emissions of i to kg [-]

1000 = constant [g/K]

273 = constant 0°C [K]

0.34 = release rate for biogas [-]

The complete emission profile of 1 kg of biogas can be seen in Table 7. All gases from the NPI list were taken except those which are not defined in the used LCA software.

Table 7 Emission profile of 1 kg of biogas

G/mol[1]	Ci [ppmv][1]	Emission	[kg/kg]
133.41	0.48	1,1,1-Trichloroethane	$1.38 \cdot 10^{-7}$
133.41	0.10	1,1,2-Trichloroethane	$2.87 \cdot 10^{-8}$
98.97	2.35	1,1-Dichloroethane	$5.00 \cdot 10^{-7}$
98.96	0.41	1,2-Dichloroethane	$8.72 \cdot 10^{-8}$
96.94	0.20	1,1-Dichloroethene	$4.17 \cdot 10^{-8}$
112.99	0.18	1,2-Dichloropropane	$4.37 \cdot 10^{-8}$
60.11	50.10	2-Propanol	$6.47 \cdot 10^{-6}$
58.08	7.01	Acetone	$8.75 \cdot 10^{-7}$
53.06	6.33	Acrylonitrile	$7.22 \cdot 10^{-7}$
78.11	1.91	Benzene	$3.21 \cdot 10^{-7}$
163.83	3.13	Bromodichloromethane	$1.10 \cdot 10^{-6}$
58.12	5.03	Butane	$6.28 \cdot 10^{-7}$
76.13	0.58	Carbon disulfide	$9.49 \cdot 10^{-8}$
28.01	141	Carbon monoxide	$8.49 \cdot 10^{-6}$
153.84	0.004	Carbon tetrachloride	$1.32 \cdot 10^{-9}$
112.56	0.25	Chlorobenzene	$6.05 \cdot 10^{-8}$
64.52	1.25	Chloroethane	$1.73 \cdot 10^{-7}$
119.39	0.03	Chloroform	$7.70 \cdot 10^{-9}$
50.49	1.21	Chloromethane	$1.31 \cdot 10^{-7}$
147.00	0.21	Dichlorobenzene	$6.64 \cdot 10^{-8}$
102.92	2.62	Dichlorofluoromethane	$5.80 \cdot 10^{-7}$
84.94	14.30	Dichloromethane	$2.61 \cdot 10^{-6}$
30.07	889.00	Ethane	$5.75 \cdot 10^{-5}$
46.08	27.20	Ethanol	$2.69 \cdot 10^{-6}$
106.17	4.61	Ethylbenzene	$1.05 \cdot 10^{-6}$
86.18	6.57	Hexane	$1.22 \cdot 10^{-6}$
34.08	35.50	Hydrogen sulfide	$2.60 \cdot 10^{-6}$
200.61	2.92 · 10-04	Mercury	$1.26 \cdot 10^{-10}$
48.11	2.49	Methyl mercaptan	$2.58 \cdot 10^{-7}$
72.15	3.29	Pantane	$5.10 \cdot 10^{-7}$
44.09	11.10	Propane	$1.05 \cdot 10^{-6}$
92.13	39.30	Toluene	$7.78 \cdot 10^{-5}$
96.94	2.84	t-1,2-Dichloroethene	$5.92 \cdot 10^{-7}$
62.50	7.34	Vinyl chloride	$9.86 \cdot 10^{-7}$
106.16	12.10	Xylenes	$2.76 \cdot 10^{-6}$
		Methane	$2.61 \cdot 10^{-1}$
		Carbon Dioxide	$1.27 \cdot 10^{-7}$

1 taken from [18]

6.3 Material Recycling Facility

In all options recyclables are sent to a Material Recycling Facility (MRF). At the MRF materials are sorted and baled for further transport to the reprocessing facility. For a detailed description of the MRF please refer to Appendix A. Assumptions for energy requirements of the sorting process were taken from [24]. 19.8 MJ of electrical input and 0.97 kg of diesel per tonne of materials are needed. The following table shows the reject rates for all materials. In general, 10% of all loads have to be disposed without further sorting due to a high degree of contamination. Often hazardous wastes like medical residues are the reason for this [25]. The table just refers to material recycling; where energy recycling takes place; there are 10% of rejects which have to be disposed for fractions to be combusted.

Table 8 Reject rates for source separation [%]

Recyclables	Losses prior to MRF	Reject rates	Total reject rates
Paper	10	15[2]	23.5
ONP	10	15[1]	23.5
Cardboard	10	15[2]	23.5
LPB	10	33[1]	39.7
Aluminium	10	2.1[1]	11.9
Tin Plate	10	51	14.5
Glass	10	20[1]	28.0
PET	10	51	14.5
HDPE	10	51	14.5

1 taken from [12]

2 assumed to be the same like ONP

6.4 Waste-to-Energy (Combustion)

In Option 2 and 3 WTE was considered for varying amounts of domestic waste. While in Option 2 energy recycling was just chosen for recyclables with a high calorific value, in Option 3 all domestic waste and recyclable rejects are combusted except green waste. WTE is done for three reasons: the volume is minimised, residues are nearly inert and energy is produced. The plant in this study is designed according to an incinerator in Spittelau, Austria. For a detailed description of the combustion technology please refer to Appendix A.

6.4.1 Energy Output

As mentioned above, the production of energy is a reason for WTE. It is taken into account as an avoided product. The output of energy depends on the calorific value of the waste, the efficiency of the plant and the type of energy delivered. Here, just electricity is provided.

Assuming a flue gas temperature of 1200°C the energy efficiency of the mass incinerator was calculated as shown in the next table. The first loss of energy is caused by the ash, followed by thermal losses from the furnace. For a well designed furnace it might not be higher than 1%. Then, the flue gas must be cooled down by a boiler. When converting steam energy into mechanical energy 60% and with the connected generator further 2% will be lost. Another deduction of the energy appears by the own demand of the plant. This is due to water pumps, electrostatic filters for the flue gas cleaning, the crane to feed the incineration chamber with waste or other electrical devices [26].

Table 9 Energy efficiency and losses for mass burn incineration [%]

	Energy Efficiency	Losses
Energy lost with hot ashes		1.0
Thermal losses from furnace		1.0
Boiler efficiency (quenching 400°C)	68.3	31.7
Turbine efficiency (steam at 480°C)	40.0	60.0
Generator efficiency	98.0	2.0
Electrical energy to drive water pumps		1.0
Other electrical plant		1.5
Overall efficiency	25.4	74.6

Source: [26]

The overall efficiency of 25.4 fits well with other literature. The Öko-Institut sees the efficiency for modern plants at 28% before deduction of their own energy-demand [27]. The IPPC quotes an efficiency of 25 – 30% for plants with electricity as the only form of energy recovery [28].

Table 10 shows the calorific value and their output in a mass incinerator. The calorific values have been taken from [23]. The outputs were calculated with the next equation:

$$E_e = LHV \times \eta \qquad (12)$$

where:

E_e = energy (electrical) [MJ/kg]

LHV = Lower heating value [MJ/kg]

η = efficiency

As there are no valuable data about the Lower Heating Value of food and garden waste, it had to be calculated according to BOIE [29]:

$$\begin{aligned} LHV_C &= 34.835\times C + 93.870\times H + 6.280\times N + 10.465\times S \\ &\quad -10.800\times O_2 - 2.440\times W_C \end{aligned} \tag{13}$$

where:

LHV_C = Lower heating value of the combustible [kg/kg]

C = Carbon content [kg/kg]

H = Hydrogen content [kg/kg]

N = Nitrogen content [kg/kg]

S = Sulphur content [kg/kg]

O_2 = Oxygen content [kg/kg]

W_c = Water content of the combustible [kg/kg]

LHV for food waste:

$$\begin{aligned} LHV_{FW} &= 34.835\times 0.1302 + 93.870\times 0.0174\times 6.280\times 0.006 + 10.465\times 0.00072 \\ &\quad -10.800\times 0.0861 - 2.440\times 0.7 = 3.58\frac{MJ}{kg} \end{aligned} \tag{14}$$

LHV for garden waste:

$$\begin{aligned} LHV_{GW} &= 34.835\times 0.2778 + 93.870\times 0.024 + 6.280\times 0.0042 + 10.465\times 0.0003 \\ &\quad -9.840\times 0.234 - 2.440\times 0.4 = 8.681\frac{MJ}{kg} \end{aligned} \tag{15}$$

Table 10 Net calorific values of waste fractions and energy output in an mass burn incinerator

	Net calorific value (MJ/kg)	Output (MJ/kg)
Paper	15.75_a	4.00
Cardboard	16.38_a	4.16
ONP	18.55_a	4.71
LPB	26.35_a	6.69
HDPE	40.32_a	10.24
PET	40.32_a	10.24
PVC	22.59_a	5.74
LDPE	40.32_a	10.24
Mixed Plastics	34.41_a	8.74
Aluminium	0_a	0
Tin Plate	0_a	0
Glass	0_a	0
Food	3.58_b	0.91
Garden Waste	8.681_b	2.20
Mixed Waste	10_c	2.54

a taken from [26]
b calculated
c estimated

6.4.2 Residues of the combustion process

It is assumed, that the residues after combustion can be calculated according to the inert content of each material. Organic leftovers, which were not burnt, are not taken into account. Further, due to a lack of data, the inert content of paper was also taken for ONP and cardboard, and iron is assumed to be the same like tin plate. As metals and glass are contaminated with organics, they do not have an inert content of 100%. This, however, does not affect the net calorific value of these fractions. 11% of the inert material is fly ash (derived from data from [9]). While slag is landfilled the fly ash is due to its high content of heavy metals mixed with water and cement and used as construction material on the landfill site. The effects were not considered in Table 11 due to lack of data. The bottom ash is landfilled.

Table 11 Inert contents

Material	inert [% of wet substance]	Fly ash [kg/kg]	Bottom ash [kg/kg]
Paper	11.6[a]	0.01276	0.10324
ONP	11.6[b]	0.01276	0.10324
Cardboard	11.6[b]	0.01276	0.10324
LPB	17.4[a]	0.01914	0.15486
Plastics	0.9[a]	0.00099	0.00801
Glas	94.1[a]	0.10351	0.83749
Tin Plate	86.0[b]	0.0946	0.7654
Al	47.4[a]	0.05214	0.42275
Garden Waste	2.7[c]	0.00297	0.02403
Food Waste	1.5[c]	0.00165	0.01335

[a] taken from [30]

[b] adjusted to [30]

[c] taken from [31]

6.4.3 Emissions to Air, Water and Soil

In the next step emissions had to be calculated for the combustion process. For calculating these emissions, transfer coefficients (TC) were used again. These refer to flue gas (after emission control), slag and waste water (after waste water treatment). The treatment of leachate from landfilled slag and the derivation of emissions correspond to leachate from garbage, but other transfer coefficients are used. Some of the TC for flue gas had to be calculated, as literature doesn't provide them in a way that includes the mole weight of the element and the final emission. Their derivation is shown in Appendix C. All TC are listed in Table 12 and Table 13.

Table 12 Transfer coefficients for waste combustion

	Transferred to flue gas as	Flue gas [-]	Slag [-]	Waste water [-]
C-fossil	CO_2	$3.62633_{a,c}$	-	-
Cl	HCl	0.04_{b}	0.071_{a}	0.909^{1}
N-tot	N_2	$0.982077_{a,c}$	-	$0.004429^{1,3,7}$
	NO	$0.011073_{a,c,d}$		
	NO_2	$0.000894\ _{a,c,d}$		
	N_2O	$0.001865_{a,c}$		
	CN	$0.000096_{a,c}$		
	NH_3	$0{,}000901\ _{a,c}$		
S-tot	SO_2	0.08_{b}	-	-
Pb		0.002_{b}	0.066_{a}	0.0_{a}
Cd		0.005_{b}	0.003_{a}	0.0_{a}
Hg		0.133_{b}	0.006_{a}	0.01_{a}
Cu		0.001_{b}	0.801_{a}	0.0_{a}
Cr		0.002_{b}	0.455_{a}	0.003_{a}
Ni		0.001_{b}	0.901_{a}	0.0_{a}
Zn		0.002_{b}	0.003_{a}	0.0_{a}
Dust		$1.78 \cdot 10^{-5}{}_{b,e}$	-	-
CO		$0.0015_{b,f}$		
PAH		$3.41 \cdot 10^{-8}\ _{b,f}$	-	-
Dioxins		$3.40 \cdot 10^{-12}\ _{b,f}$	-	-

- not available or not relevant for the model

a taken from [17]

b taken from [9]

c transfer coefficients calculated in (33) - (21)

d Achternbosch et al. (2002) assumes a ratio for No_x of NO 95% and NO_2 5% [32]

e weight allocation

f c- allocation

g as Nitrate

Table 13 Transfer coefficients for landfilled slag, reduction rate for STP and final discharge to sea

	Leachate	Reduction rate (emissions to soil)	Discharge
Pb	$1.50 \cdot 10^{-5}{}_{a}$	0.8_{a}	0.2
Cd	$4.00 \cdot 10^{-3}{}_{a}$	0.5_{a}	0.5
Hg	$6.06 \cdot 10^{-3}{}_{b}$	0.8_{a}	0.2
Cu	$4.00 \cdot 10^{-3}{}_{a}$	0.5_{a}	0.5
Cr	$3.00 \cdot 10^{-4}{}_{a}$	0.6_{a}	0.6
Ni	$2.22 \cdot 10^{-3}{}_{b}$	0.4_{a}	0.6
Zn	$1.00 \cdot 10^{-5}{}_{a}$	0.9_{c}	0.1

1 taken from [9]

2 derived from leaching tests in [33]

3 taken from [12]

The emissions for the combustion of each fraction are listed in Appendix C.

6.4.4 Additional Chemicals for Flue Gas Cleaning

The flue gas cleaning includes an electrical precipitator, a wet scrubber and a Selective Catalytic Reduction (SCR) for NO_x. Residues from the flue-gas cleaning were not taken into account.

The consumption of auxiliary chemicals was based on stoichiometric ratios. “The stoichiometric ratio is defined as the ratio between equivalents of the neutralisation agents supplied to the flue gas cleaning system and equivalents of acid pollutants in the flue gas” [32]. Achternbosch et al. quotes a stoichiometric ratio for the wet scrubber of 1.1. Although literature provides even higher ratios, he doesn’t recommend them as all chemicals added in excess will increase residues of flue gas cleaning to be disposed.

Based on this, factors could be developed allowing to calculate the lime demand based on the chlorine content and the demand of caustic soda based on the sulphur content of the waste fraction. These calculations are simplified, as other acid pollutants like HF, which could not be quantified, are neutralised as well.

In the wet scrubber first HCl is neutralised by adding milk of lime. For the production of milk of lime, lime itself is used. As the reference plant in Spittelau quotes the demand on lime, the same is done for the calculated data sets. The equations (16) and (17) show the production of lime and the reaction in the wet scrubber where HCl is neutralised, (18) shows the reaction in the wet scrubber:

$$CaCO_3 \rightleftharpoons CaO + CO_2 \tag{16}$$

$$CaO + H_2O \rightleftharpoons Ca(OH)_2 \tag{17}$$

$$2\ HCl + Ca(OH)_2 \rightleftharpoons CaCl_2 + 2\ H_2O \tag{18}$$

These equations result in a $CaCO_3$ demand of 0.5 mole per mole CL.

$$f_{CaCO_3} = \frac{\frac{M_{CaCo_3}}{2}}{M_{Cl}} \times 1.1 = \frac{\frac{100 \frac{g}{mole}}{2}}{36 \frac{g}{mole}} \times 1.1 = 1.52778 \tag{19}$$

where:

f_{CaCO_3} = factor for calculation of $CaCO_3$ demand [kg/kg Cl]

M_{CaCO_3} = mole mass for $CaCO_3$ [g/mole]

M_{Cl} = mole mass for Cl [g/mole]

1.1 = stoichiometric factor

To calculate the demand on lime, the factor had to be multiplied with the Cl-content.

In the second stage of the wet scrubber, sulphur dioxide is removed with an efficiency up to 95% [6]. For this, caustic soda is required. The next equation shows the reaction of caustic soda with sulphur dioxide:

$$SO_2 + 2\ NaOH \rightleftharpoons Na_2SO_3 + H_2O \tag{20}$$

This equation results in a NaOH demand of 2 mole per mole SO_2.

$$f_{NaOH} = \frac{M_{NaOH}}{M_S} \times 2 \times 1.1 = \frac{40 \frac{g}{mole}}{32 \frac{g}{mole}} \times 2 \times 1.1 = 2.75 \tag{21}$$

where:

f_{NaOH} = factor for calculation of NaOH demand

M_{NaOH} = mole mass for NaOH [g/mole]

M_S = mole mass for S [g/mole]

To calculate the demand on caustic soda, the factor had to be multiplied with the S-content.

The wet scrubber is followed by the SCR, where Ammonia (NH_3) is added to remove Nitrogen Oxides (NO_x). 95% of the NO_x are NO, while 5% are NO_2 [32]. The reactions for the SCR are as follows[32]:

$$4\ NO + O_2 + 4\ NH_3 \rightleftharpoons 4\ N_2 + 6\ H_2O \qquad (22)$$

$$2\ NO_2 + O_2 + 4\ NH_3 \rightleftharpoons 3\ N_2 + 6\ H_2O \qquad (23)$$

A factor could be calculated as well to estimate the demand of NH_3. For the calculation the stoichiometric ratio of 1 was taken. The reactions (22) and (23) show a NH_3 demand of 1 mole per mole of NO and 2 moles per mole of NO_2.

$$\begin{aligned} f_{NH_3} &= \frac{M_{NH_3}}{M_{NO}} \times 0.0055 \times 0.95 + \frac{M_{NH_3}}{M_{NO_2}} \times 0.0055 \times 0.05 \times 2 \\ &= \frac{17\frac{g}{mole}}{30\frac{g}{mole}} \times 0.0055 \times 0.95 + \frac{17\frac{g}{mole}}{46\frac{g}{mole}} \times 0.0055 \times 0.05 \times 2 \\ &= 0.003164 \end{aligned} \qquad (24)$$

where:

f_{NH_3} = factor for calculation of NH_3 demand

M_{NH_3} = mole mass of NH_3 [g/mole]

M_{NO} = mole mass of NO [g/mole]

M_{NO_2} = mole mass of NO_2 [g/mole]

0.0055 = factor for conversion from N to NO_x

0.95 = percentage of NO from NO_x

0.05 = percentage of NO_2 from NO_x

To calculate the demand on ammonia, the factor had to be multiplied with the N-content.

6.5 Reprocessing

Reprocessing of valuable materials is an important part of all options. Only in Option 2 energy recycling is seen as an alternative to material recycling. Energy recycling is only discussed for the calorific rich fractions. The information for this chapter have mainly been taken from [12], others are marked differently.

To model the reprocessing of different materials inventory data on reprocessing of the recyclable material are needed. Further, data on the primary production of the product which is replaced (avoided product) are needed. The benefits from reprocessing result from the difference in inputs (material, energy) and outputs (emissions) between the reprocessing stage and the avoided product stage.

This section gives a brief description for the reprocessing of paper and newsprint, cardboard, LPB, PET, HDPE, aluminium and tin plate.

6.5.1 Paper and Newsprint

In NSW newsprint is reprocessed to newsprint again. Paper is reprocessed to paper, newsprint and cardboard. Due to a lack of data, the reprocessing to paper could not be modelled. Therefore, all paper is reprocessed to newsprint in order to avoid “downcycling” This is a process, where the reprocessed product has a lower quality level than the primary product. It would decrease the benefits of recycling.

Paper is trucked 500 km to Albury where it is reprocessed. The reprocessing involves mechanical pulping and the addition of virgin softlogs and chemical additives to strengthen the fibres and facilitate chemical breakdown. As it has to be de-inked, pulp is mixed with a soap solution and air is vented through the mix. For each kg of newspaper recyclate delivered, 0.6 kg have to be disposed. These consist not just out of paper but also biosolids from the process. No data were available about the ratio of these waste fractions, therefore it is completely taken into account as newsprint. The avoided product is newsprint.

6.5.2 Cardboard

Recycling cardboard replaces unbleached kraft pulp, the precursor to cardboard and linerboards. The complete feedstock is assumed to be recyclable material and not virgin. This assumption is based on a Visy cardboard reprocessing plant in Victoria. As a consequence of no virgin input, the end product is low grade testliner. To add strength to the degraded fibres, 24.4 kg of starch from wheat is needed per tonne of recycled cardboard.

Recycling cardboard results in an energy saving, as reprocessing to pulp is largely a mechanical process, whereas primary production is a thermo-chemical process. In the pulping stage reprocessing requires less energy than primary production as well. But as less energy is produced within the recycling system, more external heat energy will be used for the drying process, where steam is required. 555 KWh are used to produce one tonne of linerboard. As the system boundary covers the pulping process only, approximately 60% of the electricity is used in this stage (333 KWh). The avoided product is unbleached kraft pulp.

6.5.3 Liquid Paper Board

LPB represents the smallest fraction of the functional unit. The material composition is 12% LDPE and 88% Cardboard, of which 67% are recovered. The remaining material is sent to landfill, except in Option 2, where LPB is energy recycled. Possible end products for LPB are e.g. cardboard and tissues – the chosen avoided product is unbleached kraft pulp.

It is assumed that the energy inputs for reprocessing are the same as for paper reprocessing.

6.5.4 HDPE

Recovered HDPE is shreddered, washed and dried. The reject rate at reprocessing is approximately 10%. Total energy inputs for reprocessing are 779 kWh/t and can be splitted as follows (Table 14):

Table 14 Energy Inputs for Reprocessing HDPE [24]

Process	**Energy [kWh/t]**
Shredding	1
Conveyor	3
Milling	20
Fine Milling	3.6
Separation	0.36
Spin dry	4.5
Dry	0.6
Extrusion	746
Total	779

The extrusion is the most energy intensive process within this chain.

Additionally, a front end loader is used. Approximately 0.04 hours are needed to debale and move one tonne of material. The avoided product is HDPE.

6.5.5 PET

PET is assumed to have the same energy input and the same reject rate as HDPE. The avoided product is crystalline PET. As there is no PET production in Australia, overseas data were used. The avoided product is crystalline PET.

The energy inputs for crystalline PET are approximately 86 MJ/kg. Further, 13.4 kg of Oxygen are required for each tonne.

6.5.6 Aluminium

Reprocessing aluminium in a rotary furnace requires 9.4 MJ electricity per kg recyclate. The reject rate is approximately 18%. As the avoided product is highly energy intensive, there are considerable benefits in reprocessing aluminium: the total energy required for primary production is 223 MJ/kg, therefore the saving is more than 95%.

6.5.7 Tin Plate

Bailed tin plate is transported to BHP at Port Kembla. 25% of the recyclables are fed through a de-tinning process and shredded, while the other 75% are shredded straight away. After the shredding both fractions are fed to the furnace. The avoided product is pig iron.

For every tonne of shredded tin plate, 39 kg of shredder dust are produced and taken to landfill.

6.5.8 Glass

Glass is separated at the MRF by hand into clear, green and brown glass fractions. These fractions are transported to the benefication plant in Botany where they are cut into cullets. This process requires 0.02 MJ/kg of power. The cullets are then transported to Penrith, where they are melted in a gas fuelled furnace. For every 10% of feedstock that is recyclate, a 2% reduction of energy demand occurs. ACI Australia, for instance, uses an average of 45% of cullet. With an energy requirement of 8.38 MJ/kg of primary production, there is a 0.75 MJ/kg saving in using this fraction for the glass melt.

6.6 Windrow Composting

Composting of garden waste is just practiced in 12 councils. Still, a huge percentage of garden waste is finally disposed of at landfill.

The data for this chapter have been taken from [34].

After recyclables are collected at the council, they are not brought to a transfer station but straight to the composting facility, as squeezing garden waste does not improve the process of composting.

After the receival of feedstock material physical contaminants are removed. These contaminants are transported to landfill, but this is, as mentioned above, neglected in this study. The clean feedstock is stockpiled.

The composting process to follow includes shredding, windrow formation and screening. The last step is the dispatch. Table 15 shows the fuel and electricity consumption of each step per tonne of feedstock.

Table 15 Fuel and electricity consumption during composting operations

Operation	**Diesel [l]**	**Electricity [kW]**
Receival	0.48	0
Composting process (shredding, windrow formation and screening)	5.02 (3.65 + 0.58 + 0.79)	0.13
Dispatch	0.03	0
Total	5.53	0.13

As end product of the composting process composted mulch was chosen, applied in agriculture on grapevine. Applied on 1 hectare with a layer of 10 cm depth, it replaces 72 – 108 kg of N, 120 – 180 kg of P and 90 – 135 kg of K-fertiliser within 3 – 5 years of application. As a conservative assumption the minimum replacement was taken for each avoided product. The derivation of factors for the avoided product is shown in Appendix C, the results are listed in Table 16.

Table 16 Conversion factor for avoided products

	Factor [kg/kg]
N-fertiliser	0.000144
P-fertiliser	0.00024
K-fertiliser	0.00018

Please note, that just little benefits that compost is able to provide could be taken into account. So far, there is no method to include benefits like improved irrigation efficiency, which is of special interest for Australia, and better protection against erosion in an LCA.

7 Life Cycle Impact Assessment

In this chapter, the impact categories will be chosen from a list of resource use and environmental impact categories. They will be explained, the results of the LCI will be assigned to them (classification) and they will be characterised. For more detailed information concerning the general methodology please refer to Chapter 2.3. Interpretation of results and recommendations are subject to Chapter 2.4.

In the first part of the LCIA the impact categories are chosen and briefly explained.

7.1 Description of selected Impact Categories and Classification

In the following, explanation and classification of chosen impact categories are combined. This is helpful for a better understanding. Please note that impact categories address the *potential* effect to the environment and to humans. They do not measure real impacts.

