Environmental Project No. 822 2003
Miljøprojekt

# Systems Analysis of Organic Waste Management in Denmark

Andras Baky
Swedish Institute of Agricultural Enviromental Engineering

Ola Eriksson
Royal Institute of Technology

**Danish Environmental Protection Agency**
Danish Ministry of the Environment

The Danish Environmental Protection Agency will, when opportunity offers, publish reports and contributions relating to environmental research and development projects financed via the Danish EPA.

Please note that publication does not signify that the contents of the reports necessarily reflect the views of the Danish EPA.

The reports are, however, published because the Danish EPA finds that the studies represent a valuable contribution to the debate on environmental policy in Denmark.

# Indhold

# Preface

The Danish Environmental Protection Agency (Danish EPA) contacted JTI, Swedish institute of agricultural and environmental engineering and KTH, Royal institute of technology in November 2001. They inquired about the possibility to use the computer-based model ORWARE (ORganic WAste REsearch) to evaluate the consequences of increased recycling of household waste. A preliminary meeting between the three parties were conducted 6 December 2001 in Copenhagen.

The project consists of two sets of scenarios and six different sensitivity analysis of the two scenario sets. The systems analysis evaluated the environmental impact and use of resources for management of organic household waste in Denmark. The systems analysis was conducted on a national level.

The project is conducted jointly by JTI and KTH. Overall project manager is Hans Bertil Wittgren, JTI. Andras Baky, JTI and Ola Eriksson, KTH made the systems analysis.

# Sammenfatning

I Danmark er organisk husholdningsaffald er en ressource, som i dag ikke udnyttes fuldt ud ved kompostering eller bioforgasning. Der indsamles årligt ca. 1.7 millioner tons husholdningsaffald, hvoraf den organiske del udgør ca. 700,000 tons. For at vurdere betydningen for samfundet, hvis biologisk behandling af organisk husholdningsaffald øges, har Miljøstyrelsen gennemført en samfundsøkonomisk analyse af øget biologisk behandling af dette affald. En samfundsøkonomisk analyse bygger på opgørelser over materialestrømme, ressourceanvendelse, energi, samt udledninger til luft, vand og jord. Denne rapport beregner og viser ressourceforbrug, udledninger til luft, vand og jord, energianvendelse og –fremstilling, samt miljømæssige virkninger på nationalt plan.

Systemerne for håndtering og behandling af organisk husholdningsaffald beskrives ved hjælp af systemanalyser. Beregningen af strømme, udledninger og miljøvirkninger af håndteringen af organisk husholdningaffald er foretaget ved hjælp af computermodellen ORWARE (ORganic WAste REsearch).

ORWARE er et redskab, der kan bruges til at vurdere miljøkonsekvenserne for et "materiale flow" - i dette tilfælde håndteringen af affald. ORWARE består af en række delmodeller, som tilsammen kan bruges til opstilling af et affaldssystem for f.eks. en by, en kommune eller en virksomhed. Materialet strømmer fra forskellige kilder (affald) gennem forskellige behandlingsmetoder (kompostering, bioforgasning osv.) til slutbrugerne (spredning af affald på landbrugsjord eller deponering på losseplads). Udledninger fra transport, behandling osv. indregnes som udledninger til luft, vand og jord. Ved hjælp af metoder for livscyklusanalyser (LCA) opgøres forskellige miljøpåvirkninger.

Undersøgelsen består af to sæt scenarier og en række følsomhedsanalyser. I det ene sæt scenarier indgår 5 multiscenarier, hvoraf det ene er et referencescenarie, som tager udgangspunkt i, hvordan de 700.000 ton organisk dagrenovation i Danmark blev håndteret i 2001. De øvrige scenarier implementerer forskellige niveauer for bioforgasning eller kompostering. Scenarierne dækker en kortsigtet tidsramme og en langsigtet tidsramme, baseret på anvendelse af organisk husholdningsaffald på nationalt plan. Resultaterne af analysen af multiscenarierne omfatter kerne, up-/downstream, samt kompenserende systemer.

I det andet scenariesæt, monoscenarierne, sammenholdes emissioner af tre forskellige behandlingsteknologier. Alt organisk affald behandles med én behandlingsmetode: forbrænding, bioforgasning eller kompostering. I hvert af disse scenarier beregnes udledningerne for de forskellige faser: indsamling, transport, behandling og efterfølgende downstreamprocesser (anvendelse af gas, udbringning af organisk gødning) Resultaterne af analysen af monoscenarierne fremlægges som udledninger til luft og vand. I disse scenarierne indregnes den kompenserende produktion ikke.