For this study the following impact categories were selected:

- Total energy
- Climate change
- Eutrophication potential (EP)
- Photochemical oxidant formation potential (POCP)
- Human toxicity potential Australia (HTPAU)
- Freshwater aquatic ecotoxicity potential Australia (FAEP)
- Marine aquatic ecotoxicity potential Australia (MAEP) and
- Terrestrial ecotoxicity potential Australia (TEP)

The impact categories will be explained in the following.

7.1.1 Total Energy

Total energy is a helpful category for analysing the energy intensity of the waste management systems. It also provides useful data when analysing results on climate change and other impact categories.

This category covers renewable (e.g. biogas, wood) and non-renewable (e.g. coal, oil) energy sources. It can be seen as an indicator for the depletion of energy resources and is expressed in MJ. Therefore it is not an environmental indicator.

7.1.2 Climate Change

Climate change is of national and international interest. Currently, Australia is one main emitter of greenhouse gases, which promote climate change, worldwide.

The effects of climate change on Australia can be seen as significant. Climate change is assumed to increase extreme weather phenomena like El-Niño-Southern-Oscillation (ENSO). This is not proven yet, but it is fact that since mid-1970s an increase of ENSO events happened [4]. Models suggest a connection between emitted greenhouse gases and ENSO. With a doubled amount of atmospheric CO_2 by 2050 it predicts more frequent ENSO [35]. Draught is an effect ENSO has on Australia. Another effect of climate change is a general increase in temperature in Australia. Simulations suggest a decrease of 0.4 to 2.0 °C by 2030, and 1.0 to 6.0 °C by 2070, relative to 1990 [36].

The impact category considers all emissions which have an impact on climate change. Main contributors to this category are carbon dioxide (CO_2), methane (CH_4), halocarbons (halons, chlorofluorocarbons (CFC), hydro chlorofluorocarbons (HCFCs), nitrogen oxides (NO_x), including nitrogen dioxide (NO_2), nitric oxide (NO), and nitrous oxide (NO_2), non-methane volatile organic compounds (NMVOC) and particulate matter of various compositions and sizes. Climate change can be evaluated in an LCA on a time scale of 20, 100 or 500 years. Here, the most usual category of 100 years [12] has been chosen.

The equivalency factors, determined by the Intergovernmental Panel on climate change (IPCC), are shown in Table 94.

7.1.3 Eutrophication Potential

Eutrophication is a nutrient enrichment culminating in over nourishment in aquatic and terrestrial ecosystems. This may cause a shift in the composition of species, an increase of biomass production. In aquatic ecosystems less sunlight reaches deeper layers due to increased growth of algae. Less photosynthesis occurs and oxygen concentration decreases. Dead plants sink to deeper layers and are degraded. This requires oxygen. Finally, the concentration of oxygen is too low for fishes and other animals to survive. Degradation processes happen without oxygen, they are anaerobic. Gases like methane are produced.

For terrestrial ecosystems eutrophication might cause a change in flora and fauna, biodiversity can decrease.

Eutrophication is caused by excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). The contribution of relevant emissions is expressed in PO_4^{3-} equivalents.

The full list of relevant substances and their equivalence factors, determined by the CML, are listed in Table 95.

7.1.4 Photochemical oxidant formation potential

POCP addresses the formation of photo-oxidants in the troposphere, especially in urban areas. Photochemical oxidants can damage human as well as ecosystem health. They are formed by oxidation of volatile organic compounds or by carbon monoxide in the presence of nitrogen and the influence of ultraviolet light [12]. If it comes to high concentrations it is called photochemical smog.

In this category the release of organic compounds which contribute to photochemical ozone formation are considered. Most of them are hydrocarbons, e.g. ethylene, propene, benzene toluene, and aromatic aldehydes [12]. Although two components (NO_x and hydrocarbons) and sunlight are required for generation of photochemical smog, it is limited in metropolitan areas by sunlight and hydrocarbons. Therefore, NO_x are not included in the list of smog precursors [12, 37].

The full list of relevant substances and their equivalence factors, determined by the CML, are listed in Table 96.

7.1.5 HTPAU and Ecotoxicity Categories

Human toxicity, marine and freshwater aquatic and terrestrial eco-toxicity affect the health of humans and flora and fauna directly. The main contributor are heavy metals, emitted to air, water and soil. These toxicity classes are generally considered as very important if WTE is examined [12].

The impact category *HTPAU* contains effects of toxic substances on humans. These effects depend on actual emissions, their fate, and the time of exposure; therefore they are difficult to model [12]. The equivalence factors, which are listed in Table 97, were modelled for Australian conditions. It contains e.g. heavy metals, hydrocarbons and halogenated organic emissions.

Ecotoxicity deals with effects of toxic substances on terrestrial and aquatic ecosystems. The potential effect depends on the actual emission, the exposure to them and their fate in the ecosystems. The equivalence factors for these impact categories were again modelled for Australian conditions. They are listed in Table 98 - Table 100.

7.2 LCIA Results – Characterisation

Characterisation is the weighting of each intervention compared to the reference substance for each impact category. The weightings are the results from models used. In this study, already existing weightings from the computer programme GaBi 4 were used. These so-called equivalence factors are listed for every impact category in Appendix D.

8 Interpretation

In this chapter the results for all options and all impact categories are shown. For all categories except total energy the results are presented in equivalence factors as explained above. This allows a good comparison of options. Additional graphs give information about the contribution of garbage, MRF rejects, recycling and windrow composting.

This is followed by a sensitivity analysis where parameters are changed. A sensitivity analysis provides indication about consistency in results. Finally, data quality is evaluated and gaps in data are identified with a prognosis on their effects.

Some of the results have little difference for a few basis points. In these cases no recommendations can be given. Small differences could result e.g. out of rounding in the model calculation. Further, rounding occurs in calculation of different material streams. Next to this, accuracy in data could also provide a range of uncertainty in results, as assumptions had to be made and emissions were calculated.

8.1 Total Energy Results

Total energy provides information on energy that is being consumed and generated within each option and that is required for the production of the avoided materials. The results for each option are shown in the next table:

Table 17 Total energy for each option [MJ/FU]

	Base Case	**Option 1**	**Option 2**	**Option 3**
Total energy	$-1.45 \cdot 10^{10}$	$-1.49 \cdot 10^{10}$	$-4.96 \cdot 10^{9}$	$-2.24 \cdot 10^{10}$

The combination of garbage combustion and material recycling provides the largest benefit as one can see in Table 17. The Base Case and Option 1 are essentially the same, small differences arise out of windrow composting in the Base Case – less biogas is produced at landfill and therefore utilised to energy. Results for Option 2 show clearly that energy recycling by WTE is no reasonable alternative for material recycling, especially not, as the main argument is the production of energy. When comparing the recycling systems in regard to energy it is interesting to note, that the options with material recycling LDPE, PVC and mixed plastics rejects are disposed, while in Option 2 they are recycled to energy. Still, this option can not compete with others. Figure 16 shows the contribution of the main material streams, the disposal of garbage and MRF rejects, reprocessing and windrow composting.

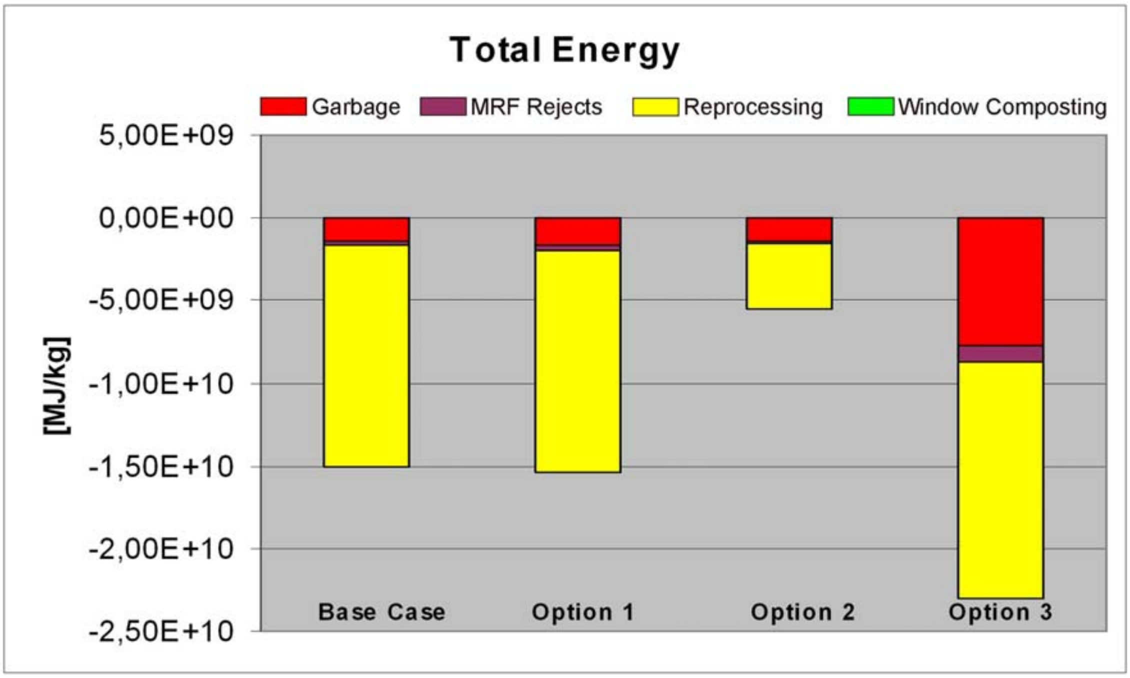


Figure 16 Total energy – comparison for each option

It is obvious that reprocessing provides the main savings while windrow composting contributes with less than 1%.

The next table shows examples where MR and ER are compared, the results are for the total recycled amount each year:

Table 18 Comparison of MR and ER [MJ]

	MR	ER
HDPE	$-4.68 \cdot 10^8$	$-1.76 \cdot 10^8$
ONP	$-6.51 \cdot 10^9$	$-1.48 \cdot 10^9$
Cardboard	$-6.30 \cdot 10^8$	$-4.85 \cdot 10^8$

The ratio of energy savings from material recycling to energy recycling are 2.7 for HDPE, 4.4 for ONP and 1.3 for cardboard.

8.2 Climate Change Results

The model provides a clear overall result in regard to the impact category climate change: Table 19 shows, that Option 3 generates significant savings, while Option 2 again performs the worst. Option 1 is slightly higher than the Base Case, due to a higher biogas production in landfilling.

Table 19 Climate change for each option [kg CO_2-eq./FU]

	Base Case	Option 1	Option 2	Option 3
Climate change	$5.94 \cdot 10^8$	$6.33 \cdot 10^8$	$6.45 \cdot 10^8$	$-1.07 \cdot 10^9$

As mentioned before, the results from the impact category total energy provide useful information for the interpretation of this category. Still, the results need a closer look at, as their relations are not necessarily consistent. Table 20 shows the emission of CO_2-eq. in relation to generated electricity.

Table 20 Ratio of total energy and climate change

	CO_2-eq. / MJ
Base Case	0.04
Option 1	0.04
Option 2	0.13
Option 3	-0.05

As only Option 3 generates savings concerning climate change, it is the only result with a negative ratio. While the Base Case and Option 1 have the same ratio, Option 2 shows a production of about three times more greenhouse gases per MJ. The negative ratio for Option 3 results from a better energy utilisation than the generator at landfill is able to provide. Secondly, the emissions from the combustion plant are to a large extent CO_2, whereas CO_2 from biogenic sources is even deducted. Biogenic CO_2 is not taken into account for the landfill as well, but the main part of the emissions is methane – and every kg of methane counts 21 kg CO_2-eq..

The differences between Base Case/Option 1 and Option 2 result from different emission profiles for material recycling and energy recycling. Here, emissions of combustion have a bigger impact on climate change. Less energy savings but more greenhouse gas emissions consolidate the last place of all options. The contribution of each material stream is shown in the next figure.

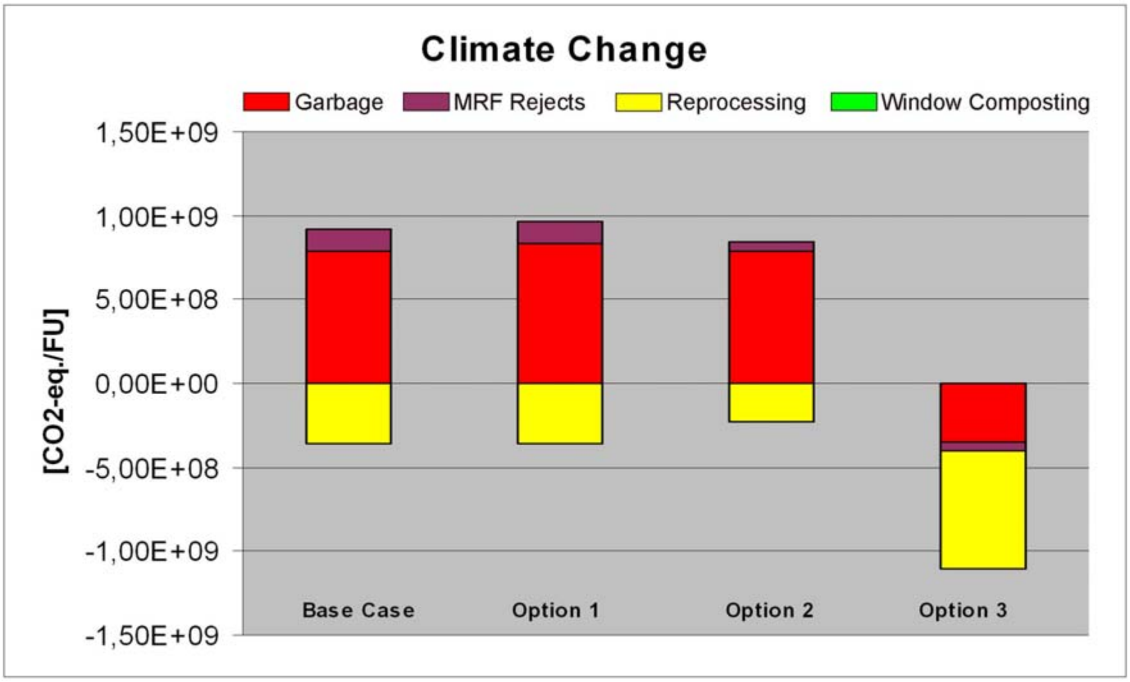


Figure 17 Climate change – comparison for each option

Garbage is the biggest contributor for the Base Case, Option 1 and Option 2, while reprocessing is the main contributor for Option 3. Contributions of windrow composting can be neglected.

8.3 Eutrophication Potential Results

The model presents a clear ranking for the impact category eutrophication potential. Option 1 produces a small saving compared to the Base Case. While Option 2 is the main contributor to this impact category, Option 3 provides large savings (Table 21).

Table 21 Eutrophication potential for each option [kg PO_4^{3-}-eq./FU]

	Base Case	**Option 1**	**Option 2**	**Option 3**
EP	$-1.09 \cdot 10^5$	$-1.15 \cdot 10^5$	$4.79 \cdot 10^4$	$-4.94 \cdot 10^5$

Again, there is a close link to the impact category total energy. The benefits from Option 1 are slightly bigger due to higher biogas production and therefore higher energy utilisation. Every MJ of electricity produced contributes to this impact category with $8.3763 \cdot 10^{-5}$ kg PO_4^{3-}-eq.. This is not very much but sums up if e.g. $1.49 \cdot 10^{10}$ MJ are produced.

But there are other sources for eutrophication as well. Main impacts are transportation, leachate from landfill, exhaust from WTE and reprocessing of glass (due to a high level of nitrogen oxide emissions).

Benefits are, next to produced electricity, provided by the reprocessing of paper, newsprint, PET, aluminium and tin plate.

Option 2 profits from less rejects due to energy recycling. Looking at MRF rejects, the Base Case and Option 1 emit approximately 1.40 · 10^4 kg of PO_4^{3-}-eq., while Option 3 emits 4.90 · 10^3 kg. But talking about emissions with the magnitude of 10^5, these savings are just of minor importance.

As mentioned above, material recycling of calorific rich fractions provides significant benefits, which makes Option 2 come off badly compared to the other options. Option 3 benefits again from its higher energy production. The contributions of the main material streams are explained in Figure 18.

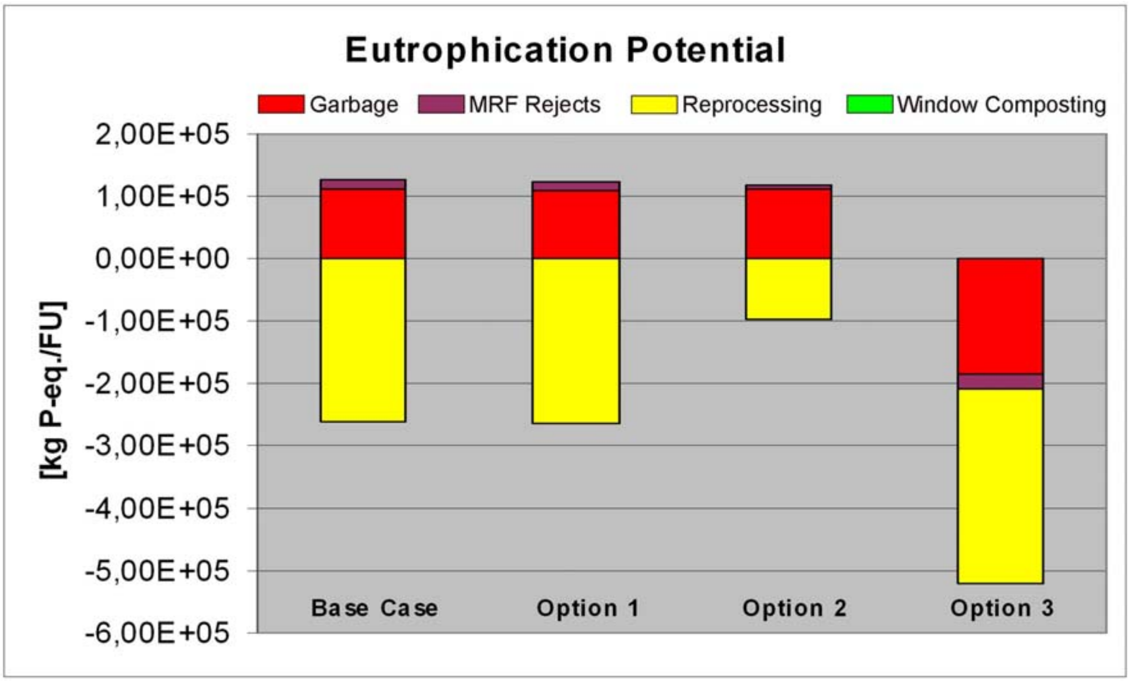


Figure 18 Eutrophication potential – comparison for each option

It is obvious that the material stream for reprocessing is the most important factor in this category while windrow composting does not play a role at all as it contributes less than 1% to all options.

8.4 POCP Results

A similar ranking as with the previous impact categories can be seen for POCP (Table 22).

Table 22 POCP for each Option [C_2H_4-eq./FU]

	Base Case	**Option 1**	**Option 2**	**Option 3**
POCP	$1.47 \cdot 10^5$	$1.61 \cdot 10^5$	$1.91 \cdot 10^5$	$-2.37 \cdot 10^5$

Biogas from landfill is a main contributor to POCP, as well as the combustion of Diesel due to emissions of CO, NMVOCs and VOCs, therefore transport plays a major role. Avoided electricity production provides savings again, as well as material recycling of plastics and tin plate.

More biogas production is the reason for Option 1 getting a slight worse result than the Base Case. Energy recycling proves to be a bad alternative to material recycling again. The landfilling of MRF rejects emits, due to less material to be landfilled, less contributions to this category. But the reprocessing itself generates much less savings than the other options.

Option 3 is the only option to provide savings, because no biogas is produced from landfill and a high degree of electricity production at WTE. Figure 19 shows the contributions of the main material streams.

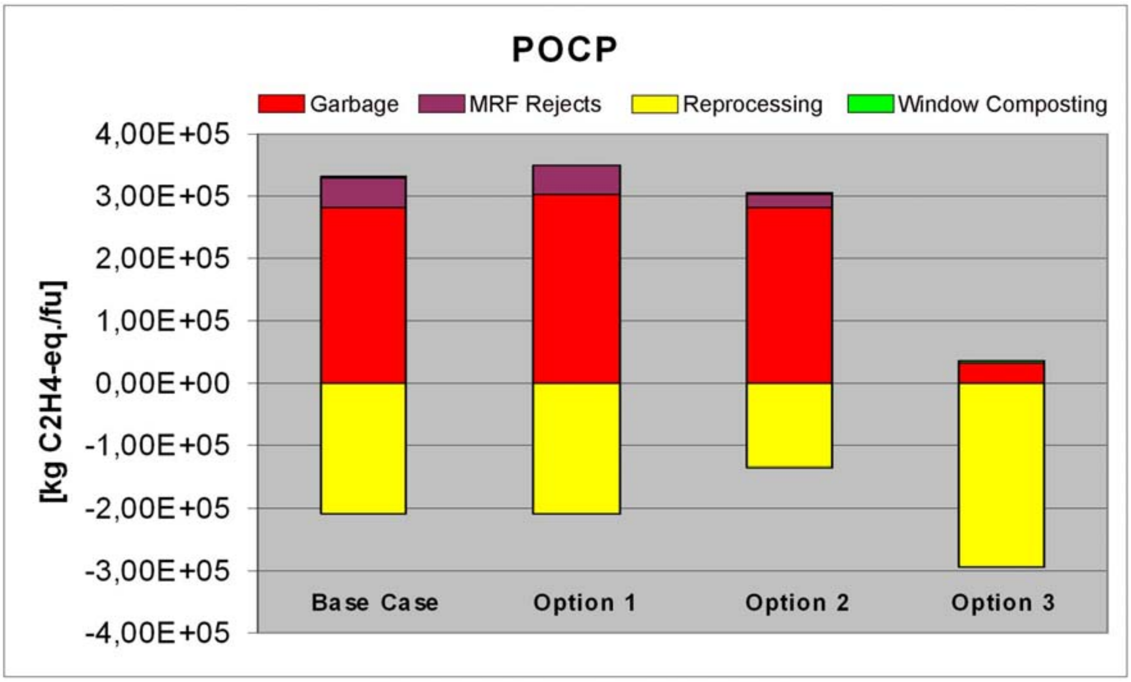


Figure 19 POCP – Comparison for each option

For the Base Case and the first two options garbage is obviously the main contributor. Contributions of windrow composting are approximately 1% for Option 1 and 2 and of no effects for Option 3.

8.5 Human Toxicity and Ecotoxicity Category Results

Every option generates savings for each of the four toxicity impact categories. The ranking for the impact category human toxicity potential Australia is pretty much the same like the other options; the impact category freshwater aquatic ecotoxicity potential has a unique ranking under all impact categories: Option 1 is the best with a very thin advantage compared to the Base Case and Option 3. The range between these categories is approximately of 4%, so no serious ranking could be given based on these results. In fact, the relation of the Base Case and the first two options is very steady for all toxicity impact categories, as Table 23 shows. For the impact categories MAEP and TEP the combustion of garbage (Option 3) is of clear advantage.

Table 23 Toxicity Potentials for each Option [DCB-eq./FU]

	Base Case	**Option 1**	**Option 2**	**Option 3**
HTPAU	$-1.47 \cdot 10^6$	$-1.48 \cdot 10^6$	$-4.42 \cdot 10^5$	$-2.52 \cdot 10^6$
FAEP	$-4.65 \cdot 10^5$	$-4.78 \cdot 10^5$	$-2.43 \cdot 10^5$	$-4.60 \cdot 10^5$
MAEP	$-1.87 \cdot 10^{10}$	$-1.95 \cdot 10^{10}$	$-1.07 \cdot 10^{10}$	$-3.59 \cdot 10^{10}$
TEP	$-6.43 \cdot 10^6$	$-6.66 \cdot 10^6$	$-3.21 \cdot 10^6$	$-1.06 \cdot 10^7$

8.5.1 Human Toxicity Potential Australia

Main benefits arise out of avoided electricity, while released biogas, exhaust from the electricity generator at landfill, leachate and exhaust from WTE cause impacts. For the combustion of Waste in Option 3 mixed waste with its high contents of heavy metals is the main contributor. Figure 20shows how the main material streams contribute to this category.

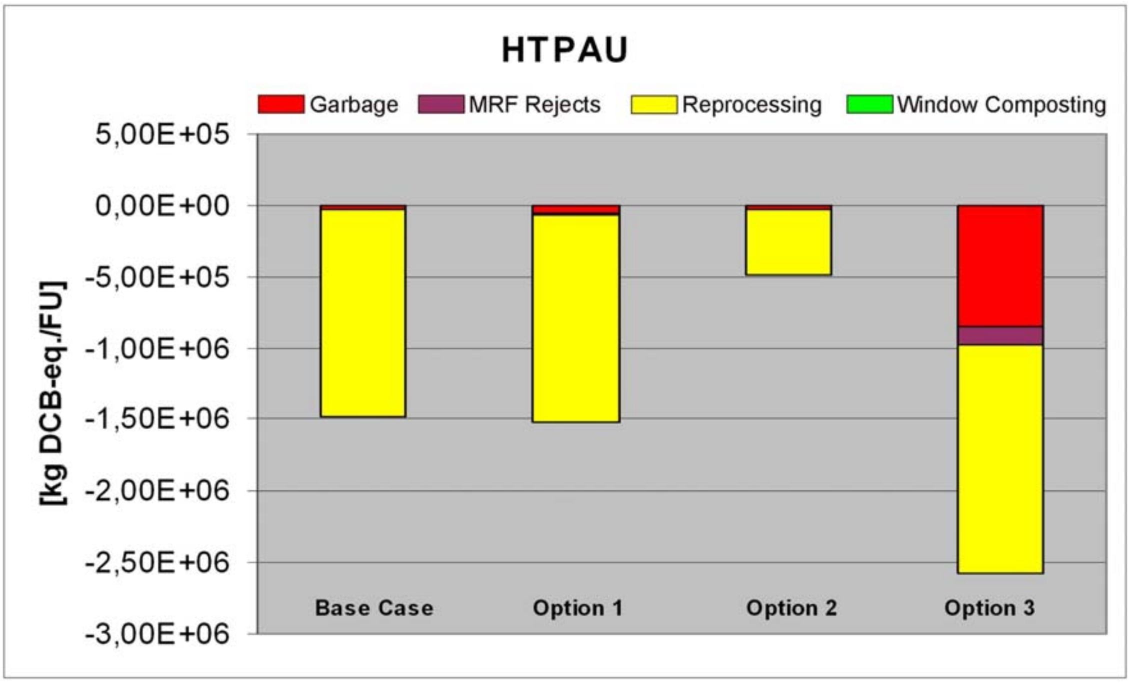


Figure 20 HTPAU – Comparison for each option

As the figure above shows, reprocessing clearly provides the biggest savings for all options. Contributions of windrow composting can be neglected.

8.5.2 Freshwater Aquatic Ecotoxicity Potential Australia

This impact for this category arise mainly out of heavy metal emissions from leachate to water. As they are especially high for leachate from slag, it explains the similar results for the Base Case, Option 1 and 3. Savings from avoided electricity are not high enough to equalize this and to make Option 3 a clear “No 1” again. In Figure 21 contributions of the main material streams are shown.

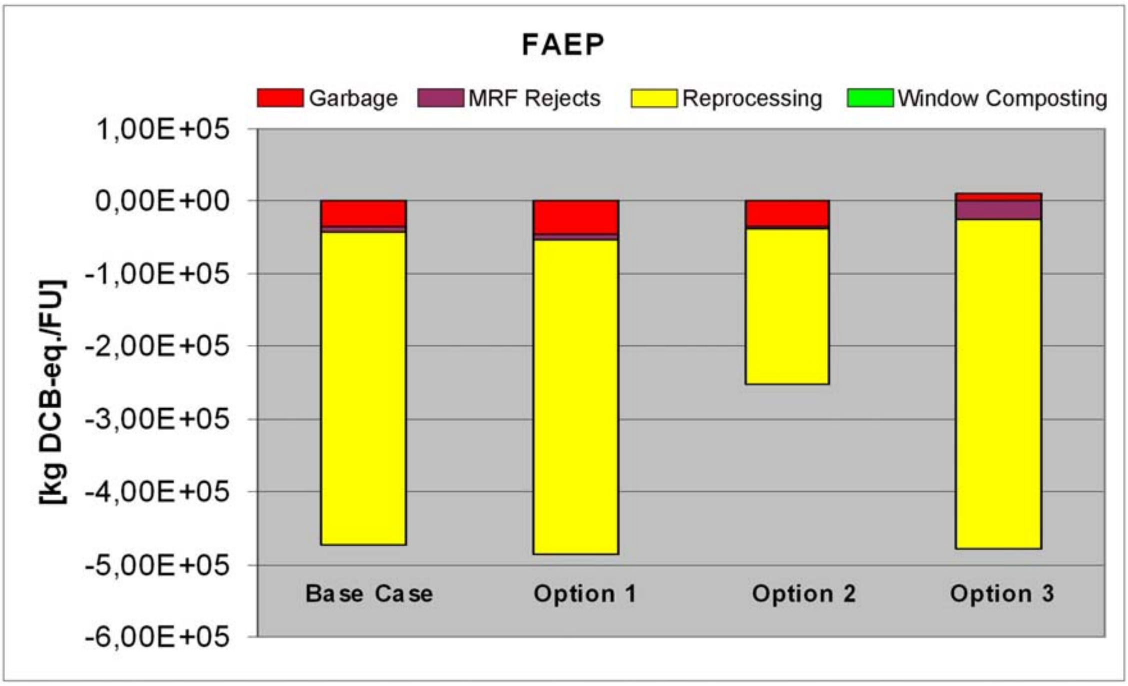


Figure 21 FAEP – Comparison for each option

Main savings arise out of material reprocessing (avoided energy). No effects are caused by windrow composting.

8.5.3 Marine Aquatic Ecotoxicity Potential Australia

The results for this impact category are determined by impacts caused by leachate (emissions to water and soil), exhaust fumes and reprocessing plastics and cardboard while savings are due to avoided electricity. Although the reprocessing of HDPE, PET and cardboard provide savings for the impact category total energy, these savings are not electricity but among others oil or gas. As oil is the basis for the production of plastics, reprocessing helps conserving this resource. Nevertheless, electricity demand for reprocessing is higher, as primary production requires nearly none – natural gas is needed, though. Impacts by exhaust from garbage combustion are of little relevance compared to savings from avoided electricity. Therefore, Option 3 acts as No 1 again, followed by Option 1 and the Base Case in similar positions and finally, far behind, Option 2 as the next figure shows.

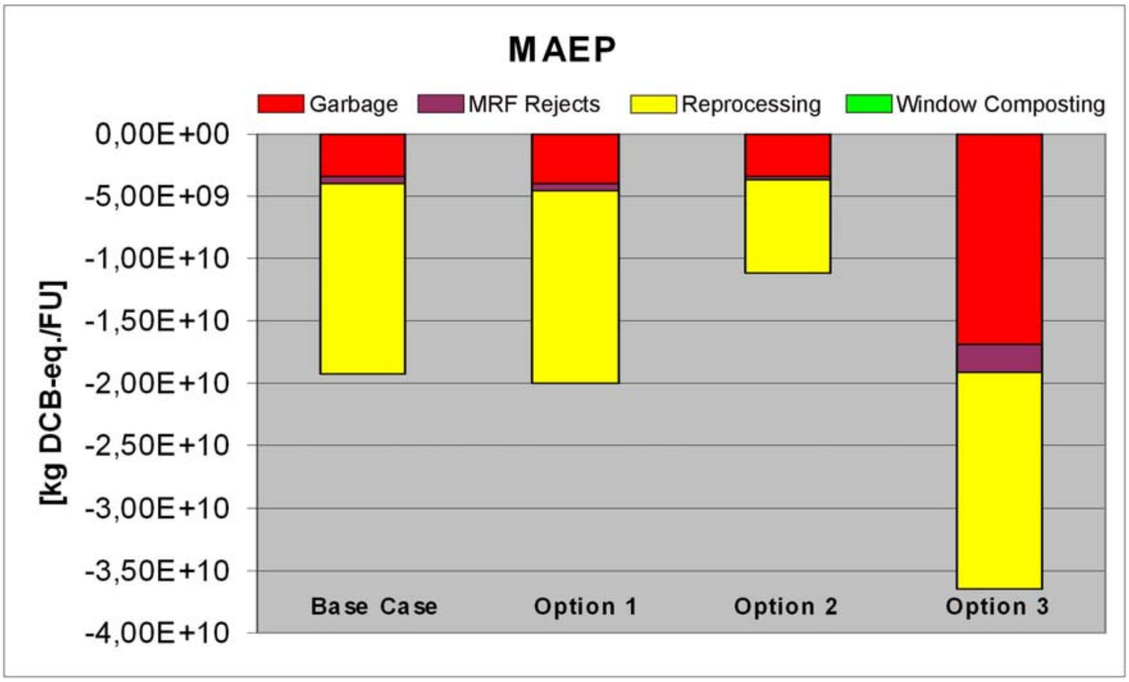


Figure 22 MAEP – Comparison for each option

The biggest savings arise out of material recycling and the combustion of waste. Very little savings come from windrow composting.

8.5.4 Terrestrial Ecotoxicity Potential Australia

Exhaust from WTE, diesel consumption (e.g. for transportation) and waste handling are the main factors causing impacts while avoided electricity provides the savings. The ranking is the same like for the impact category MAEP: Option 3 is providing the biggest savings in emissions, followed by Option 1 and the Base Case (with the usual gauzy difference) and Option 2 with the worst results, although still providing savings. Figure 23 shows the savings of all options.

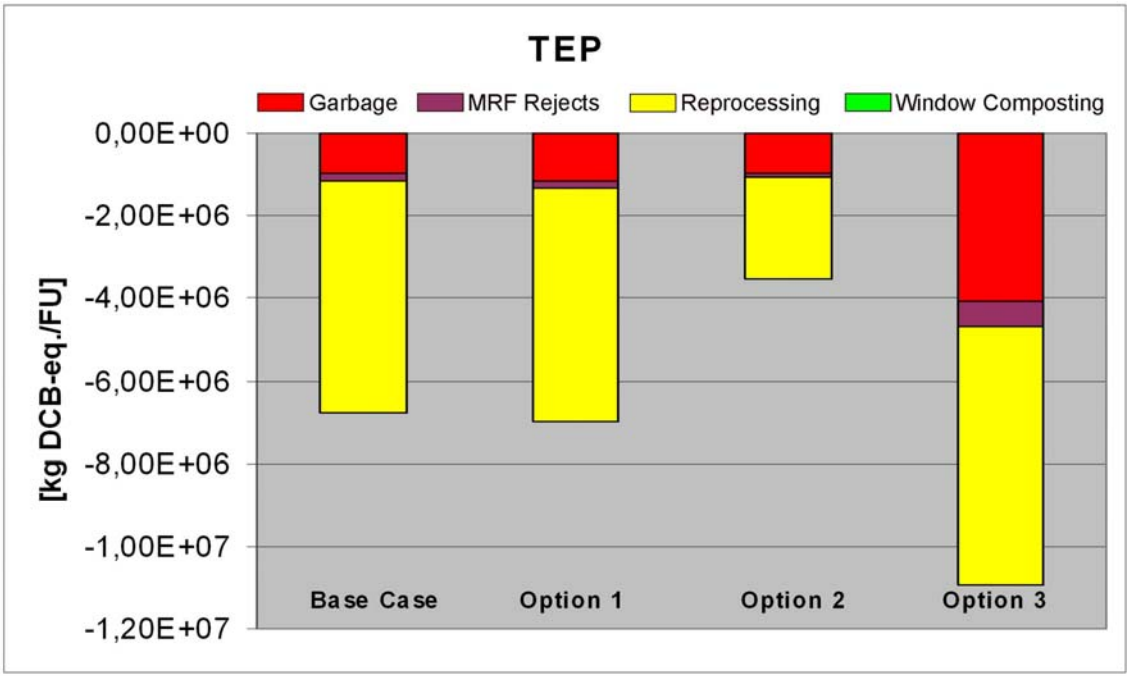


Figure 23 TEP – Comparison for each option

This figure is shaped by avoided electricity from reprocessing again. Savings from windrow composting are about 1%.

8.5.5 Summary of Impact Categories

To give a better overview over the results discussed above, they will be shown for every option and each impact category in Table 24.

Table 25 will show the comparison of the options for each category. The current situation, the Base Case, is equal 0%. The other results show how the other options affect the outcome of the model, expressed in %. A negative result means additional benefits, and a positive result means a change for the worse.

Table 24 Results for all impact categories for each option

	Base Case	**Option 1**	**Option 2**	**Option 3**
Total energy [MJ/FU]	$-1.45 \cdot 10^{10}$	$-1.49 \cdot 10^{10}$	$-5.01 \cdot 10^{9}$	$-2.25 \cdot 10^{10}$
Climate change [CO_2-eq/FU]	$5.94 \cdot 10^{8}$	$6.33 \cdot 10^{8}$	$6.44 \cdot 10^{8}$	$-1.07 \cdot 10^{9}$
EP [PO_4^{3-}eq/FU]	$-1.09 \cdot 10^{5}$	$-1.15 \cdot 10^{5}$	$4.78 \cdot 10^{4}$	$-4.95 \cdot 10^{5}$
POCP [C_2H_4-eq/FU]	$1.47 \cdot 10^{5}$	$1.61 \cdot 10^{5}$	$1.91 \cdot 10^{5}$	$-2.37 \cdot 10^{5}$
HTPAU [DCB-eq /FU]	$-1.43 \cdot 10^{6}$	$-1.43 \cdot 10^{6}$	$-1.43 \cdot 10^{5}$	$-1.43 \cdot 10^{6}$
FAEP [DCB-eq /FU]	$-4.78 \cdot 10^{5}$	$-4.65 \cdot 10^{5}$	$-2.43 \cdot 10^{5}$	$-4.61 \cdot 10^{5}$
MAEP [DCB-eq /FU]	$-1.87 \cdot 10^{10}$	$-1.95 \cdot 10^{10}$	$-1.07 \cdot 10^{10}$	$-3.59 \cdot 10^{10}$
TEP [DCB-eq /FU]	$-6.43 \cdot 10^{6}$	$-6.66 \cdot 10^{6}$	$-3.21 \cdot 10^{6}$	$-1.06 \cdot 10^{7}$

Table 25 Comparison of each option to Base Case [%]

	Base Case	**Option 1**	**Option 2**	**Option 3**
Total energy	0	-3	65	-55
Climate change	0	7	8	-281
EP	0	-6	144	-356
POCP	0	9	30	-262
HTPAU	0	-3	69	-76
FAEP	0	-3	48	1
MAEP	0	-4	43	-92
TEP	0	-4	50	-65

Table 25 provides a good overview of the relation of the impact categories. It becomes clear that for most impact categories Option 3 provides the best results, while Option 2 is always the last choice.

8.6 Sensitivity Analysis

In a sensitivity analysis certain parameters are changed to examine the effects on the system and the results. This happens, as LCA always comes along with uncertainties and assumptions which had to be made but are not necessarily right. Most studies vary transport distance or other parameters like capture rate for biogas or energy efficiency. Often these changes are suggested after a review by an external person which is supposed to be neutral. For this study, no external peer-review was done.

The author selected two additional scenarios to evaluate:

- The calculated emission profile for combustion was exchanged against a general profile from a incineration plant in Spittelau, Austria
- Based on calculated emission profiles as in Option 3, the diversion rate of recyclables from the waste stream incl. garden waste was improved

The outcomes of the two changes will be discussed in the following.

8.6.1 General Emission Profile of a Combustion Plant

As mentioned above, this part of the sensitivity analysis is based on plant data from an Austrian combustion plant. This plant was set up in 1971 and expanded with a wet flue gas cleaning system in 1986/1989 and a SCR stage in 1989. It is based on grate technology (see Appendix A) [33]. The flue gas cleaning system for the data to be calculated was chosen according to this plant to improve comparability. The plant in Spittelau was chosen for several reasons: 1st it is a typical plant for European standards, 2nd it is just fed with domestic waste and 3rd the emission profile is available in detail.

The emission profile includes the flue gas after cleaning, the effluent after the waste water treatment system and leaching tests for slag. The results of leaching tests do not comply with the chosen time frame of 100 years for the landfill; they must be seen as long-term results. This is the most reasonable choice in methodology as using transfer coefficients again would be no check of data at all. All data are listed in Appendix D. The results of the first part of the sensitivity analysis are shown in Table 26 and the differences in % are shown in Table 27.

Table 26 Comparison of all Options including Sensitivity Analysis with general Profile (SAGP)

	Base Case	Option 1	Option 2	Option 3	SAGP
Total energy [MJ/FU]	$-1.45 \cdot 10^{10}$	$-1.49 \cdot 10^{10}$	$-5.01 \cdot 10^{9}$	$-2.25 \cdot 10^{10}$	$-1.62 \cdot 10^{10}$
Climate change [CO_2-eq/FU]	$5.94 \cdot 10^{8}$	$6.33 \cdot 10^{8}$	$6.44 \cdot 10^{8}$	$-1.07 \cdot 10^{9}$	$-8.42 \cdot 10^{8}$
EP [PO_4^{3-}-eq/FU]	$-1.09 \cdot 10^{5}$	$-1.15 \cdot 10^{5}$	$4.78 \cdot 10^{4}$	$-4.95 \cdot 10^{5}$	$-3.43 \cdot 10^{5}$
POCP [C_2H_4-eq/FU]	$1.47 \cdot 10^{5}$	$1.61 \cdot 10^{5}$	$1.91 \cdot 10^{5}$	$-2.37 \cdot 10^{5}$	$-2.58 \cdot 10^{5}$
HTPAU [DCB-eq /FU]	$-1.43 \cdot 10^{6}$	$-1.43 \cdot 10^{6}$	$-1.43 \cdot 10^{5}$	$-1.43 \cdot 10^{6}$	$-1.80 \cdot 10^{6}$
FAEP [DCB-eq /FU]	$-4.78 \cdot 10^{5}$	$-4.65 \cdot 10^{5}$	$-2.43 \cdot 10^{5}$	$-4.61 \cdot 10^{5}$	$-4.61 \cdot 10^{5}$
MAEP [DCB-eq /FU]	$-1.87 \cdot 10^{10}$	$-1.95 \cdot 10^{10}$	$-1.07 \cdot 10^{10}$	$-3.59 \cdot 10^{10}$	$-4.61 \cdot 10^{5}$
TEP [DCB-eq /FU]	$-6.43 \cdot 10^{6}$	$-6.66 \cdot 10^{6}$	$-3.21 \cdot 10^{6}$	$-1.06 \cdot 10^{7}$	$-5.89 \cdot 10^{6}$

Table 27 Difference for each Option incl. SAGP to current situation [%]

	Base Case	Option 1	Option 2	Option 3	SAGP
Total energy	0	-3	65	-55	-12
Climate change	0	7	8	-281	-242
EP	0	-6	144	-356	-216
POCP	0	9	30	-262	-276
HTPAU	0	-3	69	-76	-26
FAEP	0	-3	48	1	1
MAEP	0	-4	43	-92	100
TEP	0	-4	50	-65	8

The sensitivity analysis provides similar rankings as Option 3 for most impact categories except TEP and MAEP. For MAEP, combustion in SAGP comes last with 100% less savings than the Base Case. For TEP the general profile provides little less savings than the Base Case but still performs better than Option 2.

Results from the sensitivity analysis show less savings for all impact categories except POCP and FAEP (where results are the same) than Option 3. But differences are not big enough to lead to a general change in ranking.

Disadvantages compared with the calculated profile form Option 3 can be seen in the more detailed emission profile. Another reason for the toxicity classes is the use of leaching results for emissions from landfilled slag. Results from leaching tests are considered to be long-term emissions [17]. The amount of heavy metals emitted to water and soil is higher than in Option 3 for most of them.

These results are surprising, because the general profile is much more detailed. This shows that emission data based on calculations are able to produce reliable results within a life cycle Assessment.

8.6.2 Improvement of Diversion Rate

In this part of the sensitivity analysis it is assumed, that 50% of all recyclables currently disposed of with garbage are diverted to the recycling bin. This diverts additional 151,210 tonnes from combustion to recycling. This scenario is seen as moderate, therefore possible to be realised. The results are shown in Table 28 and their comparison in % in Table 29.

Table 28 Results for all impact categories for each option including sensitivity analysis with a higher diversion Rat (SAHDR)

	Base Case	Option 1	Option 2	Option 3	SAHDR
Total energy [MJ/FU]	$-1.45 \cdot 10^{10}$	$-1.49 \cdot 10^{10}$	$-5.01 \cdot 10^{9}$	$-2.25 \cdot 10^{10}$	$-2.64 \cdot 10^{10}$
Climate change [CO_2-eq/FU]	$5.94 \cdot 10^{8}$	$6.33 \cdot 10^{8}$	$6.44 \cdot 10^{8}$	$-1.07 \cdot 10^{9}$	$-1.26 \cdot 10^{9}$
EP [PO_4^{3-}eq/FU]	$-1.09 \cdot 10^{5}$	$-1.15 \cdot 10^{5}$	$4.78 \cdot 10^{4}$	$-4.95 \cdot 10^{5}$	$-5.84 \cdot 10^{5}$
POCP [C_2H_4-eq/FU]	$1.47 \cdot 10^{5}$	$1.61 \cdot 10^{5}$	$1.91 \cdot 10^{5}$	$-2.37 \cdot 10^{5}$	$-6.23 \cdot 10^{5}$
HTPAU [DCB-eq /FU]	$-1.43 \cdot 10^{6}$	$-1.43 \cdot 10^{6}$	$-1.43 \cdot 10^{5}$	$-1.43 \cdot 10^{6}$	$-2.96 \cdot 10^{6}$
FAEP [DCB-eq /FU]	$-4.78 \cdot 10^{5}$	$-4.65 \cdot 10^{5}$	$-2.43 \cdot 10^{5}$	$-4.61 \cdot 10^{5}$	$-8.44 \cdot 10^{5}$
MAEP [DCB-eq /FU]	$-1.87 \cdot 10^{10}$	$-1.95 \cdot 10^{10}$	$-1.07 \cdot 10^{10}$	$-3.59 \cdot 10^{10}$	$-3.88 \cdot 10^{10}$
TEP [DCB-eq /FU]	$-6.43 \cdot 10^{6}$	$-6.66 \cdot 10^{6}$	$-3.21 \cdot 10^{6}$	$-1.06 \cdot 10^{7}$	-1.21 · 107

Table 29 Differences for each option [%]

	Base Case	Option 1	Option 2	Option 3	SAHDR
Total energy	0	-3	65	-55	-82
Climate change	0	7	8	-281	-311
EP	0	-6	144	-356	-438
POCP	0	9	30	-262	-524
HTPAU	0	-3	69	-76	-107
FAEP	0	-3	48	1	-82
MAEP	0	-4	43	-92	-107
TEP	0	-4	50	-65	-88

Total energy: Improving the recycling collection provides significant benefits (50%) especially to the MRF System, while little losses occur to the combustion of garbage.

Climate change: Due to more avoided electricity the impact category climate change is able to profit as well (approximately 11% more savings). The ratio CO_2/MJ is the same like in Option 3, which shows a consistence in results.

Eutrophication potential: As mentioned above, main factors influencing this impact category are avoided electricity and reprocessing providing savings and leachate contributing emissions. More electricity is avoided, more recyclables are reprocessed and due to less garbage less emissions occur from leachate. The result is approximately 20% more savings compared to Option 3.

POCP: Avoided electricity and recycling plastics and tin plate provide benefits, therefore savings are doubled compared to Option 3.

HTPAU: 40% more savings are produced, compared to Option 3 due to less exhaust from WTE and more avoided electricity.

FAEP: The only impact category, where Option 3 was weak, is improving significantly by nearly 82 times. This is mainly due to less emissions from leachate.

MAEP: This impact category just provides smaller savings (about 16%) due to avoided electricity and less exhaust from WTE, but the difference is fairly small due to impact by the reprocessing of cardboard and plastics

TEP: 35% savings occur due to less exhaust and more avoided electricity.

8.7 Data Quality

According to ISO 14043 data quality issues have to be addressed within an LCA study. Within this process, data gaps are identified and the degree of confidence with present data is estimated.

In Table 30 known data gaps are listed for all options including the sensitivity analysis. Further, the possible effect of their consideration (addition) is estimated. These estimations should give an idea of the direction the results of an option will go once these gaps are filled.

Table 30 Missing data and effect of their introduction on results

Landfilling of boiler and fly ash	☹☹	Negative effects due to high heavy metal contents specially on toxicity classes
Treatment of ashes	☺☺	Improvement of landfill behaviour
Additional heating	☹ - ☹☹	Maybe little effect for Option 3, bigger effect for SAHDR, as waste is lower in energy due to improved diversion rate
Recycling of metals from ash	☺☺	recycling of metals is highly energy saving and provides savings to all impact categories
Utilisation of steam and heat energy	☺☺	Increased savings for Total energy and therefore for all impact categories
Production chain of auxiliary chemicals	☹	Little contributions to all impact categories
Landfilling of sludge from incinerator STP	☹ - ☹☹	More transport and higher leachate contamination
Use of ashes with low contamination for construction purposes	☺	Would result in energy savings and savings for other impact categories as well due to avoided products from the construction industry; less landfilling
Gaseous emissions from landfilled slag	☹	Can not be quantified and research on this topic is still on
Special leachate treatment on site	☺☺	Less emissions to water and soil from STP
Energy demand for leachate treatment in STP	☹	Little effects as energy demand is quite low
Energy demand of running a landfill	☹	Higher energy demand and more emissions
Leachate going through base sealing	☹ - ☹☹	Amounts are fairly small, but highly contaminated and therefore a threat to groundwater

☺	slightly positive effect
☺☺	positive effect
☹	slightly negative effect
☹☹	negative effect

Table 31 shows a qualitative assessment of the data for the different waste management options. Just emissions and the FU were evaluated. Data for reprocessing are not included, as they were completely taken from other studies.

Table 31 Evaluation of Data Confidentiality

	Confidence	**Detail**
Biogas	Middle	NPI assumes own data as fairly confident, added data can be rated L- M
Leachate	Low	Leachate is extremely hard to predict, Model based calculations
Flue gas	Middle	Model based calculations as result of long-term research
Leachate from slag	Low	Model based calculations
Emission profile of reference incinerator	High	Very detailed profile based on measurement
FU	Middle - High	A sufficient no. of councils with different socio-demographic background provided valuable data

9 Conclusions and Recommendations

After the results were presented and interpreted in the last chapter, conclusions can be drawn and recommendations can be given. The conclusions include a brief ranking of options as well as the identification of the main influence factor for all options. Based on these conclusions, recommendations for further activities will be given.

9.1 Conclusions from Interpretation

According to the model, Sydney would significantly benefit from the introduction of an incinerator. In almost every impact category Option 3 is able to provide large benefits. An exception is FAEP, as the Base Case, Option 1 and 3 are so close that no recommendation can be given (see above).

For the other categories, preferences are made clear. It is also made clear, that energy recycling, as it happens in Option 2, is no serious alternative. It has the worst results for all impact categories, even for total energy. The ranking for all impact categories is shown in Table 32.