I tilslutning til analysen af de to sæt af scenarier er der gennemført følsomhedsanalyser med henblik på at vurdere betydningen af forskellige parametre og forudsætninger, som ikke indgår i scenarierne:

- Ingen genanvendelse af slagger til vejkonstruktion.
- Rejectandelen ændres fra 35% til 10% i forbindelse med bioforgasning og fra 15% til 5% ved kompostering.
- Biogasproduktionen udgør 150 $Nm^3$ i stedet for de oprindelige 125 $Nm^3$ pr. ton forbehandlet organisk dagrenovation.
- Landbrugsjord kan bruges som kulstofdræn og således reducere $CO_2$-udledningerne.
- Anvendelse af naturgas som marginal elproduktion.
- Varme fra kul erstattes af varme fra naturgas.

Undersøgelsen gav en lang række resultater, som indgår i den samfundsøkonomiske undersøgelse, som Miljøstyrelsen har gennemført. Generelt viser resultaterne, at sammenholdt med den nuværende situation indvirker bioforgasning både positivt og negativt på miljøet.

Øget milekompostering og reaktorkompostering til fordel for forbrænding er – med visse undtagelser – værre end den nuværende situation, især når det langsigtede komposteringsscenarie (nr. 5) sammenholdes med referencescenariet. Overordnet set er der en større forskel mellem langsigtede scenarier for kompostering end for de langsigtede scenarier for bioforgasning.

Til hvert enkelt scenarie er knyttet produktioner af forskellige mængder af næringsstoffer og energi:

- Kg kvælstof (N-tot) tilbageført til landbrugsjord
- Kg phosphor (P-tot) tilbageført til landbrugsjord
- Kg kalium (K-tot) tilbageført il landbrugsjord
- TJ elektricitet produceret i forbindelse med affaldsbehandling
- TJ varme (som fjernvarme) produceret i forbindelse med affaldsbehandling

Når hovedparten af den organiske dagrenovation bioforgasses som i scenarie 3, opnås det største udbytte af kvælstof og el på henholdsvis 1.162 t N og 483 TJ el. Forbrændingsscenariet giver det største udbytte af varme med 1.761 TJ varme. Komposteres hovedparten af affaldet som i scenarie 5, fås det største udbytte af næringsstofferne P og K med henholdsvis 311 t P og 761 t K.

Følsomhedsanalyserne viser visse ændringer i forhold til de oprindelige scenarier. Inddragning af landbrugsjord som kulstofdræn indvirker på det globale opvarmningspotentiale GWP. Det er til gunst for de langsigtede scenarier for bioforgasning og kompostering, fordi der her er tale om en større grad af tilbageføring af kulstof til landbrugsjord.

Mindre rejectandel betyder at mere affald bioforgasses eller komposteres. Det resulterer i, at der bliver fremstillet mere elektricitet og tilført mere kvælstof, fosfor og kalium til jorden. Kun udbyttet af fjernvarme er det samme som i de oprindelige scenarier. Den globale opvarmning stiger i alle scenarier, og forskellene mellem referencescenariet og biogasscenariet udjævnes. Kompostering bliver mindre fordelagtig med hensyn til GWP end tidligere. Forsuring og eutrofiering bliver større, men deres indbyrdes rangordenen

bevares. Samme resultat findes for fotokemiske oxidanter og forbruget af primære energibærere.

Når biogasproduktionen pr. ton affald øges, fås mere elkraft og mere kvælstof. For GWP er forskellene ringe, men biogasscenariet bliver bedre, sammenholdt med referencescenariet, og komposteringen værre. For de øvrige grupper af miljøvirkninger er forskellene meget små, og deres indbyrdes rangorden forbliver uforandret i de forskellige scenarier. Forbruget af primære energibærere undergår samme ændringer som GWP.

Omlægning af elproduktionen fra kul til naturgas mindsker udledningerne fra elfremstilling og ændrer den indbyrdes rangorden af scenarierne. Anvendelse af naturgas indvirker positivt på lomposteringsscenariet, som bruger større mængder kompenserende el. Skiftet af energibærer indvirker således negativt på biogasscenariet, fordi der fremstilles mest elektricitet på grundlag af biogas.