Table 32 Ranking for all Options and all Impact Categories

	Total energy	Climate change	EP	POCP	HTPAU	FAEP	MAEP	TEP
Base Case	2	2	2	2	2	1	2	2
Option 1	2	3	3	3	2	1	2	2
Option 2	4	3	4	4	4	4	4	4
Option 3	1	1	1	1	1	1	1	1

The main reason for success or failure of different options can be seen in the factor energy. This is, because Australia's energy mix is largely based on fossil fuels. In 2001, approximately 85% of the energy were thermal power (mainly coal), about 14% were renewables (mostly hydro power). While eastern Australia relies on coal powered plants, the western parts rely on gas [38]. Due to this, emissions from energy production are the main contributor to most impact categories. Therefore, avoided emissions from avoided electricity production provides the biggest savings for the most impact categories. This is proved in Table 33, where the impact of landfilled garden waste from the Base Case and Option 1 are compared. In Option 1 more garden waste is landfilled, which results in a higher biogas production and therefore a higher energy utilisation.

Table 33 Comparison of landfilled Garden Waste from the Base Case and Option 1

	Base Case	Option 1
Total energy	$-1.58 \cdot 10^{8}$	$-4.44 \cdot 10^{8}$
Climate change	$2.33 \cdot 10^{7}$	$6.53 \cdot 10^{7}$
Eutrophication potential	$-2.70 \cdot 10^{3}$	$-7.56 \cdot 10^{3}$
POCP	$9.20 \cdot 10^{3}$	$2.58 \cdot 10^{4}$
HTPAU	$-1.90 \cdot 10^{4}$	$-5.32 \cdot 10^{4}$
FAEP	$-5.44 \cdot 10^{3}$	$-1.53 \cdot 10^{4}$
MAEP	$-3.59 \cdot 10^{8}$	$-1.01 \cdot 10^{9}$
TEP	$-1.08 \cdot 10^{5}$	$-3.02 \cdot 10^{5}$

Only those impact categories, where emissions from biogas have a bigger impact (climate change and POCP) show a different tendency. For these categories the Base Case is the preferable one.

9.2 Recommendations for further Action

The model developed for this study should serve as a basis for ongoing research. Other technologies, which have proved practicability, should be included as well. This could be among others mechanical biological treatment, aerobic and anaerobic digestion or a bioreactor, where landfill leachate is recirculated to speed up degradation processes. All these technologies are listed in the Wright Report [5]. Further, more recent technologies like the new technology at Eastern Creek, where recyclables are diverted from the garbage, followed by percolation and composting, should be included as well.

For the included waste treatment methods like landfilling and combustion of garbage state-of-the-art technologies should be introduced. This includes a site-based leachate treatment plant for the landfill as well as a modern flue gas cleaning system and slag treatment including metal recovery after combustion. Additionally, a mechanical biological pre-treatment previous to combustion is possible. This reduces water content and therefore increases the calorific value.

Emission profiles should be completed, e.g. with maximum levels of missing substances. New scientific results should be included as well. Identified data gaps from Table 30 should be filled as far as possible.

To improve research results and make them “Sydney specific” the introduction of a database would mean a big support. As mentioned above, reliable data are rare. This database should contain statistics about tonnages and waste composition, garbage as well as recyclables and garden waste. The information should be council specific and, if possible, have the same auditing method. Council specificity is important to be able to model transports of waste. To consider the influence of different seasons, audits could be done every one and a half year. Next to this trends should be worked out and changes in waste management strategy should be highlighted. The information in this data base should be non-commercial and available to all researchers and interested groups. Depending on interested groups, sensitive information can be coded, such as the link between a council and a certain statistic.

The following list of recommendations are not just technology based but refer to strategy and planning waste management in Sydney. Still, they should be modelled as well.

1. Recommendation: Deconstruction of landfill

For Option 3, where garbage is combusted, a deconstruction of landfill should be considered. To *reduce the demand for landfill capacity* and *avoid the construction of a pure slag landfill*, the set up of an incinerator close to Lucas Heights should be considered. As landfill will reach its maximum capacity within 2005/2006, *operation time of the landfill could be expanded* by rebuilding and combusting the waste. This would create new *space for slag* and *reduce after treatment costs*. The volume of slag leaving the incinerator should equalize the volume taken out of the landfill to avoid further growth of the landfill body.

2. Recommendation: Diversion of food waste

Food is the waste fraction with the biggest mass contribution to garbage. Currently, that is 38 % or 337,491 tonnes per annum. If this amount could be diverted from the garbage stream, this would have significant effects on landfilling or combustion of garbage. For landfilling this is less moisture to be introduced to the landfill body which helps *reducing the leachate*. Further, as food is a very reactive fraction, degradation processes would decrease and *less biogas* would be produced. The diverted food waste could be either processed with garden waste or treated separately, e.g. in anaerobic digestion. Benefits from anaerobic digestion would be *energy production* and digested products for use as *compost*. Both, the combined treatment of food and garden waste and the separated treatment should be modelled.

3. Recommendation: Introduction of an improved recyclable collection system

Currently, commingled and paper recyclables are placed in the same bin. As an effect, paper becomes contaminated by liquids from the commingled and glass fines from broken glass. This is a reduction in quality of otherwise high quality paper products. A separated collection of the paper and glass fractions should be considered. as well as public containers for glass, which can be separated by colours. Less rejects would have to be landfilled and quality of recycling products would increase. If a change in system would lead to financial improvements must be evaluated.

4. Recommendation: Introduction of a separated garden waste collection for all councils

By this measurement, the diversion of garden waste from landfill would increase. Currently, this fraction in garbage is about 9%. Windrow composting can just convince for two impact categories out of eight. But contributions as well as savings are so small that these results are hardly decisive. The target of a full diversion from landfill should be seriously considered.

This is as the application of compost product improves irrigation and reduces soil erosion – which are huge benefits when considering the Australian situation. As mentioned above, these effects could not be modelled, but are of enormous importance, especially for agriculture. The model could be expanded in a way where these benefits play a role.

In the current situation sewage sludge is applied in agriculture, land rehabilitation and composting. These biosolids usually have a high content of heavy metals, which have a negative impact on environment and humans. Therefore, a comparison of these products should be underdone.

5. Recommendation: Change in energy mix

As explained in detail above, the results for this study are mainly dependent on Sydney’s energy mix. Therefore it would be helpful to improve the ratio of renewable and fossil energy towards more renewables. This could be hydropower as well as solar or wind power. It is likely that this change is going to happen, as demanded by the Greens [39]. The application in the model would prove long-term liability of results.

6. Recommendation: “Towards zero waste” strategy

Environmental groups and the Greens call for a waste management strategy which allows within a certain time-range to completely abandon waste to be disposed [39,40]. Although above suggestions about diverting food and garden waste from landfill and increasing the recycling quote are a waste minimisation they are not going that far. In case politicians decide to follow this strategy, it should be modelled as well. The introduction of this system doesn’t happen within a short time. Therefore, the time where changes take place until realisation of a “zero waste” society should be modelled as well. Naturally, as this might take a decade or at least a few years, every year must be included in the model with its specific changes.

A “zero waste” strategy is, for sure, the optimal approach, as no waste causes no emissions, no matter, how good techniques for final disposal are.

10 Economic Assessment

This chapter gives an overview over the waste management technologies evaluated in the chapters before: landfilling, combustion and windrow composting. All data except cost allocation for incinerators and data on the Woodlawn landfill are based on a report done for the European Commission [42]. The costs include investment and operational costs. Operational costs include input dependent and independent costs. In no case rebuilding and sale of grounds is involved. A brief technical description and the country of origin will be given for each technology. For conversion of currencies the course of 0.58 € / AUD was used (listed on 04/09/29) [42].

10.1 Landfill Costs, 175,000 tpa

The following costs refer to an extension of an already existing site. Energy recovery is not considered. These data have been derived in the UK.

Table 34 Investment costs for extending a landfill [Mio. AUD]

Site assessment and aquisition	3.310
Capex and development	24.291
Restoration / aftercare	9.451
TOTAL	37.052

Operational costs for this landfill site are approximately 50 AUD. No revenue like gate fee or energy utilisation from biogas is included. As this investment costs concern an extension of an already existing landfill, changes might occur for setting up a new landfill. The Woodlawn landfill west of Sydney has investment costs of 60 Mio AUD upwards, with gate fees of 102 AUD [43]. This gate fee includes 10% GST, 20% EPA landfill levy and 15% win (assumed). This results in operational costs of 62 AUD.

10.2 Grate Incinerator Costs, 200,000 tpa

The data for the incinerator have been derived in Germany. More detailed, plant specific data on investment costs can be obtained from [32].

Table 35 Investment costs for a Grate Incinerator [AUD]

Site costs	0.635
Development of site	0.588
Construction costs	37.291
Technical installations and machinery	120.241
Electro technical installations	22.897
Fees	12.671
Prefinancing	15.895
TOTAL	210.218

Operational costs for this incinerator are approximately 181 AUD. They include fees for disposal of residues from the combustion process. No revenue or levy like gate fee, energy sale or metal recovery is included.

A rough estimation for cost allocation for smaller incinerators is [44]:

site and construction	approx. 17 – 20%
Technical installations, machinery, equipment	approx. 72.5%
Planing	approx. 7.5% - 10%

10.3 Windrow Composting Facility Costs, 20,000 tpa

The financial data for the windrow composting facility have been derived from Italy. At this facility food and garden waste is accepted.

Table 36 Investment costs for a windrow composting facility [AUD]

Site costs	0.862
Development of site, construction costs	3.112
Technical equipment	1.966
TOTAL	5.940

Operational costs for this composting facility are approximately 91 AUD. They include the disposal of rejects. No revenue or levy like gate fee or sale of compost products is included.

11 Bibliography

URL's were added to the listed publications as far as possible. They were valid in October 2004 and provided the publication for download. If information were taken from the site itself the URL is given as well.

Sources are listed according to their sequence of use in the text.

[1] WRIGHT, A.G. (2000): *Independent Public Assessment – Landfill Capacity and Demand*. (Report. State Government of New South Wales)
→ www.dipnr.nsw.gov.au/

[2] www.collex.com.au

[3] RESOURCE NSW (Publisher) (2003): *Waste Avoidance and Resource Recovery Strategy 2003*
→ www.resource.nsw.gov.au

[4] IPPC Intergovernmental Panel On Climate Change (Publisher) (2001): *IPCC Third Assessment Report – Climate Change.*
→ www.ipcc.ch

[5] WRIGHT, T. (2000): *Report of the Alternative Waste Management Technologies and Practices Inquiry*. (State Government of New South Wales)

[6] SUNDQVIST, J.-O. (1999): *Life cycles assessments and solid waste – Guidelines for solid waste treatment and disposal in LCA.* (IVL Swedish Environmental Research Institute – Final Report)
→ www.naturvardsverket.se

[7] AS/NZS 1998: *AS/NSZ ISO 14040: Environmental Management – Life cycle assessment – Principles and framework*. Standards Australia and Standards New Zealand, Homebush

[8] GUINEE, J. (final editor) (2001): *Life Cycle Assessment - An operational guide to the ISO standards*. (CML Centre of Environmental Science, Leiden University – Final Report)

[9] FINNVEDEN, G.; JOHANNSSON, J.; LIND, P.; MOBERG, A. (2000); *Life Cycle Assessmenst of Energy from Solid Waste.* (fms Forskningsgruppen för Miljöstrategiska Studier, Stockholm)
→ www.infra.kth.se/fms/

[10] AS/NZS 2001: *AS/NSZ ISO 14042: Environmental Management – Life cycle assessment – Life cycle impact assessment*. Standards Australia and Standards New Zealand, Homebush

[11] AS/NZS 2001: *AS/NSZ ISO 14043: Environmental Management – Life cycle assessment – Life cycle interpretation*. Standards Australia and Standards New Zealand, Homebush

[12] LUNDIE et al. (2001, unpublished) (CWWT Centre for Water and Waste Technology, Sydney)

[13] AS/NZS 1999: *AS/NSZ ISO 14041: Environmental Management – Life cycle assessment – Goal and scope definition and inventory analysis*. Standards Australia and Standards New Zealand, Homebush

[14] GaBi 4 Manual (2003): *GaBi 4 - Get ready for tomorrow*. (IKP Institut für Kunststoffprüfung, Stuttgart / PE Europe GmbH, Leinfelden-Echterdingen)

[15] A. PRINCE CONSULTING: Several Audits (2000 – 2003)

[16] Personal communication with DARRYL STUCKEY, Department of Environment and Conservation, Sydney. May 2004

[17] HELLWEG, S. (2000): *Time- and Site-Dependent Life-Cycle Assessment of Thermal Waste Treatment Processes.* Dissertation. Submitted to the Swiss Federal Institute of Technology, Zürich
→ www.ethz.ch

[18] NPI National Pollutant Inventory (2002): *Emission Estimation Technique Manual for Municipal Solid Waste (MSW) Landfills, Version 1.1*. (Environment Australia, Canberra)
→ www.npi.gov.au

[19] SABERY, F. (2004): *Modell zur Vorkalkulation von mechanisch-biologischen Restabfallbehandlungsanlagen zur Herstellung von Ersatzbrennstoffen*. Dissertation an der Fakultät III Prozesswissenschaften der Technischen Universität Berlin
→ www.tu-berlin.de

[20] www.sydneywater.com.au/

[21] SUNDQVIST, J.-O. (project leader) (1999): *Systemanalys av energiutnyttjande fran avfall – utvärdering av energi, miljö och ekonomi*. (IVL Svenska Miljöinstitutet AB, Stockholm)
→ www.ivl.se

[22] RAMKE, H.-G. (2001): Script *Abfallwirtschaft und Deponietechnik/* Übung *Deponiegasprognose* - Fachhochschule Lippe und Höxter, Abt. Höxter, Fachbereich Technischer Umweltschutz

[23] KUCHLING, H. (1999): *Taschenbuch der Physik*. 16th Edition, Fachbuchverlag Leipzig

[24] GRANT, T.; JAMES, K.L.; LUNDIE, S.; SONNEVELD, K. (2001): *Stage 2 Report for Life Cycle Assessment for Paper and Packaging Waste Management Scenarios in Victoria*. (ECORECYCLE VICTORIA, Melbourne – Final Report)
→ www.cfd.rmit.edu.au

[25] Personal communication with NATHAN LOPEZ, THIESS, Sydney. March – April 2004

[26] C-TECH INNOVATION Ltd. (2003): *Thermal methods of municipal waste treatment.* (Report. Part of the BIFFAward Programme on Sustainable Resource Use) → www.capenhurst.com

[27] DEHOUST, G. et al. (1999): *Vergleich der rohstofflichen und energetischen Verwertung von Verpackungskunststoffen.* (Öko-Institut, Darmstadt)

[28] IPPC Integrated Pollution Prevention and Control (2003): *Draft Reference Document on Best Available Techniques for Waste Incineration.* (European Commission, Directorate-General JRC, Joint Research Centre, Institute for Prospective Technological Studies (Seville), Technologies for Sustainable Development, European IPPC Bureau)
→ www.jrc.es

[29] HENNE, K.-H. (2004): Script *Thermische Abfallbehandlung,* 5. Semester - Fachhochschule Lippe und Höxter, Abt.. Höxter, Fachbereich Technischer Umweltschutz

[30] DEHOUST, G. et al. (2001): *Stoffstromanalyse Leichtverpackungen – Sachbilanz.* (Öko-Institut, Darmstadt)
→ www.oeko.de

[31] Anonymus: *Landfill gas – Origin, Generation mechanisms, etc.* (PPT-Presentation. University of Nottingham, School of Chemical, Environmental and Mining Engineering)
→ www.nottingham.ac.uk

[32] ACHTERNBOSCH, M; RICHERS, U. (2002): *Material Flows and Investment Costs of Flue Gas Cleaning Systems of Municipal Solid Waste Incinerators*. (Wissenschaftliche Berichte FZKA 6726. Forschungszentrum Karlsruhe GmbH, Karlsruhe - Institut für Technikfolgeabschätzung und Systemanalyse/ Institut für Technische Chemie)
→ www.itas.fzk.de

[33] STUBENVOLL, J.; BÖHMER, S.; SZEDNYI, I. (2002): *Stand der Technik bei Abfallverbrennungsanlagen*. (Study. Prepared for Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien)
→ www.umweltbundesamt.at

[34] Recycled Organics Unit (2003): *Life Cycle Inventory And Life Cycle Assessment Of Windrow Composting Systems.* (Report. Prepared for NSW Department of Environment and Conservation, Sustainability Programs Division; Published by Recycled Organics Unit, University of New South Wales)
→ www.recycledorganics.com

[35] www.greenhouse.gov.au

[36] PITTOCK, B. (2003): *Climate Change: An Australian guide to the Science and the Potential Impacts*. (Published by the Australian Greenhouse Office, Canberra)
→ www.greenhouse.gov.au

[37] www.ikpgabi.uni-stuttgart.de

[38] www.eia.doe.gov

[39] www.nsw.greens.org.au

[40] www.nccnsw.org.au

[41] HOGG, D (2001): *Costs for Municipal Solid Waste Management* (Final Report to Directorate General Environment, European Comission)

[42] www.spiegel.de

[43] Personal communication with PAUL ZAGAMI, COLLEX, Sydney. September 2004

[44] Personal communication with HENRY NAWRATH, SULO, Herford. September 2004

[45] www.deponieforschung.de

[46] Dritte Allgemeine Verwaltungsvorschrift zum Abfallgesetz (TA Siedlungsabfall), May 1993

[47] *Materials Recycling Facility in Chullora* - Info-Flyer THIESS, Sydney

[48] Anonymus (2003): *Ergebnisbericht über Forschung und Entwicklung 2003*. (Wissenschaftliche Berichte – FZKA 7031. Forschungszentrum Karlsruhe GmbH, Karlsruhe - Institut für Technische Chemie)
→ www.fzk.de

[49] KROBATH, P. (Editor): *The Spittelau Thermal Waste Treatment plant*. (Brochure. Published by Thermische Abfallbehandlungsanlage Spittelau, Wien)
→ fww.pressestelle.at/

[50] fww.pressestelle.at/

[51] www1.agric.gov.ab.ca

[52] BINNER, E. (2003): *Kompostierung biogener Abfälle*. (Script. Universität für Bodenkultur, Wien, Department für Wasser, Atmosphäre und Umwelt, Institut für Abfallwirtschaft)
→ http://www.wau.boku.ac.at

[53] BACKHUS Kompost-Technologie, Info-CD. May 2002

[54] www.backhus.de

[55] GUDLADT, U. (2001): *Emissionsminderungspotentiale prozessintegrierter Maßnahmen bei der Kompostierung von Bioabfall*. Dissertation an der Mathematisch-Naturwissenschaftlichen Fakultät der Christian-Albrechts-Universität, Kiel.

[56] GaBi 4-Software

Appendix A – Waste Treatment Technologies

Within this appendix the following waste treatment technologies are explained: Landfill, Material Recycling Facility, Waste-to-Energy (Combustion) and windrow composting.

1. Landfill

A landfill is a site for the final disposal of solid waste – in case of this study for the disposal of municipal solid waste. Therefore it is called a Municipal Solid Waste (MSW) Landfill. A discrete area or an excavation can be used as site, if several requirements are fulfilled (e.g. an appropriate groundwater situation). An example for a discrete area would be Lucas Heights, while the Woodlawn dump to come is an excavation, as it will be set up in an old mine.

A MSW landfill is a long-term emitter of hazardous substances via leachate and biogas, it needs technological measurements to reduce danger. Leachate arises out of rain and water contained in waste. For preventing its leakage in the ground, the multi barrier concept is commonly used. In this concept, “several barriers, respectively independently of each other effective, shall make sure that pollutants can not escape a landfill unchecked in any phase. Most important barriers are the waste body itself, the geological barrier of an appropriately suitable underground, the base sealing system and the surface sealing system.” [45] The *geological barrier* can be clay or stone (without cracks) and should have a low water conductivity. Further, clay has a good retention. Between this barrier and the base sealing a base layer is installed as a connection between the landfill and the ground. The *base sealing* consists out of several layers of clay. The base sealing should be covered by a *plastic* and an additional *protective layer.* This is to avoid damage to the plastic layer due to heavy pressure. *Leachate collection pipes* are based on this system, topped with a *drainage layer* to improve leachate flow. Jammed leachate on the bottom might cause problems. Finally, this system is topped with a first layer of waste, ideally shredded to small peaces to avoid damage by bulky or sharp waste penetrating the barrier.

The next protection is the *waste body* itself. Waste should be filled in thin, highly compressed layers, as even as possible. This can be achieved with a compactor, which might stream roll the waste by passing it several times. Compartments out of operation should be covered with a layer of soil or similar materials, to avoid odour, increase in vermin, landfill fire and to reduce rain entering the landfill body.

Leachate is collected at the bottom by a network of pipes and pumped to the surface. There, it can either be discharged in the sewer to be cleaned by a STP. Otherwise, if the landfill has a treatment plant, it can be decontaminated on site. Figure 24 shows a set up for the bottom sealing of a landfill according to the multi barrier concept.

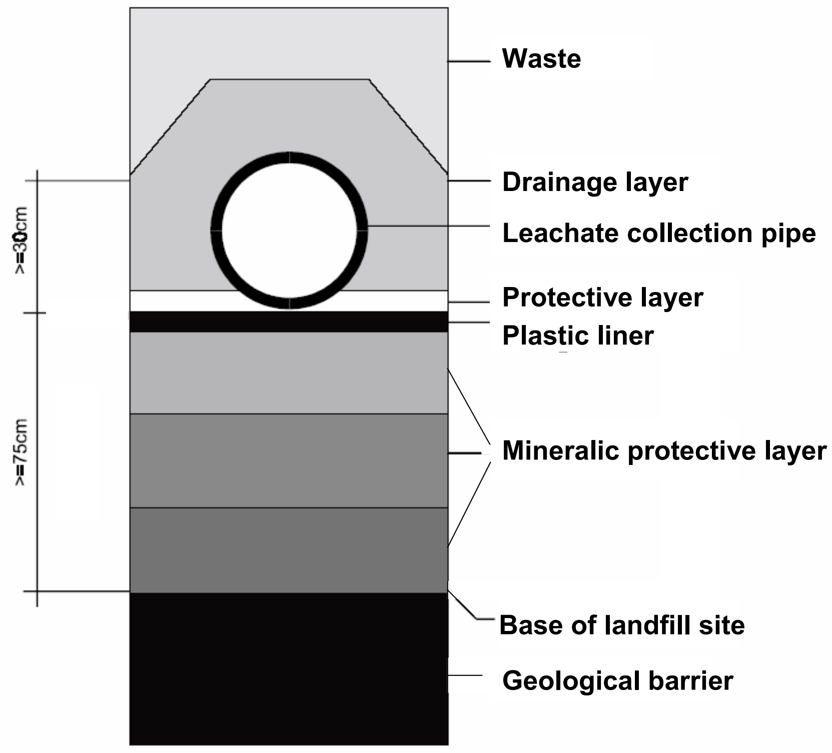


Figure 24 Geological Barrier and Base Sealing [46]

When the operation time of a compartment or the complete landfill comes to an end, the surface sealing has to be built. This consists of several layers again. The set up might vary due to different conditions and even purposes. One purpose could be to let pass some of the rain into the landfill body in order to speed up processes of biodegradation. On the one hand, more gas and therefore electricity is produced in a certain time frame, on the other hand this can reduce the time of after care of the landfill once it is closed, as degradation processes are finished earlier. Gas production decreases significantly and leachate becomes less. The other way of planing this surface cover is to close it as good as possible to avoid more degradation and leachate. A possible set up which has proved efficiency is shown in Figure 25. The set up of the top sealing system depends a lot on climate conditions of the landfill area.

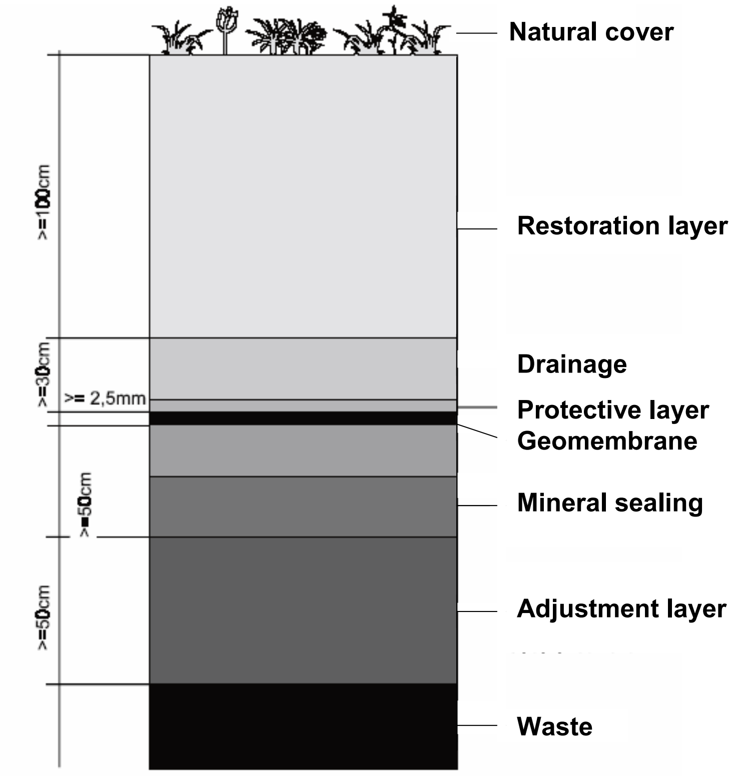


Figure 25 Example of a Top Sealing System [46]

Another technical “barrier” is the gas collection system. Pipes are crossing the whole landfill body to collect the gas. This is achieved by using vacuum pumps producing under-pressure in the pipe system. These horizontal drains should be installed during operation time of landfill, they are set up with disposal of waste. This net is combined with several collection wells where the gas is pumped out. On its way to the generator, where it is utilised to energy, or to the flare, the moisture is reduced by condensate knock-out vessels.

But there are other, non-technical, barriers as well. A good entrance control of waste to avoid the disposal of non-allowed (hazardous) waste is very important. The examination is organoleptic. If problems occur, an analysis of the delivered waste has to be done in the security area. Afterwards it can be decided if the waste can be disposed of or not. In landfill registers it is kept an account of where each delivery is built in. This is important if problems become aware afterwards. With this register the place can be identified and the waste can be mined. Also, if landfill fires occur the fire brigade is able to identify the sort of waste which is burning. Problematic emissions can be predicted. This is important for the safety of the people as well.

2. Material Recycling Facility

The process described in this chapter is from the Chullora Material Recycling Facility. The information is taken from [47] and from personal communication with Nathan Lopez [25].

The Chullora MRF is recovering the following product range out of the recycling stream:

Paper Products:

- Old Newspaper (ONP)
- Old Cardboard Containers (OCC)
- Mixed Paper (MXP)

Container Products:

- Coloured glass cullet – brown, green and clear
- Metal containers – steel and aluminium
- Plastics – clear and coloured PET, HDPE and mixed plastics

MXP consists out of office paper, LPB and ONP not recovered before hand. Mixed plastics contain PVC products.

When entering the facility, the truck passes the weighbridge. After the truck has been weighed, it drops the collected recycling material off at the so-called “One-Stop-Drop”, of which two on opposite sites of the hall exist. The material will be undergoing an eye-check, if it contains visible contamination, such as medical waste. Once such contamination is spotted, the whole load will be landfilled. When the recyclables are released for sorting, a back loader pushes them on a conveyor belt. The actual sorting process starts with manual sorting, where gross waste and OCC are diverted

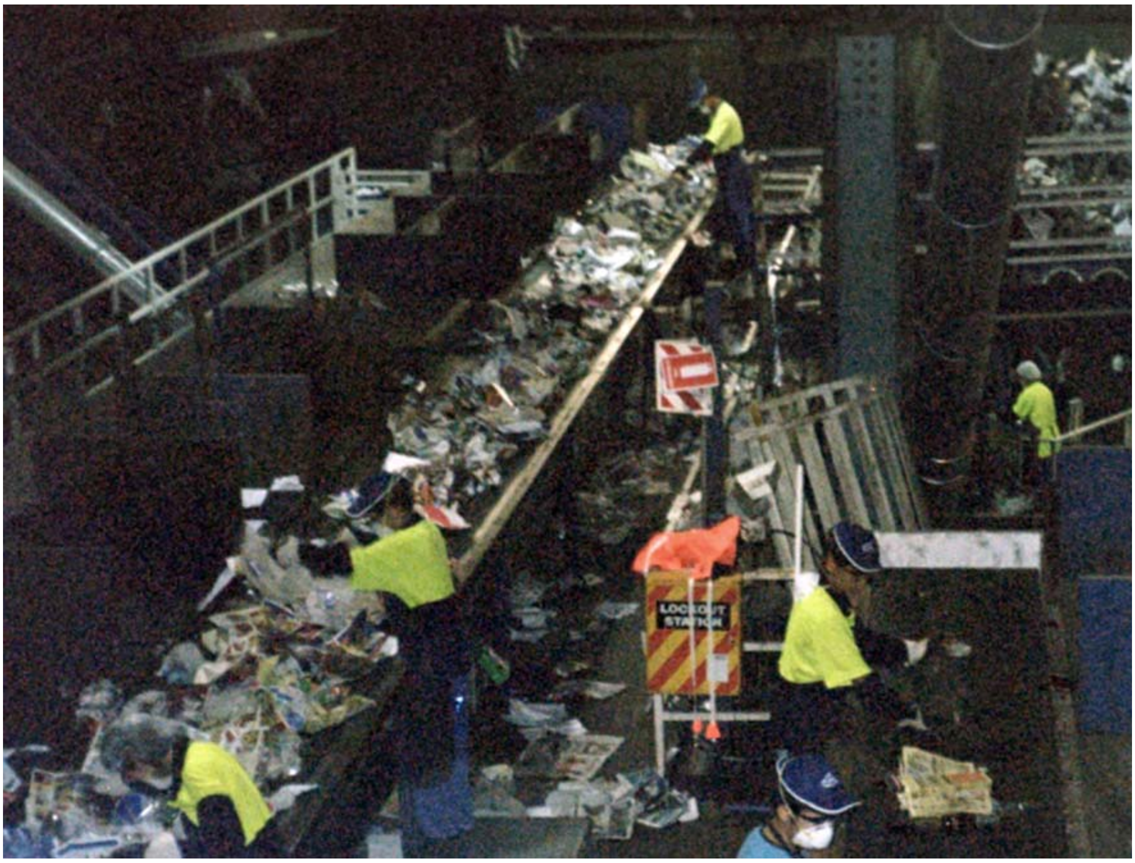


Figure 26 Manual sorting process at Chullora

This manual sorting process is shown in Figure 26. Both fractions are transported via conveyer belt; the waste to the waste compactor and the cardboard to the stocks for baling. The next station for the remaining fractions is the Containers Line, where both material streams from the two dropping points meet. Here, screens separate containers and MXP, while glass fines are removed, simply by falling through the holes in the bottom. The glass fines, which are of too poor quality to be recycled, are going to landfill. By this step, a higher quality for fibre products is achieved, as little fines are often mixing up with fibres. Once again, waste is manually removed from the container line.

The containers then pass the Trom Mag, a magnetic separator, where steel cans will be removed. After this, an air classifier is passed, where heavy fractions like glass are separated from light fractions, i.e. aluminium & plastic. An eddy current recovers the aluminium. The plastics are manually sorted into several fractions. All these different fractions are stored until the stocks are big enough to be baled for further transportation to the recycling plant (Figure 27). Glass is separated manually into different colours and collected outside (Figure 28).

Figure 27 Baled plastics ready for transportation to the recycling plant

Figure 28 Brown glass culets at Chullora

The MXP, which are diverted from the packaging materials, are transported on a separate conveyor to the last sorting step. ONP is removed in the ONP screen, by blowing air volume in the stream (Figure 29) and transported to the end of the line where it is collected for baling (Figure 30). Remaining contaminants are removed from both lines. When a sufficient amount of ONP is collected the truck is loaded with the help of Transpak, a machine increasing loading efficiency by squeezing the load into the truck.

Figure 29 Removing ONP from the belt by blowing air from the bottom in the stream…

Figure 30 …and collecting it for baling

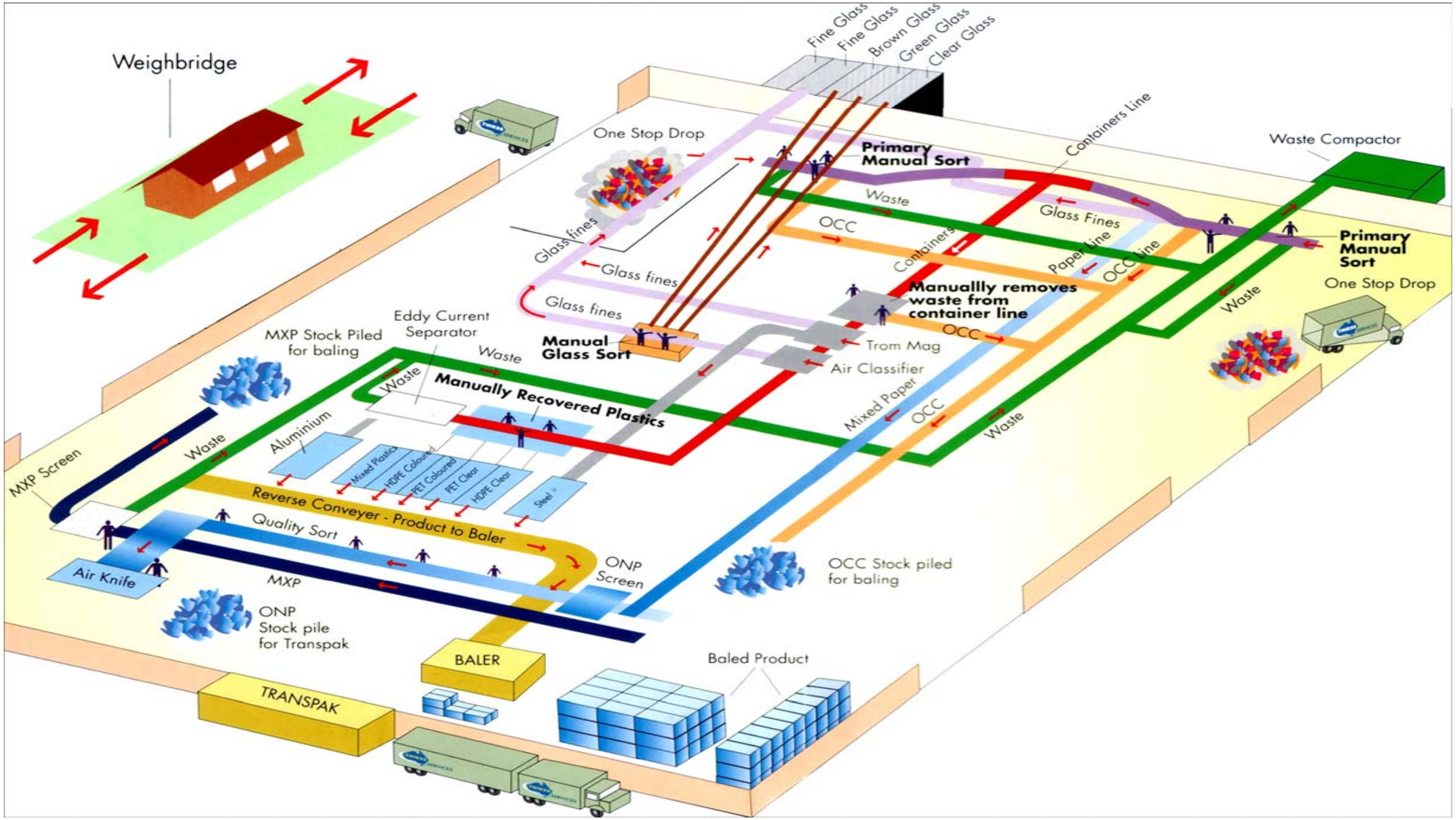


Figure 31 MRF Process (modified from [47])

3. Waste-To-Energy (Combustion)

The gross of information in this chapter have been taken from the “Draft Reference Document on Best Available Techniques for Waste Incineration” (Draft May 2003) by the IPPC [28]. Other sources are marked separately.

The main purposes of waste combustion are the reduction of volume and hazard. Reducing the hazard is of special interest for hazardous waste and sewage sludge, which both are not taken into account in this study, but also for domestic waste which can cause emissions, too, once disposed at landfill without further pre-treatment. The residues of the combustion process can be considered as largely inert. Further, it can provide energy production and the recovery of certain fractions from the residues, e.g. metals (if not separated before hand) and minerals. However, residues in this study are not treated any further but disposed of at landfill. Energy can be gained in the form of steam, heat and electricity.

Domestic waste arrives at the waste delivery area, from where the collection trucks dump it straight into the bunker. Generally, no pre-treatment is required, although homogenisation by shredding allows a more effective combustion. Only if pressed bales are delivered, they need to be shredded. This might happen, if the waste is baled at Transfer Stations under heavy pressure for increasing transport efficiency.

In the bunker, the waste is piled and mixed by cranes equipped with grapples. The mixing helps achieving a constant heating value, as waste is usually very heterogenic. The air from the bunker is extracted as incineration air for the furnace plants to avoid emissions of dust and odour. This prevents gas formation as well and reduces the risk of fire or explosions.

There are several furnace systems for municipal wastes, but the most common, the grate furnace, will be described. It essentially consists of six components:

- Supply equipment
- Incineration grate
- Ash remover
- Incineration air duct system
- Incineration chamber and
- Auxiliary burners

A incineration system with grate furnace is shown in Figure 32.

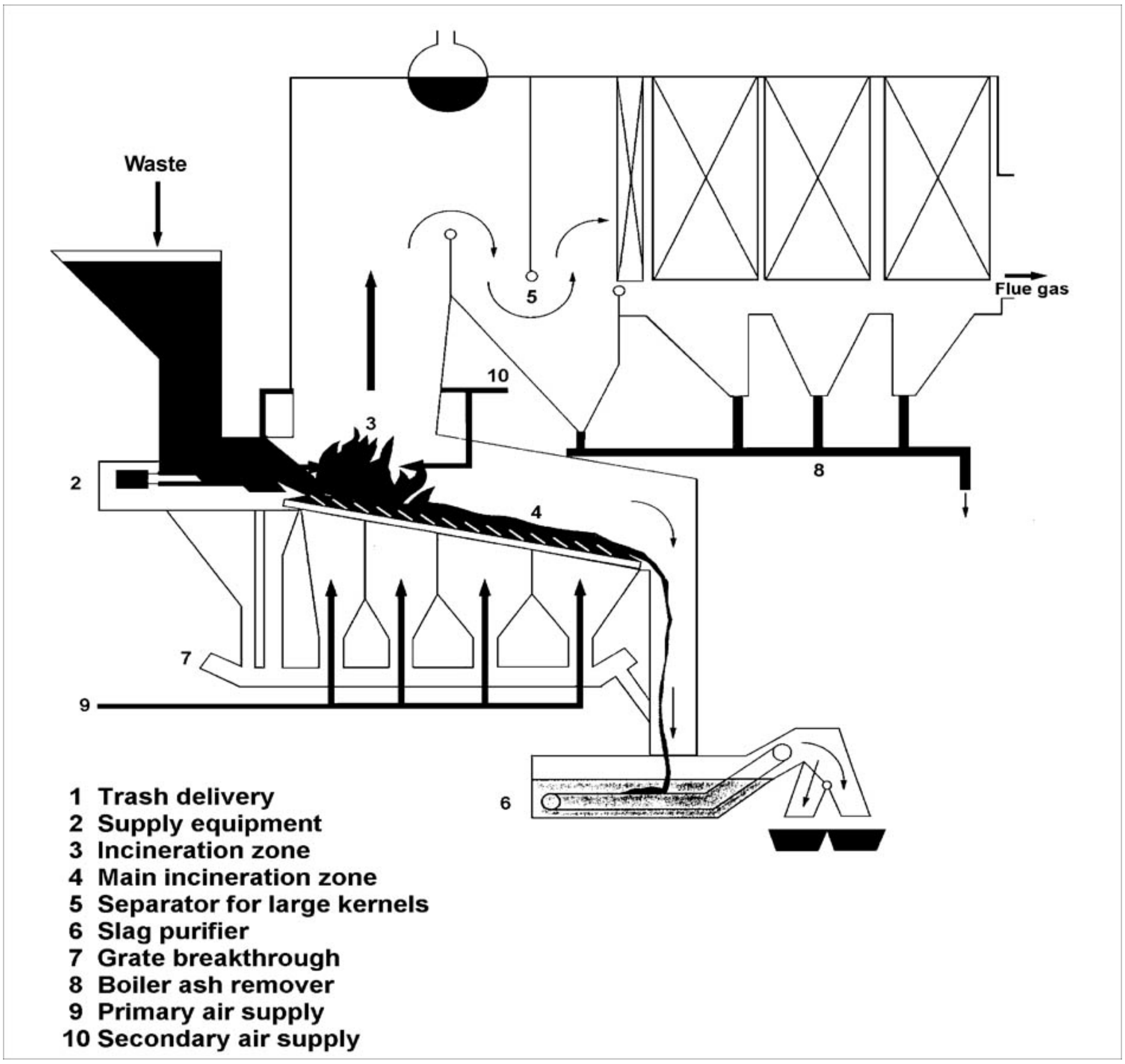


Figure 32 Incinerator with grate furnace [28]

Cranes feed the waste batch wise to the filling hopper, which serves as a continuous waste supplier to the combustion grate, where the waste is transported through the furnace. During this transport, it is stoked and loosened and finally positioned in the main combustion zone. Primary air is blown in through openings in the grate into the fuel layer. Secondary air is added above waste level to increase the efficiency of combustion. During the first stage of the incineration, called drying and degassing, volatile contents are evolved. This is followed by the gasification, where solid organic matter is converted to gaseous products. The gases just produced are then oxidised. This happens in the combustion chamber high above the waste. The residues, which are left on the grate, are then removed and cooled by the ash remover.

As combustion is an exothermic process, produced flue gases are very energy rich and therefore hot. They have to be cooled down to allow cleaning. After the cooling, temperatures must not be higher than 200° C to avoid the formation of dioxins (De-Novo-Synthesis) [48]. The cooling can be achieved by a boiler, placed on the ceiling of the incineration chamber. The energy is transferred from the gases to a fluid, which might be transformed into steam. This steam can be used for flue gas cleaning or be provided to industrial or domestic users. The steam can also be converted into electrical energy by using turbines, which are connected to generators. Is the water not transformed to steam, hot water can be supplied again to other users as a source of heat. In this study, just electricity is generated and fed into the public grid.

It is essential, that the flue gas is further treated after being cooled down. There are many ways of treating them and a general solution can't be given, as it depends on several factors such as particle load in the gas stream and the temperature of the flue gas. Here, the elements of the reference plant in Spittelau are listed and their effects briefly explained.

Fumes are cooled down to 180° C before they enter the electrostatic precipitator (ESP). The ESP is responsible for separating dust (fly ash) from the fumes. Its efficiency goes up to 99% [32].

The electric filter is followed by a 2-stage wet scrubber. A wet scrubber is the most common system in combustion plants for the removal of acid pollutants like HCl, HF and SO_2. These are absorbed by an aqueous solution [32]. In the first stage gases are quenched down to 65° C. Lime milk is added [49] to remove HCl (18) and HF. In the second stage, caustic soda is added for the removal of SO_2 (20), responsible for acid rain. The waste water from the scrubber is further treated in the facility owned waste water treatment plant.

The next stage of the flue gas cleaning system is the selective catalytic reduction (SCR) for the removal of nitrogen oxides. After reheating fumes, ammonia water is injected in addition to a catalyst to improve reaction((22) and (23)). By the reheating, dioxins are destroyed as well with more then 95% efficiency [49]. This is very important, as dioxins are highly toxic cancer causing substances. Finally, gases are cooled down again and emitted by chimneys [33]. The diagram of the whole plant including waste water treatment is shown in Figure 33.

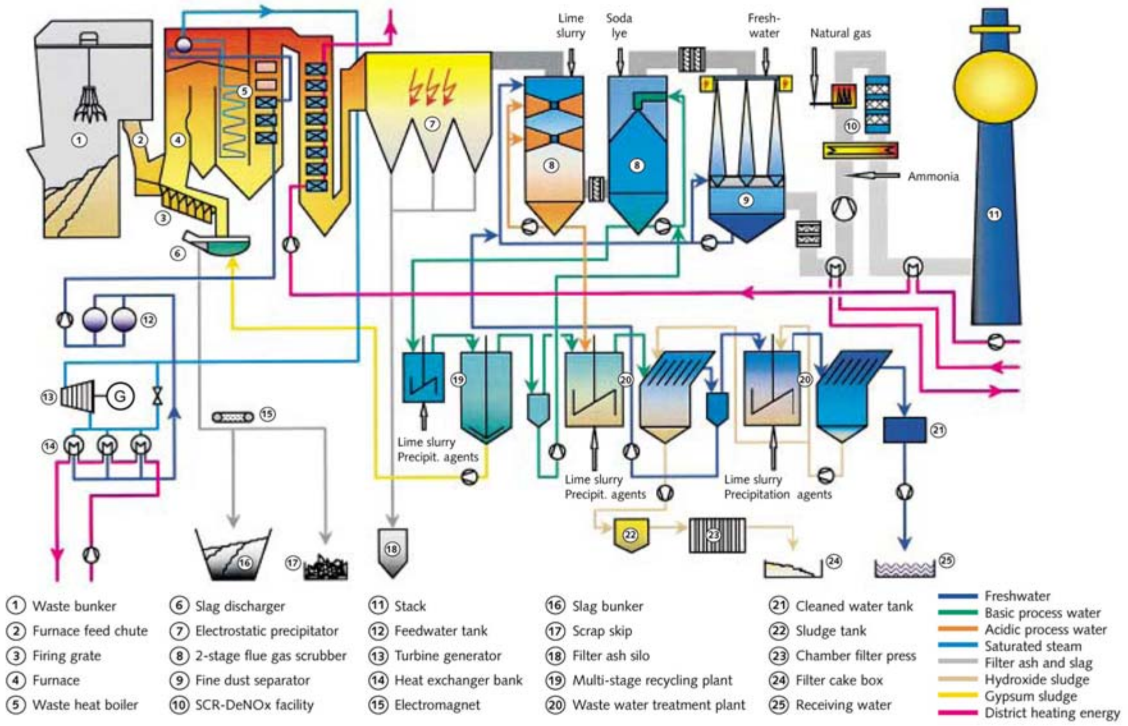


Figure 33 Diagramm of the Spittelau incinerator [49]

Figure 34 The Spittelau incinerator, designed by Friedrich Hundertwasser [50]

The combustion of waste is a highly accepted alternative of waste treatment in the European Union (EU) and America. The capacity of combustion plants in the EU is about 50 million tonnes. However, there are no such plants operating in Australia.

4. Windrow Composting

There are several methods of composting but in this study windrow composting is used, as this is the current technology in Sydney. It is fairly uncomplicated and does not require high technology. Ideally, windrows are piled under a roof to be protected against unfavourable weather – but this is no pre-condition.

The composting process is based on aerobic and thermophilic degradation of organic material. “During this process, bacteria, fungi, and other micro-organisms break down organic materials into a stable mixture called compost, while consuming oxygen and releasing heat, water, and carbon dioxide (CO_2).” [51]

The product is stable and contains nutrients for plants. The process can be divided into four stages:

- initial stage
- thermophilic stage
- mesophilic stage
- curing

During the initial stage mesophilic micro-organisms degrade starch, sugar and proteins [51]. The temperature in the windrow rises. By the heat pathogens are destroyed. During this thermophilic stage e.g. fats and some lignin is degraded. Most of the carbon degradation is achieved by now. In the next stage, the mesophilic stage, temperature goes down. More lignin and protein are degraded, which generate the precursors of humic substances [52]. The carbon degradation rate decreases as well. During the final stage, the curing, humic fractions are produced. Figure 24 shows the temperature graph and the degradation graph for carbon.

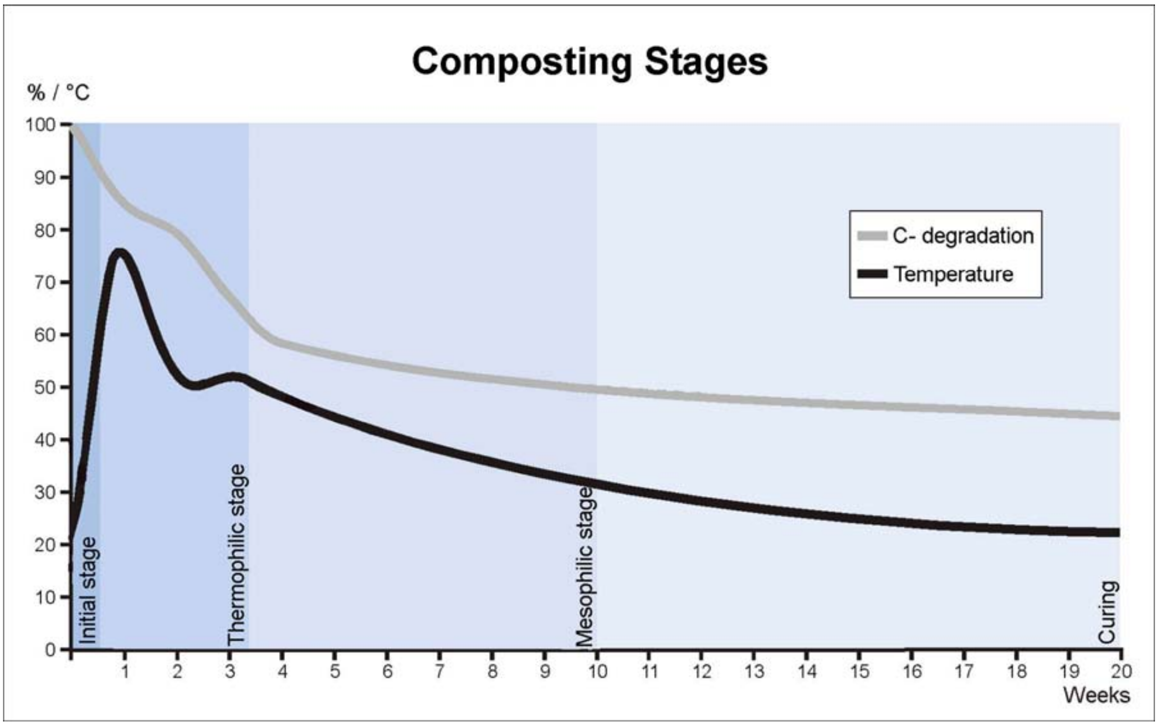


Figure 35 The four stages of composting (modified from [51])

During the process, important factors to keep hand on are temperature, moisture and aeration. The highest degradation rate occurs at Temperatures between 50 – 55° C [34] and with a moisture content of 40 – 55%. Moisture is important, as micro organisms can only assimilate nutrients and oxygen which are dissolved in water. If the water content is higher, the aerobic digestion turns anaerobic, which causes emissions like odour and a reduction in degradation. The water content can be regulated by adding water for increasing it or paper for turning it down. Aeration and temperature can be regulated by turning the material or venting it. By aerating the material the production of methane and odour due to anaerobic zones in the windrow can be avoided. The turning is done by windrow turners (Figure 36 and Figure 37).