Den sidste følsomhedsanalyse omfatter et skift af brændstof fra kul til naturgas for kompenserende varme. Eftersom graden af kompenserende varme øges i scenarierne, påvirker ændringen i brændstofanvendelse scenarierne i forhold hertil. Ændringerne er dog ikke så store, at rangordenen mellem scenarier ændres.

# Summary

Organic household waste is a resource that is not fully utilised in Denmark today through composting or anaerobic digestion. On a yearly basis about 1,7 million tons of household waste is collected. The organic part is about 700 000 tons. To get a better understanding of the consequences when increasing biological treatment of organic household waste, the Danish EPA is conducting a socio-economic survey of increased biological treatment of organic household waste. In order to do an socio-economic survey, there is need to quantify flows of material, use of resources, energy, emissions to air, water and soil. In this project use of resources, emissions to air, water and soil, use and generation of energy and environmental impacts are calculated and presented on a national level.

To describe the system for handling and treatment of organic household waste a system analytical approach is used. In order to calculate the flows, emissions and environmental impact from handling organic household waste a computer-based model ORWARE (ORganic WAste REsearch) is used for the systems analysis.

ORWARE is a tool for environmental systems analysis of waste management. It is a computer-based model for calculation of substance flows, environmental impacts, and costs of waste management. ORWARE consists of a number of separate sub models, which may be combined to design a waste management system for e.g. a city, a municipality or a company. ORWARE is a model primarily for material flow analysis (MFA). The material flows from different sources (wastes) through different methods for waste treatment (composting, anaerobic digestion etc) to different end uses (spreading of residues on agricultural soil or landfill). Emissions from transports, treatments etc are allocated as emissions to air, water and soil. Using methodology for impact analysis from life cycle assessment (LCA) different environmental impact categories are calculated.

The study consists of two sets of scenarios and a number of sensitivity analyses. The first set of scenarios, the multi-treatments scenarios, incorporates the different waste management technologies into five different scenarios that reflect the implementations of different treatment technologies available for treatment of organic household waste. The scenarios describe increased composting and anaerobic digestion in favour of incineration. This is made in a short-term timeframe and a long-term timeframe based on utilisation of organic household waste at a national level. The results from the multi-treatment scenarios are presented for core-, up-/ downstream and compensatory system levels.

The second scenarios are set up in order to compare specific emissions from three different treatment technologies. All organic waste is directed to one type of treatment; incineration, anaerobic digestion or composting. In each scenario, emissions are expressed for the different stages: collection, transport, treatment and downstream processes (gas utilisation and spreading of organic fertiliser). The results from the mono-treatment scenarios are presented as

emissions to air and water. These scenarios only cover the core and upstream system, compensatory production is not accounted for.

In addition to the two sets of scenarios a number of sensitivity analysis were conducted in order to conclude the importance of different parameters and assumptions not covered by the scenarios:

- No recycling of slag to road construction?
- Losses from source-separation are changed from 35 % to 10 % for biogas and from 15 % to 5 % for compost.
- A sensitivity analysis with a higher biogas production, 150 $nm^3$ instead of originally 125 $nm^3$ is carried out.
- Arable land can be used as a carbon sink in order to decrease $CO_2$-emissions.
- Utilising natural gas to be the marginal power production.
- Heat from coal is replaced by heat from natural gas.

The study produced a large amount of results, which are incorporated in the socio-economic study carried out by Danish EPA. In general, the results show that increased anaerobic digestion compared to the present situation has both positive and negative impacts on the environment.

Advantages and disadvantages depend on which environmental impacts that are considered. An increase in windrow and reactor composting in favour of incineration is with some exception worse than the present treatment situation, especially when the long-term compost scenario (No. 5) is compared to the reference scenario. In an overall perspective the differences is larger between long-term scenarios for composting than the long-term scenario for anaerobic digestion.

Different amount of functions is generated from each scenario. In this project following functions were identified:

- kg Nitrogen (N-tot) recycled to agricultural soil
- kg Phosphorus (P-tot) recycled to agricultural soil
- kg Potassium (K-tot) recycled to agricultural soil
- TJ electricity generated from waste treatment
- TJ heat (as district heating) generated from waste treatment.

The amount of functions from each multi-treatment scenario is distributed as follows: Maximum amount of P and K is generated in scenario 5, 311 and 761 tonnes P and K respectively. Maximum amount of N is generated in the scenario 3, 1 162 tonnes, electricity in scenario 3 and heat in scenario 1, 483 TJ el. and 1 761 TJ heat.

The sensitivity analysis show some changes compared to the original scenarios.
Valuing arable land as carbon sink affects solely on GWP. It is favourable for the long-term biogas and compost scenarios, because of a high degree of recycling of carbon to arable land.