Figure 36 Windrow turner [53]

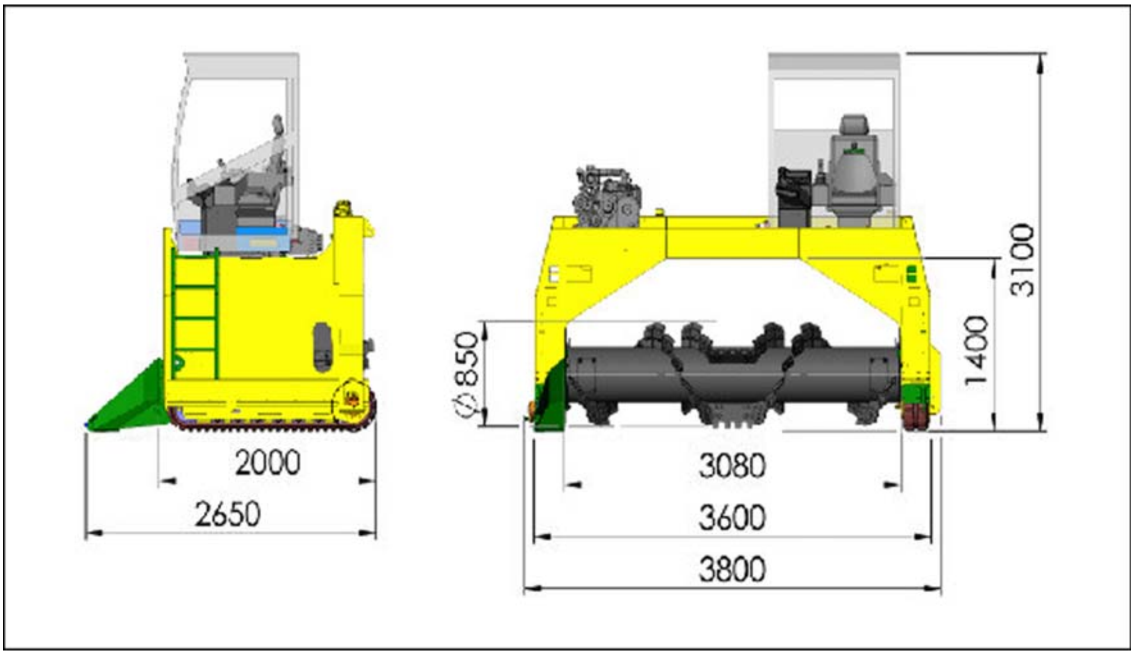


Figure 37 Side view and front view of a windrow turner including measurement [54]

Other important parameters, which can not be regulated easily are C/N-ratio and pH-value. The nutrient ratio C/N should be adjusted between 20:1 and 35:1 [55] before starting by varying inputs materials such as grass clippings or wood chips. The pH-value should be between 6 and 8 [52]. If it has to be increased, lime can be added.

The end product is compost which can be used e.g. as mulch or soil conditioner.

The procedure of windrow composting is shown in Figure 38. Garden waste is delivered to the facility and checked for contaminants. After their removal the organics are shredded. Then it is placed in windrows. They are 3 – 6 meters wide and can be 1.5 – 3 meters high. The length depends on the size of the hall or the place.

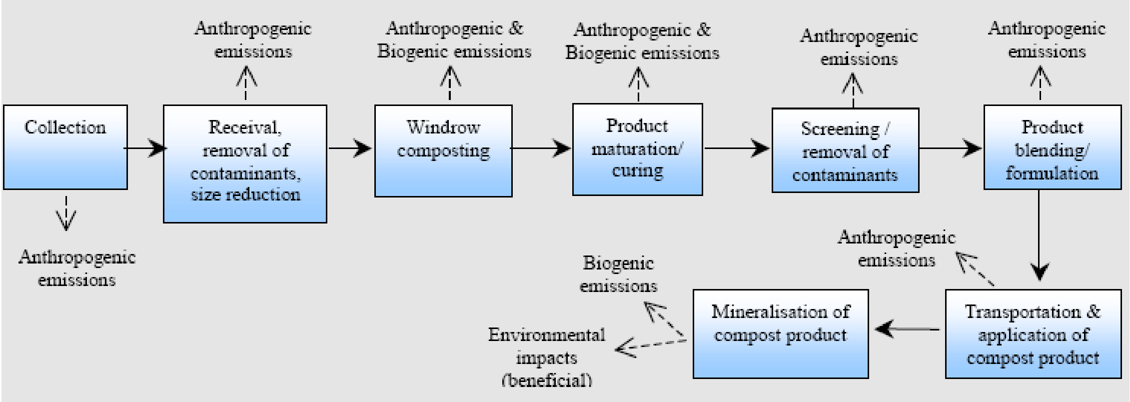


Figure 38 Sequence of Steps during Windrow Composting [34]

To avoid emissions to ground, the facility needs a runoff and leachate management. The water can be collected and used for watering the windrows on demand. So, emissions by water are avoided and use of external water for processing garden waste is replaced [34]. If the windrow composting is not happening in a hall it can cause heavy odour emissions. To avoid this, suction aeration is often used. By this, surrounding air is sucked through the windrow to the ground and conducted through a biofilter. With this type of aeration windrows tend to dry at the outer areas and collect water near the bottom. This can cause anaerobic conditions again.

Appendix B – Functional Unit

Table 37 Composition of garbage [%] [15]

Council	Paper	Card-board	ONP	LPB	HDPE	PET	PVC	LDPE	Mixed Plastics	Alu-minium	Tin Plate	Glass	Food	Vege-tation	Mixed Waste	Total	Audit year
1	11.53	2.25	0.62	0.34	0.5	0.57	0.04	0.03	12.23	0.46	2.05	3.28	47.21	2.55	18.35	100.01	2000
2	3.28	2.39	1.78	0.07	0.63	0.96	0.00	0.00	5.36	0.18	1.68	3.86	26.72	25.96	27.14	100.01	2001
3	10.8	4.74	3.2	0.61	1.02	0.72	0.12	0.01	8.95	0.66	2.74	3.84	37.71	8.91	15.97	100.00	2001
4	9.22	3.71	3.95	.31	0.85	0.77	0.02	0.01	8.50	0.47	2.99	4.20	34.13	15.92	14.95	100.00	2001
5	9.88	2.17	1.37	0.34	0.52	0.30	0.01	0.00	10.09	0.30	3.06	2.87	43.76	1.39	23.94	100.00	2001
6	8.10	2.20	1.78	0.35	0.39	0.39	0.01	0.02	11.32	0.41	2.90	4.87	43.01	1.07	23.15	99.97	2001
7	10.32	3.31	2.32	0.58	0.72	0.62	0.05	0.00	9.41	0.44	2.96	4.42	37.67	8.61	18.57	100.00	2001
8	11.50	2.40	2.2	0.6	0.60	0.60	0.00	0.10	9.00	0.30	2.90	4.10	43.80	5.10	16.70	99.90	2002
9	8.43	2.84	1.71	0.33	0.49	0.46	0.02	0.02	8.65	0.29	2.30	3.59	42.95	11.87	16.04	99.99	2003
10	9.80	3.80	3.1	0.05	0.70	0.70	0.00	0.00	10.80	0.40	2.60	4.30	41.20	3.30	18.80	100.00	2002
11	7.07	2.13	1.65	0.29	0.53	0.74	0.02	0.00	7.07	0.47	1.91	2.89	38.59	19.03	17.61	100.00	2001
12	10.78	5.38	5.71	1.04	0.83	1.23	0.07	0.03	9.35	0.28	3.12	9.29	29.60	9.56	13.74	100.01	2001
13	7.95	2.77	2.81	0.53	0.61	0.74	0.04	0.01	9.79	0.51	3.14	3.90	37.95	3.66	25.57	99.98	2001
14	13.13	4.46	5.05	0.77	0.65	0.77	0.03	0.01	8.86	0.46	2.77	5.72	35.58	6.66	15.07	99.99	2001
15	13.99	3.86	6.6	0.71	0.59	0.93	0.05	0.00	8.09	0.26	2.12	6.29	32.26	10.97	13.27	99.99	2001
Average	9.72	3.23	2.92	0.49	0.64	0.70	0.03	0.02	9.03	0.39	2.62	4.49	38.14	8.97	18.59	99.99	

Table 38 Composition of recycling material [%] [15]

Council	Paper/ Magaz.	Card-board	ONP	LPB	HDPE	PET	PVC	LDPE	Mixed Plastics	Alu-minium	Tin Plate	Glass	Food	Vege-tation	Mixed Waste	Total	Audit year
1	16.49	12.84	28.55	0.65	2.66	4.11	0.08	0.01	2.12	0.40	2.72	25.77	0.65	0.00	2.95	100.00	2000
2	17.60	14.43	22.91	0.29	2.68	3.82	0.00	0.00	1.72	0.75	1.95	23.89	0.00	0.00	9.94	99.98	2001
3	26.54	12.85	32.05	0.32	1.14	2.49	0.10	0.00	0.68	0.50	0.14	21.79	0.84	0.04	0.52	100.00	2001
4	19.08	15.22	29.40	0.36	1.76	2.78	0.06	0.00	0.61	0.41	0.61	29.01	0.22	0.00	0.50	100.02	2001
5	23.50	9.10	25.00	0.25	1.30	2.30	0.00	0.00	0.95	0.53	1.84	31.60	0.00	0.00	3.60	99.97	2001
6	21.20	16.50	32.10	0.30	1.80	1.70	0.10	0.00	2.60	0.22	2.90	17.00	1.40	0.00	2.20	100.02	2001
7	24.46	10.97	31.44	0.37	1.63	1.95	0.05	0.01	1.99	0.32	1.64	23.62	0.08	0.00	1.46	99.99	2001
8	21.33	8.15	35.71	0.51	1.55	2.46	0.05	0.01	0.97	0.36	1.33	26.65	0.16	0.00	0.75	99.99	2002
9	18.20	4.90	36.00	0.30	1.90	2.80	0.10	0.40	0.90	0.50	0.50	29.70	0.10	0.00	3.90	100.20	2003
10	8.24	15.29	28.14	0.44	3.43	4.41	0.24	0.00	1.58	0.95	2.48	33.34	0.50	0.03	0.91	99.98	2002
11	25.42	12.53	21.89	0.50	1.47	3.02	0.02	0.00	0.97	0.31	1.60	31.69	0.21	0.00	0.37	100.00	2001
12	18.15	9.75	33.48	0.68	1.33	2.05	0.04	0.00	1.16	0.11	1.32	30.23	0.21	0.00	1.48	99.99	2001
13	16.27	13.35	36.55	0.26	1.57	2.10	0.0	0.00	4.20	0.15	1.82	19.27	1.21	0.06	3.13	100.02	2001
14	10.24	9.66	30.74	0.49	0.98	1.70	0.06	0.03	0.40	0.17	0.26	44.55	0.32	0.00	0.40	100.00	2001
15	18.83	13.76	32.80	0.67	2.09	2.12	0.08	0.02	1.34	0.42	1.51	24.90	0.09	0.00	1.37	100.00	2001
16	22.66	9.40	36.55	0.26	1.09	1.60	0.09	0.00	0.72	0.04	0.13	27.36	0.00	0.00	0.11	100.01	2001
17	20.45	6.77	35.34	0.30	0.53	1.26	0.01	0.00	0.37	0.04	0.40	33.70	0.20	0.04	0.34	99.75	2001
Average	**19.33**	**11.50**	**31.10**	**0.41**	**1.70**	**2.51**	**0.07**	**0.03**	**1.37**	**0.36**	**1.36**	**27.89**	**0.39**	**0.01**	**2.00**	**100.02**	

Appendix C – Life Cycle Inventory

1. Elementary Composition of Waste Fractions

Table 39 Elementary composition of waste fractions [kg/kg TS]

	Paper[a]	**Card-board[b]**	**ONP[b]**	**LPB[b]**	**HDPE[b]**	**PET[b]**	**PVC[b]**	**LDPE[b]**	**Mixed Plastics[a]**	**Alu-minium[a,e]**	**Tin Plate[a,e]**	**Glass[a]**	**Food[b]**	**Vege-tation[a]**	**Mixed Waste[c]**
TS	8.80E-1	8.80E-1	8.80E-1	8.90E-1	9.50E-1	9.50E-1	9.50E-1	9.50E-1	9.50E-1	1.00	1.00	1.00	3.00E-1[f]	6.00E-1[f]	7.00E-1[d]
C-fossil	-	1.70E-1	8.00E-3	2.52E-1	8.56E-1	6.40E-1	4.01E-1	8.56E-1	7.30E-1	-	-	-	-	-	1.43E-1[d]
C-bio	4.70E-1	4.00E-1	4.00E-1	3.52E-1	-	-	-	-	-	-	-	-	4.34E-1	4.63E-1	1.43E-1[d]
H	6.40E-2	6.90E-2	5.00E-2	7.78E-2	1.42E-1	2.10E-2	5.10E-2	1.42E-1	1.20E-1	-	-	-	5.80E-2	4.00E-2	-
O	4.70E-1	-	3.80E-1	3.60E-4	3.00E-3	3.40E-1	6.50E-3	3.00E-3	4.80E-2	-	-	-	2.87E-1	3.90E-1	-
Cl	8.50E-4	1.70E-3	6.00E-6	1.50E-3	-	-	5.38E-1	-	3.80E-2	-	-	-	3.90E-3	5.00E-3	-
N-tot	2.80E-3	2.60E-3	-	2.29E-3	-	-	-	-	3.00E-3	-	-	-	2.00E-2	7.00E-3	-
P-tot	2.00E-4	4.70E-4	-	4.14E-4	-	-	-	-	8.20E-4	-	-	-	3.80E-3	1.00E-3	-
S-tot	1.20E-3	1.20E-3	-	1.06E-3	-	-	-	-	1.50E-3	-	-	-	2.40E-3	5.00E-4	-
Al	-	-	1.50E-2	-	-	-	-	-	-	-	-	-	-	-	-
K	1.40E-3	1.20E-3	-	1.06E-3	-	-	-	-	1.50E-3	-	-	-	9.30E-3	5.00E-3	-
Ca	1.90E-2	1.40E-2	6.00E-3	1.23E-2	-	-	4.00E-2	-	4.90E-3	-	-	-	2.80E-2	1.00E-2	-
Pb	1.30E-5	4.00E-6	3.50E-6	2.63E-5	1.90E-4	1.90E-4	1.90E-4	1.90E-4	2.10E-4	1.80E-4	1.80E-4	-	1.00E-5	1.27E-5	1.90E-4
Cd	1.80E-7	3.80E-8	5.00E-8	4.78E-8	1.20E-7	1.20E-7	1.20E-7	1.20E-7	3.70E-7	-	-	-	1.30E-7	1.60E-7	2.00E-6
Hg	2.10E-8	1.80E-8	1.10E-8	2.44E-8	7.10E-8	7.10E-8	7.10E-8	7.10E-8	6.00E-8	-	-	-	2.80E-8	4.00E-8	1.10E-6
Cu	4.10E-5	2.70E-5	3.50E-5	4.54E-5	1.80E-4	1.80E-4	1.80E-4	1.80E-4	1.50E-4	4.70E-3	4.70E-3	-	3.40E-5	1.60E-5	7.15E-4
Cr	7.30E-6	1.40E-5	5.90E-6	1.39E-5	1.30E-5	1.30E-5	1.30E-5	1.30E-5	1.60E-5	1.10E-3	1.10E-3	1.80E-5	1.00E-5	1.01E-5	7.50E-5
Ni	5.40E-6	8.20E-6	6.20E-6	8.14E-6	7.70E-6	7.70E-6	7.70E-6	7.70E-6	7.60E-6	5.30E-4	5.30E-4	-	7.00E-6	5.40E-6	4.38E-5
Zn	5.6E-5	4.00E-5	4.20E-5	5.80E-5	1.90E-4	1.90E-4	1.90E-4	1.90E-4	3.30E-4	2.00E-4	2.00E-4	-	8.00E-5	6.73E-5	7.80E-4

- not available

TS = total solids

a taken from [21]

b taken from [9]

c taken from [19] if not marked differently

d estimated

e [21] just gives metal as category

f calculated

Table 40 Elementary composition of humid fraction

	Paper	Card-board	ONP	LPB	HDPE	PET	PVC	LDPE	Mixed Plastics	Alu-minium	Tin Plate	Glass	Food	Vege-tation	Mixed Waste
LHV	4	4.16	4.71	4.71	10.24	10.24	5.74	10.24	8.74	0	0	0	0.91	2.2	2.54
C-fossil	-	1.50E-1	7.04E-3	2.24E-1	8.13E-1	6.08E-1	3.81E-1	8.13E-1	6.94E-1	-	-	-	-	-	1.00E-1
C-bio	4.14E-1	3.52E-1	3.87E-1	3.13E-1	-	-	-	-	-	-	-	-	-	-	1.00E-1
H	5.63E-2	6.07E-2	4.40E-2	6.91E2	1.35E-1	2.00E-2	4.85E-2	1.35E-1	1.14E-1	-	-	-	1.74E-2	2.40E-2	-
O	4.14E-1	-	3.34E-1	3.20E-4	2.85E-3	3.23E-1	6.18E-3	2.85E-3	4.56E-2	-	-	-	8.61E-2	2.34E-1	-
Cl	7.48E-4	1.50E-3	5.28E-6	1.33E-3	-	-	5.11E-1	-	3.61E-2	-	-	-	1.17E-3	3.00E-3	-
N-tot	2.46E-3	2.28E-3	-	2.03E-3	-	-	-	-	2.85E-3	-	-	-	6.00E-3	4.20E-3	-
P-tot	1.76E-4	4.14E-4	-	3.67E-4	-	-	-	-	7.79E-4	-	-	-	1.14E-3	6.00E-4	-
S-tot	1.06E-3	1.06E-3	-	9.38E-4	-	-	-	-	1.43E-3	-	-	-	7.20E-4	3.00E-4	-
Al	-	-	1.32E-2	-	-	-	-	-	-	-	-	-	-	-	-
K	1.23E-3	1.06E-3	-	9.38E-4	-	-	-	-	1.43E-3	-	-	-	2.79E-3	3.00E-3	-
Ca	1.67E-2	1.23E-2	5.28E-3	1.09E-2	-	-	3.80E-2	-	4.66E-3	-	-	-	8.40E-3	6.00E-3	-
Pb	1.14E-5	3.52E-6	3.08E-6	2.34E-5	1.81E-4	1.81E-4	1.81E-4	1.81E-4	2.00E-4	1.80E-4	1.80E-4	-	3.00E-6	7.62E-6	1.33E-4
Cd	1.58E-7	3.34E-8	4.40E-8	4.25E-8	1.14E-7	1.14E-7	1.14E-7	1.14E-7	3.52E-7	-	-	-	3.90E-8	9.60E-8	1.40E-6
Hg	1.85E-8	1.58E-8	9.68E-9	2.16E-8	6.75E-8	6.75E-8	6.75E-8	6.75E-8	5.70E-8	-	-	-	8.40e-9	2.40E-8	7.70E-7
Cu	3.61E-5	2.38E-5	3.08E-5	4.03E-5	1.71E-4	1.71E-4	1.71E-4	1.71E-4	1.43E-4	4.70E-3	4.70E-3	-	1.02E-5	9.60E-6	5.01E-4
Cr	6.42E-6	1.23E-5	5.19E-6	1.23E-5	1.24E-5	1.24E-5	1.24E-5	1.24E-5	1.52E-5	1.10E-3	1.10E-3	1.80E-5	3.00E-6	6.06E-6	5.25E-5
Ni	4.75E-6	7.22E-6	5.46E-6	7.23E-6	7.32E-6	7.32E-6	7.32E-6	7.32E-6	7.22E-6	5.30E-4	5.30E-4	-	2.10E-6	3.24E-6	3.06E-5
Zn	4.93E-5	3.52E-5	3.70E-5	5.15E-5	1.81E-4	1.81E-4	1.81E-4	1.81E-4	3.14E-5	2.00E-4	2.00E-4	-	2.40E-5	4.04E-5	5.46E-4

2. Degradation Yield (α) of Food and Garden Waste

Table 41 C-types and C-content of food and garden waste

C-type	Food	Garden Waste
C-lignin	0.029	0.144
C-cellulose	0.107	0.266
C-starch	0.097	0.035
C-fats	0.135	0
C-proteins	0.066	0,018
TOTAL	0.434	0.463

Table 42 Degraded C for food and garden waste

C-type	α	$C_{degr.}$-Food	$C_{degr.}$-Garden Waste
C-lignin	0	0	0
C-cellulose	0.7	0.0749	0.186
C-starch	1	0.097	0.035
C-fats	1	0.135	0
C-proteins	1	0.066	0.018
TOTAL		0.3729	0.239

The total degradation yield is calculated as in (25):

$$\alpha_{tot_i} = \frac{C_{tot\,i}}{C_{\deg r.}} \qquad (25)$$

where:

α_{tot_i} = total α of substance *i*

C_{tot_i} = total carbon content of substance *i*

$$\alpha_{tot_{Food}} = \frac{0.3729}{0.434} = 0.8592 \qquad (26)$$

$$\alpha_{tot_{Garden}} = \frac{0.463}{0.239} = 0.5166 \qquad (27)$$

3. Calculation of Landfill - Biogas

The general equation for calculating the density of gases at different temperatures is [23]:

$$\rho_2 = \rho_1 \times \frac{T_1 \times p_2}{T_2 \times p_1} \quad (28)$$

where:

ρ_1, T_1, p_1 = Pressure, temperature and density under condition 1

ρ_2, T_2, p_2 = Pressure, temperature and density under condition 2

Condition no.1 complies with the standard condition, where T = 273 K and p = 101 kPa (Figures are rounded). Condition no. 2 differs in temperature and therefore in density, gas temperature is 25°C or 298 K (estimated).
The density of CO_2 is:

$$\rho_{CO_2(25°C)} = \rho_{CO_2(0°C)} \times \frac{T_1 \times 101kPa}{T_2 \times 101kPa} \quad (29)$$

where:

$\rho_{CO_2(0°C)}$ = 1.9769kg/m^3 [23]

$$\rho_{CO_2} = 1.9769\frac{kg}{m^3} \times \frac{273K \times 101kPa}{298K \times 101kPa} = 1.811053\frac{kg}{m^3} \quad (30)$$

The density of CH_4 is:

$$\rho_{CH_4(25°C)} = \rho_{CH_4(0°C)} \times \frac{T_1 \times 101kPa}{T_2 \times 101kPa} \quad (31)$$

where:

$\rho_{CH_4(0°C)}$ = 0.7168kg/m^3 [23]

$$\rho_{CH_4(25°C)} = 0.7168\frac{kg}{m^3} \times \frac{273K \times 101kPa}{298K \times 101kPa} = 0.656666\frac{kg}{m^3} \quad (32)$$

4. Landfill Emissions to Water and to Soil

Table 43 Paper to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	6.34E-4		
NO_3^-	4.36E-3		
PO_4^{3-}	1.79E-6	P	2.94E-6
Pb	1.37E-10	Pb	5.49E-10
Cd	3.56E-11	Cd	3.56E-11
Hg	1.85E-13	Hg	7.39E-13
Cu	1.26E-9	Cu	1.26E-9
Cr	1.80E-9	Cr	2.70E-9
Ni	1.43E-8	Ni	9.50E-9
Zn	9.86E-10	Zn	8.87E-9
TSS	4.35E-7		
COD	6.25E-4		

Table 44 Cardboard to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	5.88E-4		
NO_3^-	4.05E-3		
PO_4^{3-}	4.21E-6	P	6.90E-6
Pb	4.22E-11	Pb	1.69E-10
Cd	7.52E-11	Cd	7.52E-11
Hg	1.58E-13	Hg	6.34E-13
Cu	8.32E-10	Cu	8.32E-10
Cr	3.45E-9	Cr	5.17E-9
Ni	2.16E-8	Ni	1.44E-8
Zn	7.04E-10	Zn	6.34E-9
TSS	2.03E-7		
COD	6.74E-4		

Table 45 ONP to landfill: emissions to water and soil

Emission to water	**[kg/kg]**	**Emission to soil**	**[kg/kg]**
NH_3/NH_4^+	-		
NO_3^-	-		
PO_4^{3-}	-	P	-
Pb	3.70E-11	Pb	1.48E-10
Cd	9.90E-11	Cd	9.90E-11
Hg	9.68E-14	Hg	3.87E-13
Cu	1.08E-9	Cu	1.08E-9
Cr	1.45E-9	Cr	2.18E-9
Ni	1.64E-8	Ni	1.09E-8
Zn	7.39E-10	Zn	6.65E-9
TSS	4.48E-6		
COD	5.30E-4		

Table 46 LPB to landfill: emissions to water and soil

Emission to water	**[kg/kg]**	**Emission to soil**	**[kg/kg]**
NH_3/NH_4^+	5.23E-4		
NO_3^-	3.60E-3		
PO_4^{3-}	3.74E-6	P	6.90E-6
Pb	2.81E-10	Pb	1.69E-10
Cd	9.56E-11	Cd	7.52E-11
Hg	2.16E-13	Hg	6.34E-13
Cu	1.41E-9	Cu	8.32E-10
Cr	3.45E-9	Cr	5.17E-9
Ni	2.17E-9	Ni	1.44E-8
Zn	1.03E-9	Zn	6.34E-9
TSS	1.46E-9		
COD	6.38E-4		

Table 47 HDPE to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	-		
NO_3^-	-		
PO_4^{3-}	-	P	-
Pb	2.17E-9	Pb	8.66E-9
Cd	2.57E-10	Cd	2.57E-10
Hg	6.75E-13	Hg	2.70E-12
Cu	5.99E-9	Cu	5.99E-9
Cr	3.46E-9	Cr	5.19E-9
Ni	2.19E-8	Ni	1.46E-8
Zn	3.61E-9	Zn	3.24E-8
TSS	3.49E-10		
COD	4.10E-5		

Table 48 PET to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	-		
NO_3^-	-		
PO_4^{3-}	-	P	-
Pb	2.17E-9	Pb	8.66E-9
Cd	2.57E-10	Cd	2.57E-10
Hg	6.75E-13	Hg	2.70E-12
Cu	5.99E-9	Cu	5.99E-9
Cr	3.46E-9	Cr	5.19E-9
Ni	2.19E-8	Ni	1.46E-8
Zn	3.61E-9	Zn	3.24E-8
TSS	1.15E-9		
COD	2.04E-5		

Table 49 PVC to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	-		
NO_3^-	-		
PO_4^{3-}	-	P	-
Pb	2.17E-9	Pb	8.66E-9
Cd	2.57E-10	Cd	2.57E-10
Hg	6.75E-13	Hg	2.70E-12
Cu	5.99E-9	Cu	5.99E-9
Cr	3.46E-9	Cr	5.19E-9
Ni	2.19E-8	Ni	1.46E-8
Zn	3.61E-9	Zn	3.24E-8
TSS	1.15E-9		
COD	1.92E-5		

Table 50 LDPE to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	-		
NO_3^-	-		
PO_4^{3-}	-	P	-
Pb	2.17E-9	Pb	8.66E-9
Cd	2.57E-10	Cd	2.57E-10
Hg	6.75E-13	Hg	2.70E-12
Cu	5.99E-9	Cu	5.99E-9
Cr	3.46E-9	Cr	5.19E-9
Ni	2.19E-8	Ni	1.46E-8
Zn	3.61E-9	Zn	3.24E-8
TSS	1.02E-9		
COD	4.10E-5		

Table 51 Mixed Plastics to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	7.33E-4		
NO_3^-	5.05E-3		
PO_4^{3-}	7.93E-6	P	1.30E-5
Pb	2.39E-9	Pb	9.58E-9
Cd	7.91E-10	Cd	7.91E-10
Hg	5.70E-13	Hg	2.28E-12
Cu	4.99E-9	Cu	4.99E-9
Cr	4.26E-9	Cr	6.38E-9
Ni	2.17E-8	Ni	1.44E-8
Zn	6.27E-9	Zn	5.64E-8
TSS	1.02E-9		
COD	3.20E-5		

Table 52 Aluminium to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	-		
NO_3^-	-		
PO_4^{3-}	-	P	-
Pb	2.16E-9	Pb	8.64E-9
Cd	-	Cd	-
Hg	-	Hg	-
Cu	1.65E-7	Cu	1.65E-7
Cr	3.08E-7	Cr	4.62E-7
Ni	1.59E-6	Ni	1.06E-6
Zn	4.00E-9	Zn	3.60E-8
TSS	2.03E-7		
COD	-		

Table 53 Tin Plate to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	-		
NO_3^-	-		
PO_4^{3-}	-	P	-
Pb	2.16E-9	Pb	8.64E-9
Cd	-	Cd	-
Hg	-	Hg	-
Cu	1.65E-7	Cu	1.65E-7
Cr	3.08E-7	Cr	4.62E-7
Ni	1.59E-6	Ni	1.06E-6
Zn	4.00E-9	Zn	3.60E-8
TSS	4.48E-6		
COD	-		

Table 54 Glass to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	-		
NO_3^-	-		
PO_4^{3-}	-	P	-
Pb	-	Pb	-
Cd	-	Cd	-
Hg	-	Hg	-
Cu	-	Cu	-
Cr	5.04E-9	Cr	7.56E-9
Ni	-	Ni	-
Zn	-	Zn	-
TSS	1.46E-9		
COD	-		

Table 55 Food to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	1.54E-3		
NO_3^-	1.06E-2		
PO_4^{3-}	1.16E-5	P	1.90E-5
Pb	3.60E-11	Pb	1.44E-10
Cd	8.78E-11	Cd	8.78E-11
Hg	8.40E-14	Hg	3.36E-13
Cu	3.57E-10	Cu	3.57E-10
Cr	8.40E-10	Cr	1.26E-9
Ni	6.30E-9	Ni	4.20E-9
Zn	4.80E-10	Zn	4.32E-9
TSS	3.49E-10		
COD	1.88E-4		

Table 56 Garden waste to landfill: emissions to water and soil

Emission to water	[kg/kg]	Emission to soil	[kg/kg]
NH_3/NH_4^+	1.08E-3		
NO_3^-	7.44E-3		
PO_4^{3-}	6.10E-6	P	1.00E-5
Pb	9.14E-11	Pb	3.66E-10
Cd	2.16E-10	Cd	2.16E-10
Hg	2.40E-13	Hg	9.60E-13
Cu	3.36E-10	Cu	3.36E-10
Cr	1.70E-9	Cr	2.55E-9
Ni	9.72E-9	Ni	6.48E-9
Zn	8.08E-10	Zn	7.27E-9
TSS	1.15E-9		
COD	2.41E-4		

Table 57 Mixed waste to landfill: emissions to water and soil

Emission to water	**[kg/kg]**	**Emission to soil**	**[kg/kg]**
NH_3/NH_4^+	-		
NO_3^-	-		
PO_4^{3-}	-	P	6.38E-9
Pb	1.60E-9	Pb	3.15E-9
Cd	3.15E-9	Cd	3.08E-11
Hg	7.70E-12	Hg	1.75E-8
Cu	1.75E-8	Cu	2.21E-8
Cr	1.47E-8	Cr	2.21E-8
Ni	9.19E-8	Ni	6.13E-8
Zn	1.09E-8	Zn	9.83E-8
TSS	1.15E-9		
COD	3.36E-5		

5. Calculation of WTE – Transfer Coefficients

In the following, equations for the TC are shown:

$$TC_C = 0.989 \times \frac{M_{CO_2}}{M_C} = 0.989 \times \frac{44 \frac{g}{mole}}{12 \frac{g}{mole}} = 3.62633 \qquad (33)$$

where:

TC_c = Transfer Coefficient from C to CO_2

0.989 = Transfer Coefficient for C [17]

M_{CO_2} = mole mass of CO_2 [g/mole]

M_C = mole mass of C [g/mole]

$$\begin{aligned} TC_{NO} &= 0.989 \times 0.0055 \times 0.95 \times \frac{M_{NO}}{M_N} \\ &= 0.989 \times 0.0055 \times 0.95 \times \frac{30 \frac{g}{mole}}{14 \frac{g}{mole}} = 0.011073 \end{aligned} \qquad (34)$$

where:

TC_{NO} = Transfer coefficient from N to NO

0.989 = Transfer coefficient for N to be transferred to flue gas

0.0055 = Coefficient for the production of NO_x from transferred N

0.95 = Coefficient for NO from NO_x

M_{NO} = mole mass of NO [g/mole]

M_N = mole mass of N [g/mole]

$$\begin{aligned} TC_{NO_2} &= 0.989 \times 0.0055 \times 0.05 \times \frac{M_{NO_2}}{M_N} = 0.989 \times 0.0055 \times 0.05 \times \frac{46 \frac{g}{mole}}{14 \frac{g}{mole}} \\ &= 0.000894 \end{aligned} \qquad (35)$$

where:

TC_{NO_2} = Transfer coefficient for NO_2 from N

0.05 = Coefficient for NO_2 from NO_x

M_{NO_2} = mole mass of NO_2 [g/mole]

$$TC_{N_2O} = 0.989 \times 0.0012 \times \frac{M_{N_2O}}{M_N} = 0.0989 \times 0.0012 \times \frac{44 \frac{g}{mole}}{28 \frac{g}{mole}} = 0.001865 \quad (36)$$

where:

TC_{N_2O} = Transfer coefficient for N_2O from N

0.0012 = Coefficient for N_2O production from transferred N

M_{N_2O} = mole mass for N_2O [g/mole]

$$\begin{aligned} TC_{CN^-} &= 0.989 \times 0.00052 \times \frac{M_{CN^-}}{M_N} \\ &= 0.989 \times 0.000052 \times \frac{26 \frac{g}{mole}}{14 \frac{g}{mole}} = 0.000096 \end{aligned} \quad (37)$$

where:

TC_{CN^-} = Transfer coefficient for CN^- from N

0.00052 = Coefficient for CN^- production from transferred N

M_{CN^-} = mole mass for CN^- [g/mole]

$$TC_{NH_3} = 0.989 \times 0.00075 \times \frac{M_{NH_3}}{M_N} = 0.989 \times 0.00075 \times \frac{17 \frac{g}{mole}}{14 \frac{g}{mole}} = 0.000901 \quad (38)$$

where:

TC_{NH_3} = Transfer coefficient for NH_3 from N

0.00075 = Coefficient for production of NH_3 from transferred N

M_{NH_3} = mole mass for NH_3 [g/mole]

6. Emissions from WTE

Table 58 Emissions from combustion of paper [kg/kg]

Air		Water	
CO_2	-		
HCl	2,99E-05	Cl^-	6,80E-04
N_2	2,42E-03	NO_3^-	1,09E-05
NO	2,73E-05		
NO_2	2,20E-06		
N_2O	4,60E-06		
CN^-	2,35E-07		
NH_3	2,22E-06		
SO_2	8,45E-05		
Pb	2,29E-08		
Cd	7,92E-10		
Hg	2,46E-09	Hg	1,85E-10
Cu	3,61E-08		
Cr	1,28E-08	Cr	1,93E-08
Ni	4,75E-09		
Zn	9,86E-08		
Dust	1,78E-05		
CO	1,50E-03		
PAH	1,41E-08		
Dioxin	1,41E-12		

Table 59 Emissions from 1 kg of paper bottom ash [kg/kg]

	Water	Soil
Pb	2,19E-11	8,78E-11
Cd	9,21E-12	9,21E-12
Hg	1,30E-12	5,21E-12
Cu	5,60E-06	5,60E-06
Cr	3,40E-09	5,10E-09
Ni	5,53E-08	3,69E-08
Zn	1,43E-12	1,29E-11

Table 60 Emissions from combustion of cardboard [kg/kg]

Air		Water	
CO_2	5,42E-01		
HCl	5,98E-05	Cl^-	1,36E-03
N_2	2,25E-03	NO_3^-	1,01E-05
NO	2,53E-05		
NO_2	2,04E-06		
N_2O	4,27E-06		
CN^-	2,19E-07		
NH_3	2,06E-06		
SO_2	0,00E+00		
Pb	6,16E-09		
Cd	2,20E-10		
Hg	1,29E-09	Hg	9,68E-11
Cu	3,08E-08		
Cr	1,04E-08	Cr	1,56E-08
Ni	5,46E-09		
Zn	7,39E-08		
Dust	1,78E-05		
CO	1,50E-03		
PAH	1,71E-08		
Dioxin	1,71E-12		

Table 61 Emissions from 1 kg of cardboard bottom ash [kg/kg]

	Water	Soil
Pb	5,91E-12	2,36E-11
Cd	2,56E-12	2,56E-12
Hg	6,82E-13	2,73E-12
Cu	4,78E-06	4,78E-06
Cr	2,75E-09	4,12E-09
Ni	6,35E-08	4,23E-08
Zn	1,07E-12	9,67E-12

Table 62 Emissions from combustion of ONP [kg/kg]

Air		Water	
CO_2	2,55E-02		
HCl	2,11E-07	Cl^-	4,80E-06
N_2	-	NO_3^-	-
NO	-		
NO_2	-		
N_2O	-		
CN^-	-		
NH_3	-		
SO_2	-		
Pb	6,16E-09		
Cd	2,20E-10		
Hg	1,29E-09	Hg	9,68E-11
Cu	3,08E-08		
Cr	1,04E-08	Cr	1,56E-08
Ni	5,46E-09		
Zn	7,39E-08		
Dust	1,78E-05		
CO	1,50E-03		
PAH	1,34E-08		
Dioxin	1,34E-12		

Table 63 Emissions from 1 kg of ONP bottom ash [kg/kg]

	Water	Soil
Pb	5,91E-12	2,36E-11
Cd	2,56E-12	2,56E-12
Hg	6,82E-13	2,73E-12
Cu	4,78E-06	4,78E-06
Cr	2,75E-09	4,12E-09
Ni	6,35E-08	4,23E-08
Zn	1,07E-12	9,67E-12

Table 64 Emissions from combustion of LPB [kg/kg]

Air		Water	
CO_2	8,13E-01		
HCl	5,32E-05	Cl^-	1,21E-03
N_2	2,00E-03	NO_3^-	9,00E-06
NO	2,25E-05		
NO_2	1,82E-06		
N_2O	3,79E-06		
CN^-	1,94E-07		
NH_3	1,83E-06		
SO_2	7,51E-05		
Pb	4,68E-08		
Cd	2,13E-10		
Hg	2,88E-09	Hg	2,16E-10
Cu	4,03E-08		
Cr	2,47E-08	Cr	3,70E-08
Ni	7,23E-09		
Zn	1,03E-07		
Dust	1,78E-05		
CO	1,50E-03		
PAH	1,83E-08		
Dioxin	1,83E-12		

Table 65 Emissions from 1 kg of LPB bottom ash [kg/kg]

	Water	Soil
Pb	2,99E-11	1,20E-10
Cd	1,65E-12	1,65E-12
Hg	1,02E-12	4,07E-12
Cu	4,17E-06	4,17E-06
Cr	4,35E-09	6,52E-09
Ni	5,61E-08	3,74E-08
Zn	9,98E-13	8,98E-12

Table 66 Emissions from combustion of HDPE [kg/kg]

Air		Water	
CO_2	2,95E+00		
HCl	-	Cl^-	-
N_2	-	NO_3^-	-
NO	-		
NO_2	-		
N_2O	-		
CN^-	-		
NH_3	-		
SO_2	-		
Pb	3,61E-07		
Cd	5,70E-10		
Hg	8,97E-09	Hg	6,75E-10
Cu	1,71E-07		
Cr	2,47E-08	Cr	3,71E-08
Ni	7,32E-09		
Zn	3,61E-07		
Dust	1,78E-05		
CO	1,50E-03		
PAH	2,77E-08		
Dioxin	2,76E-12		

Table 67 Emissions from 1 kg of HDPE bottom ash [kg/kg]

	Water	Soil
Pb	4,46E-09	1,78E-08
Cd	8,54E-11	8,54E-11
Hg	6,12E-11	2,45E-10
Cu	3,42E-04	3,42E-04
Cr	8,42E-08	1,26E-07
Ni	1,10E-06	7,31E-07
Zn	6,76E-11	6,08E-10

Table 68 Emissions from combustion of PET [kg/kg]

Air		Water	
CO_2	2,20E+00		
HCl	-	Cl^-	-
N_2	-	NO_3^-	-
NO	-		
NO_2	-		
N_2O	-		
CN^-	-		
NH_3	-		
SO_2	-		
Pb	3,61E-07		
Cd	5,70E-10		
Hg	8,97E-09	Hg	6,75E-10
Cu	1,71E-07		
Cr	2,47E-08	Cr	3,71E-08
Ni	7,32E-09		
Zn	3,61E-07		
Dust	1,78E-05		
CO	1,50E-03		
PAH	2,07E-08		
Dioxin	2,07E-12		

Table 69 Emissions from 1 kg of PET bottom ash [kg/kg]

	Water	Soil
Pb	4,46E-09	1,78E-08
Cd	8,54E-11	8,54E-11
Hg	6,12E-11	2,45E-10
Cu	3,42E-04	3,42E-04
Cr	8,42E-08	1,26E-07
Ni	1,10E-06	7,31E-07
Zn	6,76E-11	6,08E-10

Table 70 Emissions from combustion of PVC [kg/kg]

Air		Water	
CO_2	1,38E+00		
HCl	2,04E-02	Cl^-	4,65E-01
N_2	-	NO_3^-	0,00E+00
NO	-		
NO_2	-		
N_2O	-		
CN^-	-		
NH_3	-		
SO_2	-		
Pb	3,61E-07		
Cd	5,70E-10		
Hg	8,97E-09	Hg	6,75E-10
Cu	1,71E-07		
Cr	2,47E-08	Cr	3,71E-08
Ni	7,32E-09		
Zn	3,61E-07		
Dust	1,78E-05		
CO	1,50E-03		
PAH	1,30E-08		
Dioxin	1,30E-12		

Table 71 Emissions from 1 kg of PVC bottom ash [kg/kg]

	Water	Soil
Pb	4,46E-09	1,78E-08
Cd	8,54E-11	8,54E-11
Hg	6,12E-11	2,45E-10
Cu	3,42E-04	3,42E-04
Cr	8,42E-08	1,26E-07
Ni	1,10E-06	7,31E-07
Zn	6,76E-11	6,08E-10

Table 72 Emissions from combustion of LDPE [kg/kg]

Air		Water	
CO_2	2,95E+00		
HCl	-	Cl^-	-
N_2	-	NO_3^-	-
NO	-		
NO_2	-		
N_2O	-		
CN^-	-		
NH_3	-		
SO_2	-		
Pb	3,61E-07		
Cd	5,70E-10		
Hg	8,97E-09	Hg	6,75E-10
Cu	1,71E-07		
Cr	2,47E-08	Cr	3,71E-08
Ni	7,32E-09		
Zn	3,61E-07		
Dust	1,78E-05		
CO	1,50E-03		
PAH	2,77E-08		
Dioxin	2,76E-12		

Table 73 Emissions from 1 kg of LDPE bottom ash [kg/kg]

	Water	Soil
Pb	4,46E-09	1,78E-08
Cd	8,54E-11	8,54E-11
Hg	6,12E-11	2,45E-10
Cu	3,42E-04	3,42E-04
Cr	8,42E-08	1,26E-07
Ni	1,10E-06	7,31E-07
Zn	6,76E-11	6,08E-10

Table 74 Emissions from combustion of mixed plastics [kg/kg]

Air		Water	
CO_2	2,51E+00		
HCl	1,44E-03	Cl^-	3,28E-02
N_2	2,80E-03	NO_3^-	1,26E-05
NO	3,16E-05		
NO_2	2,55E-06		
N_2O	5,32E-06		
CN^-	2,72E-07		
NH_3	2,57E-06		
SO_2	1,14E-04		
Pb	3,99E-07		
Cd	1,76E-09		
Hg	7,58E-09	Hg	5,70E-10
Cu	1,43E-07		
Cr	3,04E-08	Cr	4,56E-08
Ni	7,22E-09		
Zn	6,27E-07		
Dust	1,78E-05		
CO	1,50E-03		
PAH	2,36E-08		
Dioxin	2,36E-12		

Table 75 Emissions from 1 kg of mixed plastics bottom ash [kg/kg]

	Water	Soil
Pb	4,93E-09	1,97E-08
Cd	2,63E-10	2,63E-10
Hg	5,18E-11	2,07E-10
Cu	2,85E-04	2,85E-04
Cr	1,04E-07	1,55E-07
Ni	1,08E-06	7,22E-07
Zn	1,17E-10	1,06E-09

Table 76 Emissions from combustion of aluminium [kg/kg]

Air		Water	
CO_2	-		
HCl	-	Cl^-	-
N_2	-	NO_3^-	-
NO	-		
NO_2	-		
N_2O	-		
CN^-	-		
NH_3	-		
SO_2	-		
Pb	-		
Cd	-		
Hg	-	Hg	-
Cu	4,70E-06		
Cr	2,20E-06	Cr	3,30E-06
Ni	5,30E-07		
Zn	4,00E-07		
Dust	1,78E-05		
CO	1,50E-03		
PAH	-		
Dioxin	-		

Table 77 Emissions from 1 kg of aluminium bottom ash [kg/kg]

	Water	Soil
Pb	8,43E-11	3,37E-10
Cd	-	-
Hg	-	-
Cu	1,78E-04	1,78E-04
Cr	1,42E-07	2,13E-07
Ni	1,51E-06	1,00E-06
Zn	1,42E-12	1,28E-11

Table 78 Emissions from combustion of tin plate [kg/kg]

Air		Water	
CO_2	-		
HCl	-	Cl^-	-
N_2	-	NO_3^-	-
NO	-		
NO_2	-		
N_2O	-		
CN^-	-		
NH_3	-		
SO_2	-		
Pb	-		
Cd	-		
Hg	-	Hg	-
Cu	4,70E-06		
Cr	2,20E-06	Cr	3,30E-06
Ni	5,30E-07		
Zn	4,00E-07		
Dust	1,78E-05		
CO	1,50E-03		
PAH	-		
Dioxin	-		

Table 79 Emissions from 1 kg of tin plate bottom ash [kg/kg]

	Water	Soil
Pb	4,66E-11	1,86E-10
Cd	-	-
Hg	-	-
Cu	9,84E-05	9,84E-05
Cr	7,85E-08	1,18E-07
Ni	8,32E-07	5,55E-07
Zn	7,84E-13	7,06E-12

Table 80 Emissions from combustion of glass [kg/kg]

Air		Water	
CO_2	-		
HCl	-	Cl^-	-
N_2	-	NO_3^-	-
NO	-		
NO_2	-		
N_2O	-		
CN^-	-		
NH_3	-		
SO_2	-		
Pb	-		
Cd	-		
Hg	-	Hg	-
Cu	-		
Cr	3,60E-08	Cr	5,40E-08
Ni	-		
Zn	-		
Dust	1,78E-05		
CO	1,50E-03		
PAH	0,00E+00		
Dioxin	0,00E+00		

Table 81 Emissions from 1 kg of glass bottom ash [kg/kg]

	Water	Soil
Pb	-	-
Cd	-	-
Hg	-	-
Cu	-	-
Cr	1,17E-09	1,76E-09
Ni	-	-
Zn	-	-

Table 82 Emissions from combustion of food [kg/kg]

Air		Water	
CO_2	-		
HCl	4,68E-05	Cl^-	1,06E-03
N_2	5,89E-03	NO_3^-	2,66E-05
NO	6,64E-05		
NO_2	5,36E-06		
N_2O	1,12E-05		
CN^-	5,73E-07		
NH_3	5,40E-06		
SO_2	5,76E-05		
Pb	6,00E-09		
Cd	1,95E-10		
Hg	1,12E-09	Hg	8,40E-11
Cu	1,02E-08		
Cr	6,00E-09	Cr	9,00E-09
Ni	2,10E-09		
Zn	4,80E-08		
Dust	1,78E-05		
CO	1,50E-03		
PAH	4,44E-09		
Dioxin	4,43E-13		

Table 83 Emissions from 1 kg of food bottom ash [kg/kg]

	Water	Soil
Pb	4,45E-11	1,78E-10
Cd	1,75E-11	1,75E-11
Hg	4,58E-12	1,83E-11
Cu	1,22E-05	1,22E-05
Cr	1,23E-08	1,84E-08
Ni	1,89E-07	1,26E-07
Zn	5,39E-12	4,85E-11

Table 84 Emissions from combustion of garden waste [kg/kg]

Air		Water	
CO_2	-		
HCl	1,20E-04	Cl^-	2,73E-03
N_2	4,12E-03	NO_3^-	1,86E-05
NO	4,65E-05		
NO_2	3,75E-06		
N_2O	7,83E-06		
CN^-	4,01E-07		
NH_3	3,78E-06		
SO_2	2,40E-05		
Pb	1,52E-08		
Cd	4,80E-10		
Hg	3,19E-09	Hg	2,40E-10
Cu	9,60E-09		
Cr	1,21E-08	Cr	1,82E-08
Ni	3,24E-09		
Zn	8,08E-08		
Dust	1,78E-05		
CO	1,50E-03		
PAH	9,47E-09		
Dioxin	9,45E-13		

Table 85 Emissions from 1 kg of garden waste bottom ash [kg/kg]

	Water	Soil
Pb	6,28E-11	2,51E-10
Cd	2,40E-11	2,40E-11
Hg	7,26E-12	2,91E-11
Cu	6,40E-06	6,40E-06
Cr	1,38E-08	2,07E-08
Ni	1,62E-07	1,08E-07
Zn	5,04E-12	4,54E-11

Table 86 Emissions from combustion of mixed waste [kg/kg]

Air		Water	
CO_2	3,63E-01		
HCl	-	Cl^-	-
N_2	-	NO_3^-	-
NO	-		
NO_2	-		
N_2O	-		
CN^-	-		
NH_3	-		
SO_2	-		
Pb	2,66E-07		
Cd	7,00E-09		
Hg	1,02E-07	Hg	7,70E-09
Cu	5,01E-07		
Cr	1,05E-07	Cr	1,58E-07
Ni	3,06E-08		
Zn	1,09E-06		
Dust	1,78E-05		
CO	1,50E-03		
PAH	6,82E-09		
Dioxin	6,80E-13		

Table 87 Emissions from 1 kg of mixed waste bottom ash [kg/kg]

	Water	Soil
Pb	7,40E-11	2,96E-10
Cd	2,36E-11	2,36E-11
Hg	1,57E-11	6,29E-11
Cu	2,25E-05	2,25E-05
Cr	8,05E-09	1,21E-08
Ni	1,03E-07	6,89E-08
Zn	4,60E-12	4,14E-11

7. Auxiliary Chemicals

Table 88 Auxiliary chemicals for each waste fraction

	$CaCO_3$	NaOH	NH_3
Paper	$1.14 \cdot 10^{-3}$	$2.90 \cdot 10^{-3}$	$7.80 \cdot 10^{-6}$
Cardboard	$2.29 \cdot 10^{-3}$	-	$7.24 \cdot 10^{-6}$
ONP	$8.07 \cdot 10^{-6}$	-	-
LPB	$2.03 \cdot 10^{-3}$	$2.58 \cdot 10^{-3}$	$6.43 \cdot 10^{-6}$
HDPE	-	-	-
PET	-	-	-
PVC	$7.81 \cdot 10^{-1}$	-	-
LDPE	-	-	-
Mixed Plastics	$5.52 \cdot 10^{-2}$	$3.92 \cdot 10^{-3}$	$9.02 \cdot 10^{-6}$
Aluminium	-	-	-
Tin Plate	-	-	-
Glass	-	-	-
Food Waste	$1.79 \cdot 10^{-3}$	$1.98 \cdot 10^{-3}$	$1.90 \cdot 10^{-5}$
Garden Waste	$4.58 \cdot 10^{-3}$	$8.25 \cdot 10^{-4}$	$1.33 \cdot 10^{-5}$
Mixed Waste	-	-	-

- no calculation possible due to no data in elementary analysis

8. Windrow Composting

With a density of 480 – 540 kg/m^3 the mass to be applied on one hectare is calculated as follows:

$$m_{cm} = \rho_{cm} \times a \times h \tag{39}$$

where:

m_{cm} = mass of composted mulch [kg]

ρ_{cm} = density of composted mulch [kg/m^3]

a = area of application [m^2]

h = height of layer [m]

$$m_{cm} = 500\frac{kg}{m^3} \times 10{,}000 m^2 \times 0.1 m = 500{,}000 kg \tag{40}$$

For the model, factors had to be developed to ensure the right conversion from the output of compost to the avoided products. They are listed in Table 16.

$$F_{ap_i} = \frac{ap_{ha}}{500{,}000 kg} \tag{41}$$

where:

F_{ap_i} = factor for avoided product i [-]

ap_{ha} = avoided product per hectare [kg]

9. General Emission Profile of the Spittelau Incinerator

Table 89 Input (auxiliary chemicals) [kg]

	Input
Lime	$2.90 \cdot 10^{-3}$
Caustic Soda	$2.25 \cdot 10^{-3}$
Ammonia	$2.90 \cdot 10^{-3}$

Table 90 Produced electricity and slag

	Output	**Unit**
Electricity	$1.50 \cdot 10^{-1}$	[kWh/kg]
Slag	$2.07 \cdot 10^{-1}$	[kg/kg]

Table 91 Emissions to air

	[kg/kg]
Dust	$3.64 \cdot 10^{-6}$
HCl	$3.64 \cdot 10^{-6}$
HF	$1.00 \cdot 10^{-7}$
SO_2	$9.54 \cdot 10^{-6}$
CO	$1.20 \cdot 10^{-4}$
NO_x as NO_2	$1.04 \cdot 10^{-4}$
C_{org}	$2.27 \cdot 10^{-6}$
Pb	$5.40 \cdot 10^{-8}$
Cr	$4.50 \cdot 10^{-}$
Zn	$1.45 \cdot 10^{-7}$
As	$4.50 \cdot 10^{-9}$
Co	$4.50 \cdot 10^{-9}$
Ni	$9.00 \cdot 10^{-9}$
Cd	$4.50 \cdot 10^{-9}$
Hg	$3.20 \cdot 10^{-8}$
NH_3	$3.81 \cdot 10^{-6}$
Dioxins	$9.10 \cdot 10^{-14}$

Table 92 Emissions to Water

	[kg/kg]
Al	$7.89 \cdot 10^{-8}$
Ag	$4.98 \cdot 10^{-8}$
NH_4	$1.37 \cdot 10^{-6}$
As	$8.30 \cdot 10^{-10}$
Ba	$7.89 \cdot 10^{-8}$
Ca^{2+}	$2.10 \cdot 10^{-6}$
Cd	$4.15 \cdot 10^{-10}$
Co	$2.08 \cdot 10^{-8}$
Cr	$2.08 \cdot 10^{-8}$
Cl_2	$2.08 \cdot 10^{-8}$
Cl^-	$2.94 \cdot 10^{-6}$
CN^-	$2.49 \cdot 10^{-9}$
Cu	$2.08 \cdot 10^{-8}$
Fe	$2.08 \cdot 10^{-8}$
F^-	$9.13 \cdot 10^{-7}$
Hg	$4.15 \cdot 10^{-10}$
Mn	$2.08 \cdot 10^{-8}$
NO_3^-	$1.99 \cdot 10^{-6}$
NO_2^-	$2.91 \cdot 10^{-8}$
Ni	$2.08 \cdot 10^{-8}$
P	$2.08 \cdot 10^{-8}$
Pb	$4.15 \cdot 10^{-9}$
Sn	$2.49 \cdot 10^{-8}$
SO_4^{2-}	$4.91 \cdot 10^{-7}$
S^{2-}	$4.15 \cdot 10^{-8}$
SO_3^{2-}	$4.15 \cdot 10^{-7}$
Ti	$4.15 \cdot 10^{-9}$
V	$2.08 \cdot 10^{-8}$
Zn	$2.49 \cdot 10^{-8}$
COD	$8.30 \cdot 10^{-9}$
Phenol	$4.15 \cdot 10^{-9}$

Table 93 Emission from landfilled slag [kg]

	Emission to Water	Emission to Air
Ni	$3.00 \cdot 10^{-7}$	$2.00 \cdot 10^{-7}$
Cd	$5.00 \cdot 10^{-9}$	$5.00 \cdot 10^{-9}$
Cr	$3.00 \cdot 10^{-7}$	$2.00 \cdot 10^{-7}$
Cu	$2.50 \cdot 10^{-6}$	$2.50 \cdot 10^{-6}$
Pb	$1.60 \cdot 10^{-5}$	$4.00 \cdot 10^{-6}$
Zn	$1.35 \cdot 10^{-6}$	$1.50 \cdot 10^{-7}$
Hg	$8.00 \cdot 10^{-9}$	$2.00 \cdot 10^{-9}$

Appendix D – Life Cycle Impact Assessment

Halogenated organic emissions are abbreviated HOE. All tables are taken from the GaBi 4 software.

Table 94 Equivalence factors for climate change [kg CO_2-eq.]

Carbon dioxide [Inorganic emissions to air]	1
Carbon tetrachloride (tetrachloromethane) [HOE to air]	1400
CFC 11 (trichlorfluormethane) [HOE to air]	4000
CFC 11 (trichlorofluoromethane) [HOE to air]	4000
CFC 113 (trichlorofluoroethane) [HOE to air]	5000
CFC 114 (dichlorotetrafluoroethane) [HOE to air]	9300
CFC 115 (chloropentafluoroethane) [HOE to air]	9300
CFC 116 (hexafluoroethane) [HOE to air]	12500
CFC 12 (dichlorodifluoromethane) [HOE to air]	8500
CFC 123 (dichlorotrifluoroethane) [HOE to air]	93
CFC 124 (chlorotetrafluoroethane) [HOE to air]	480
CFC 125 (pentafluoroethane) [HOE to air]	3200
CFC 13 (chlorotrifluoromethane) [HOE to air]	11700
CFC 134a (tetrafluoroethane) [HOE to air]	1300
CFC 141b (dichloro-1-fluoroethane) [HOE to air]	630
CFC 142b (chlorodifluoroethane) [HOE to air]	2000
CFC 143 (trifluoroethane) [HOE to air]	290
CFC 143a (trifluoroethane) [HOE to air]	4400
CFC 152a (difluoroethane) [HOE to air]	140
CFC 22 (chlorodifluoromethane) [HOE to air]	1700
CFC 225ca (dichloropentafluoropropane) [HOE to air]	170
CFC 225cb (dichloropentafluoropentane) [HOE to air]	530
CFC 227ea (septifluoropropane) [HOE to air]	3300
CFC 23 (trifluoromethane) [HOE to air]	12100
CFC 236fa (hexafluoropropane) [HOE to air]	8000
CFC 245ca (pentafluoropropane) [HOE to air]	610
CFC 32 (trifluoroethane) [HOE to air]	580
CFC 43-10 (decafluoropentane) [HOE to air]	1600
Dichloromethane (methylene chloride) [HOE to air]	9
Halon (1301) [HOE to air]	5600
Laughing gas (dinitrogen monoxide) [Inorganic emissions to air]	310
Methane [Organic emissions to air (group VOC)]	21
Nitrous oxide (laughing gas) [Inorganic emissions to air]	310
Sulphur hexafluoride [Inorganic emissions to air]	23900
Tetrafluoromethane [HOE to air]	6300
Trichloroethane [HOE to air]	110
Trichloromethane (chloroform) [HOE to air]	5

Table 95 Equivalence factors for eutrophication potential [kg PO_4^{3-}-eq.]

Ammonia [Inorganic emissions to air]	0,33
Ammonia [aust inorganic emissions to air]	0,33000033
Ammonium / ammonia [Inorganic emissions to water]	0,33
Ammonium nitrate [Inorganic emissions to air]	0,8
Chemical oxygen demand (COD) [Analytical measures to water]	0,022
Kjeldahl N [Analytical measures to water]	0,42
Nitrate [Inorganic emissions to water]	0,1
Nitrogen oxides [Inorganic emissions to air]	0,13
Phosphate [Inorganic emissions to water]	1
Total P (Total-P) [Analytical measures to water]	3,06

Table 96 Equivalence factors for POCP [kg C_2H_4-eq.]

Acetone (dimethylcetone) [Group NMVOC to air]	0,178
aliphatic hydrocarbons [Group NMVOC to air]	0,39799411
Aromatic hydrocarbons (unspecified) (Copy) [Group NMVOC to air]	0,760977095
Benzene [Group NMVOC to air]	0,189
Benzo{a}pyrene [Group PAH to air]	0,761
Butadiene [Group NMVOC to air]	0,906
Butane (n-butane) [Group NMVOC to air]	0,41
Butene (vinyl acetylene) [Group NMVOC to air]	0,959
Butylacetate [Group NMVOC to air]	0,323
Butylene glycol (butane diol) [Group NMVOC to air]	0,196
Butyraldehyde (n-; iso-butanal) [Group NMVOC to air]	0,568
Carbon monoxide [Inorganic emissions to air]	0,036
Carbon tetrachloride (tetrachloromethane) [HOE to air]	0,005
CFC 11 (trichlorfluormethane) [HOE to air]	0,021
CFC 11 (trichlorofluoromethane) [HOE to air]	0,021
CFC 113 (trichlorofluoroethane) [HOE to air]	0,021
CFC 114 (dichlorotetrafluoroethane) [HOE to air]	0,021
CFC 115 (chloropentafluoroethane) [HOE to air]	0,021
CFC 116 (hexafluoroethane) [HOE to air]	0,021
CFC 12 (dichlorodifluoromethane) [HOE to air]	0,021
CFC 125 (pentafluoroethane) [HOE to air]	0,021
CFC 13 (chlorotrifluoromethane) [HOE to air]	0,021
CFC 134a (tetrafluoroethane) [HOE to air]	0,021
CFC 141b (dichloro-1-fluoroethane) [HOE to air]	0,021
CFC 142b (chlorodifluoroethane) [HOE to air]	0,021
CFC 22 (chlorodifluoromethane) [HOE to air]	0,021
Chlorobenzene [HOE to air]	0,021
Chloromethane (methyl chloride) [HOE to air]	0,021
Cyclohexane (hexahydro benzene) [Group NMVOC to air]	0,761
Cyclohexanol [Group NMVOC to air]	0,196
Cyclohexanone [Group NMVOC to air]	0,761

Equivalence factors for POCP continued

Cyclopentanone [Group NMVOC to air]	0,761
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [HOE to air]	0,021
Dichlorobenzene (p-DCB; 1,4-dichlorobenzene) [HOE to air]	0,021
Dichloroethane [HOE to air]	0,021
Dichloroethane (ethylene dichloride) [HOE to air]	0,021
Dichloroethane (isomers) [Group NMVOC to air]	0,021
Dichloromethane (methylene chloride) [HOE to air]	0,01
Ethanal (Acetaldehyde) [Group NMVOC to air]	0,52701
Ethane [Group NMVOC to air]	0,082
Ethanol (ethyl alcohol) [Group NMVOC to air]	0,268
Ethene (ethylene) [Group NMVOC to air]	1
Ethine (acetylene) [Group NMVOC to air]	0,168
Ethyl benzene [Group NMVOC to air]	0,593
Ethyl benzene [Group NMVOC into air]	0,593
Ethylene acetate (ethyl acetate) [Group NMVOC to air]	0,218
Formaldehyde (methanal) [Group NMVOC to air]	0,421
Furfuryl alcohol [Group NMVOC to air]	0,196
Heptane (isomers) [Group NMVOC to air]	0,529
Hexane (isomers) [Group NMVOC to air]	0,421
Hydrocarbons [Group NMVOC to air]	0,39799411
Methane [Organic emissions into air (group VOC)]	0,007
Methane [Organic emissions to air (group VOC)]	0,007
Methanol [Group NMVOC to air]	0,123
Methyl acetate [Group NMVOC to air]	0,025
NMVOC (unspecified) [Group NMVOC to air]	0,416
Octane [Group NMVOC to air]	0,493
Pentane (n-pentane) [Group NMVOC to air]	0,408
Phenol (hydroxy benzene) [Group NMVOC to air]	0,761
Polychlorinated biphenyls (PCB unspecified) [HOE to air]	0,021
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [HOE to air]	0,021
Polychlorinated dibenzo-p-furans (2,3,7,8 - TCDD) [HOE to air]	0,021
Polycyclic aromatic hydrocarbons (PAH) [Group PAH to air]	0,76098
Propane [Group NMVOC to air]	0,42
Propanol (iso-propanol; isopropanol) [Group NMVOC to air]	0,196
Propene (propylene) [Group NMVOC to air]	1,03
Propyl acetate [Group NMVOC to air]	0,215
Propylene glycol [Group NMVOC to air]	0,196
Styrene [Group NMVOC to air]	0,761
Tetrachloroethene (perchloroethylene) [HOE to air]	0,021
Tetrafluoromethane [HOE to air]	0,021
Toluene (methyl benzene) [Group NMVOC to air]	0,563
Trichloroethane [HOE to air]	0,001
Trichloroethene (isomers) [HOE to air]	0,066
Trichloromethane (chloroform) [HOE to air]	0,021
Vinyl chloride (VCM; chloroethene) [HOE to air]	0,021
VOC (unspecified) [Organic emissions to air (group VOC)]	0,337
Xylene (dimethyl benzene) [Group NMVOC to air]	0,777

Table 97 Equivalence factors for HTPAU [kg DCB-eq.]

Acrylonitrile [Hydrocarbons to water]	1800
Acrylonitrile [Group NMVOC to air]	200
Ammonia [Inorganic emissions to air]	0,016
Ammonium / ammonia [Inorganic emissions to water]	1
Antimony [Heavy metals to water]	74
Arsenic [Heavy metals to water]	9
Barium [Inorganic emissions to water]	17
Barium [Inorganic emissions to air]	110
Benzene [Hydrocarbons to water]	190
Benzene [Group NMVOC to air]	160
Beryllium [Inorganic emissions to air]	20000
Beryllium [Inorganic emissions to water]	520
Cadmium [Heavy metals to soil]	560
Cadmium [Heavy metals to water]	0,14
Carbon disulphide [Inorganic emissions to air]	0,18
Chlorobenzene [HOE to air]	0,86
Chromium (unspecified) [Heavy metals to air]	1
Chromium (unspecified) [Heavy metals to water]	1
Chromium +VI [Heavy metals to water]	0,02
Copper [Heavy metals to water]	0,0085
Copper [Heavy metals to air]	370
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [HOE to air]	0,98
Dichloroethane [HOE to air]	0,51
Ethyl benzene [Group NMVOC to air]	0,047
Ethyl benzene [Hydrocarbons to water]	0,046
Formaldehyde (methanal) [Group NMVOC to air]	0,047
Formaldehyde (methanal) [Hydrocarbons to water]	0,019
Hydrogen chloride [Inorganic emissions to air]	0,073
Hydrogen sulfide [Inorganic emissions to air]	0,018
Lead [Heavy metals to soil]	11
Lead [Heavy metals to water]	0,06
Mercury [Heavy metals to water]	7,4
Mercury [Heavy metals to air]	1200
Mercury [Heavy metals to soil]	220
Molybdenum [Heavy metals to air]	890
Nickel [Heavy metals to water]	3,4
Nitrogen oxides [Inorganic emissions to air]	0,055
Phenol (hydroxy benzene) [Hydrocarbons to water]	0,02
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - PCDD) [HOE to water]	1
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [HOE to air]	1
Polycyclic aromatic hydrocarbons (PAH) [Group PAH to air]	1
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons to water]	1
Selenium [Heavy metals to water]	2700
Selenium [Heavy metals to air]	8100
Sulphur dioxide [Inorganic emissions to air]	0,008
Tetrachloroethene (perchloroethylene) [HOE to water]	1
Tetrachloroethene (perchloroethylene) [HOE to air]	1

Equivalence factors for HTPAU continued

Tin [Heavy metals to soil]	0,054
Tin [Heavy metals to water]	8,90E-05
Toluene (methyl benzene) [Group NMVOC to air]	0,017
Toluene (methyl benzene) [Hydrocarbons to water]	0,018
Trichloroethane [HOE to air]	1,8
Trichloroethene (isomers) [HOE to air]	1,8
Trichloromethane (chloroform) [HOE to air]	1,5
Trichloromethane (chloroform) [HOE to water]	1,5
Vanadium [Heavy metals to air]	940
Vinyl chloride (VCM; chloroethene) [HOE to water]	19
Zinc [Heavy metals to air]	9,1
Zinc [Heavy metals to water]	0,0032
Zinc [Heavy metals to soil]	1,2

Table 98 Equivalence factors for FAEP [kg DCB-eq.]

Acrylonitrile [Group NMVOC to air]	0,4
Acrylonitrile [Hydrocarbons to water]	150
Antimony [Heavy metals to water]	2,3
Arsenic [Heavy metals to water]	17
Barium [Inorganic emissions to air]	14
Barium [Inorganic emissions to water]	48
Benzene [Group NMVOC to air]	5,70E-05
Benzene [Hydrocarbons to water]	0,15
Beryllium [Inorganic emissions to air]	7500
Beryllium [Inorganic emissions to water]	26000
Cadmium [Heavy metals to water]	93
Cadmium [Heavy metals to soil]	64
Carbon disulphide [Inorganic emissions to air]	0,021
Chlorobenzene [HOE to air]	0,00031
Chromium +VI [Heavy metals to water]	1,7
Chrysene [Hydrocarbons to water]	3200
Copper [Heavy metals to water]	73
Copper [Heavy metals to air]	27
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [HOE to air]	0,002
Dichloroethane [HOE to air]	8,40E-05
Ethyl benzene [Hydrocarbons to water]	0,94
Ethyl benzene [Group NMVOC to air]	8,20E-05
Formaldehyde (methanal) [Hydrocarbons to water]	980
Formaldehyde (methanal) [Group NMVOC to air]	3,6
Lead [Heavy metals to soil]	0,56
Lead [Heavy metals to water]	0,57
Mercury [Heavy metals to air]	28
Mercury [Heavy metals to soil]	68
Mercury [Heavy metals to water]	100
Molybdenum [Heavy metals to air]	50
Nickel [Heavy metals to water]	280
Phenanthrene [Hydrocarbons to water]	390
Phenol (hydroxy benzene) [Hydrocarbons to water]	840
Selenium [Heavy metals to water]	1100
Selenium [Heavy metals to air]	300
Tin [Heavy metals to soil]	0,59
Tin [Heavy metals to water]	0,61
Toluene (methyl benzene) [Group NMVOC to air]	4,30E-05
Toluene (methyl benzene) [Hydrocarbons to water]	0,49
Trichloroethane [HOE to air]	8,20E-05
Trichloromethane (chloroform) [HOE to air]	6,90E-05
Trichloromethane (chloroform) [HOE to water]	0,067
Vanadium [Heavy metals to air]	340
Vinyl chloride (VCM; chloroethene) [HOE to water]	0,045
Zinc [Heavy metals to soil]	4,4
Zinc [Heavy metals to air]	2,2
Zinc [Heavy metals to water]	5,6

Table 99 Equivalence factor for MAEP [kg DCB-eq.]

Acrylonitrile [Group NMVOC to air]	0,27
Acrylonitrile [Hydrocarbons to water]	0,27
Antimony [Heavy metals to water]	3900
Arsenic [Heavy metals to water]	11000
Barium [Inorganic emissions to air]	1300000
Barium [Inorganic emissions to water]	220000
Benzene [Group NMVOC to air]	0,00087
Benzene [Hydrocarbons to water]	0,00094
Beryllium [Inorganic emissions to air]	770000000
Beryllium [Inorganic emissions to water]	190000000
Cadmium [Heavy metals to water]	14000
Cadmium [Heavy metals to soil]	9800
Carbon disulphide [Inorganic emissions to air]	0,39
Chlorobenzene [HOE to air]	0,047
Chromium +VI [Heavy metals to water]	210
Chrysene [Hydrocarbons to water]	160
Copper [Heavy metals to water]	16000
Copper [Heavy metals to air]	1600000
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [HOE to air]	0,35
Dichloroethane [HOE to air]	0,052
Ethyl benzene [Hydrocarbons to water]	0,0006
Ethyl benzene [Group NMVOC to air]	0,00013
Formaldehyde (methanal) [Hydrocarbons to water]	0,26
Formaldehyde (methanal) [Group NMVOC to air]	0,32
Lead [Heavy metals to soil]	65
Lead [Heavy metals to water]	67
Mercury [Heavy metals to air]	2700000
Mercury [Heavy metals to soil]	340000
Mercury [Heavy metals to water]	14000
Molybdenum [Heavy metals to air]	3200000
Nickel [Heavy metals to water]	230000
Phenanthrene [Hydrocarbons to water]	2,5
Phenol (hydroxy benzene) [Hydrocarbons to water]	0,078
Selenium [Heavy metals to water]	12000000
Selenium [Heavy metals to air]	35000000
Tin [Heavy metals to soil]	73
Tin [Heavy metals to water]	75
Toluene (methyl benzene) [Group NMVOC to air]	0,00013
Toluene (methyl benzene) [Hydrocarbons to water]	0,00053
Trichloroethane [HOE to air]	0,27
Trichloromethane (chloroform) [HOE to air]	0,043
Trichloromethane (chloroform) [HOE to water]	0,042
Vanadium [Heavy metals to air]	21000000
Vinyl chloride (VCM; chloroethene) [HOE to water]	0,0002
Zinc [Heavy metals to soil]	710
Zinc [Heavy metals to air]	130000
Zinc [Heavy metals to water]	900

Table 100 Equivalence factors for TEP [kg DCB-eq.]

Acrylonitrile [Group NMVOC to air]	0,0044
Acrylonitrile [Hydrocarbons to water]	0,0031
Antimony [Heavy metals to water]	9,50E-22
Arsenic [Heavy metals to water]	3,50E-19
Barium [Inorganic emissions to water]	5,30E-20
Barium [Inorganic emissions to air]	17
Benzene [Group NMVOC to air]	8,40E-06
Benzene [Hydrocarbons to water]	7,90E-06
Beryllium [Inorganic emissions to water]	4,80E-17
Beryllium [Inorganic emissions to air]	6700
Cadmium [Heavy metals to soil]	440
Cadmium [Heavy metals to water]	4,40E-22
Carbon disulphide [Inorganic emissions to air]	0,0032
Chlorobenzene [HOE to air]	0,00033
Chromium (unspecified) [Heavy metals to air]	1
Chromium (unspecified) [Heavy metals to water]	1
Chromium +VI [Heavy metals to water]	4,90E-21
Chrysene [Hydrocarbons to water]	0,00041
Copper [Heavy metals to air]	17
Copper [Heavy metals to water]	1,20E-22
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene) [HOE to air]	0,0002
Dichloroethane [HOE to air]	7,60E-06
Ethyl benzene [Group NMVOC to air]	1,30E-06
Ethyl benzene [Hydrocarbons to water]	1,20E-06
Formaldehyde (methanal) [Hydrocarbons to water]	0,0018
Formaldehyde (methanal) [Group NMVOC to air]	0,4
Hydrogen chloride [Inorganic emissions to air]	1
Hydrogen sulfide [Inorganic emissions to air]	1
Lead [Heavy metals to soil]	11
Lead [Heavy metals to water]	1,00E-23
Mercury [Heavy metals to water]	27
Mercury [Heavy metals to air]	58000
Mercury [Heavy metals to soil]	130000
Molybdenum [Heavy metals to air]	20
Nickel [Heavy metals to water]	3,90E-20
Nitrogen oxides [Inorganic emissions to air]	1
Phenanthrene [Hydrocarbons to water]	1,10E-05
Phenol (hydroxy benzene) [Hydrocarbons to water]	2,00E-06
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - PCDD) [HOE to water]	1
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [HOE to air]	1
Polycyclic aromatic hydrocarbons (PAH) [Group PAH to air]	1
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Hydrocarbons to water]	1
Selenium [Heavy metals to air]	220
Selenium [Heavy metals to water]	3,00E-18
Sulphur dioxide [Inorganic emissions to air]	1
Tetrachloroethene (perchloroethylene) [HOE to water]	1
Tetrachloroethene (perchloroethylene) [HOE to air]	1

Equivalence factors for TEP continued

Tin [Heavy metals to soil]	10
Tin [Heavy metals to water]	1,70E-23
Toluene (methyl benzene) [Hydrocarbons to water]	1,40E-05
Toluene (methyl benzene) [Group NMVOC to air]	1,40E-05
Trichloroethane [HOE to air]	2,90E-05
Trichloroethene (isomers) [HOE to air]	1
Trichloromethane (chloroform) [HOE to air]	9,70E-06
Trichloromethane (chloroform) [HOE to water]	9,50E-06
Vanadium [Heavy metals to air]	1300
Vinyl chloride (VCM; chloroethene) [HOE to water]	2,40E-07
Zinc [Heavy metals to water]	6,90E-23
Zinc [Heavy metals to air]	23
Zinc [Heavy metals to soil]	45