Decreased losses from source-separation will lead to functional units' increase in magnitude except for district heating which remains the same as in the original scenario-set. More waste sent to anaerobic digestion and composting results in higher electrical power generated and more nitrogen, phosphorus and potassium to soil. Global warming increases for all scenarios and the

differences between the reference scenario and the biogas scenarios are levelled out. Composting becomes less favourable with respect to GWP than before. Acidification and eutrophication increase but the internal order remains the same. The same result is found for photochemical oxidants and consumption of primary energy carriers.

Higher biogas production increases the functional units' electrical power and nitrogen increase. For GWP the differences are small but the biogas scenarios become better in relation to the reference and composting worse. For the other environmental impact categories, the differences are extremely small and the internal relation is not changed between the scenarios. The consumption of primary energy carriers goes through the same changes as GWP.

By shifting power generation from coal to natural gas decreases total emissions from power generation and changes the order between scenarios, concerning different environmental impact. Using natural gas has a positive effect on composting scenarios that uses large amount of compensatory electricity. The shift in energy carrier has therefore a negative impact in biogas scenarios because they generate most of their electricity from biogas.

The last sensitivity analysis is a change of fuel from coal to natural gas for compensatory heat. As the scenarios to a larger and larger extent include compensatory heat, the impact of fuel change affects the scenarios in correspondence to that. The changes are however never so large that the order between the scenarios is changed.

# 1 Introduction

Due to political decisions, more actions are taken by society towards more sustainable waste management solutions. On the European level, directives on landfilling (1999/31/EU directive) and incineration (2000/76/EU directive) of waste are implemented. As some 15 % of the total municipal waste flow then has to be redirected from landfilling to other treatments, these institutional changes will most probably lead to major changes in Danish waste management.

Organic household waste is a resource that is not fully utilised in Denmark today through composting or anaerobic digestion. On a yearly basis about 1.7 million tons of household waste is collected. The organic part is about 700 000 tons. To get a better understanding of the consequences when increasing biological treatment of organic household waste the Danish EPA is conducting socio-economic survey of increased biological treatment of organic household waste. In order to do an socio-economic survey, there is need to quantify flows of material, use of resources, energy, emissions to air, water and soil.

In this project use of resources, emissions to air, water and soil, use and generation of energy and environmental impacts are calculated and presented on a national level. The results from this study will bee used as environmental input data into a socio-economic survey.

To describe the system for handling and treatment of organic household waste a system analytical approach is used. The flow of organic household waste is one of many waste flows, for most parts organic waste is handled and treated together with other wastes. If the whole waste flow is studied, there is a risk that the impact from organic waste is clouded because other larger waste flows are treated at the same time and place. To avoid results, which can be allocated to handling of organic household waste, a simplified model is created to describe the organic waste flow. In order to calculate the flows, emissions and environmental impact from handling organic household waste a computer-based model ORWARE (ORganic WAste REsearch) will be used for the systems analysis.

# 2 The ORWARE model

ORWARE is a tool for environmental systems analysis of waste management. It is a computer-based model for calculation of substance flows, environmental impacts, and costs of waste management. According to Nybrant et al (1995), ORWARE was initially intended as a systems analysis tool for assessment of environmental impact from biodegradable waste handling in municipal waste management systems. The aim was to enable quantified and systematic comparison of the environmental impacts of different means to handle biodegradable waste, both solid and liquid waste. Modelling waste flows in total amounts and as specific substances and its related energy turnover did this. ORWARE has since then been expanded to cover handling of inorganic fractions in municipal waste as well.
The ORWARE model has been developed in close co-operation between four different research institutions in Sweden: KTH - Royal Institute of Technology, IVL - Swedish Environmental Research Institute, JTI - Swedish Institute of Agricultural and Environmental Engineering and SLU - Swedish University for Agricultural Sciences.

ORWARE consists of a number of separate submodels, which may be combined to design a waste management system for e.g. a city, a municipality or a company (Dalemo et al, 1997). ORWARE is a model primarily for material flows analysis (MFA). The material flows from different sources (wastes) through different methods for waste treatment (composting, anaerobic digestion etc) to different end uses (spreading of residues on agricultural soil or landfill). Emissions from transports, treatments etc are allocated as emissions to air, water and soil. Using methodology for impact analysis from life cycle assessment (LCA) different environmental impact categories is calculated (ISO 14042:2000).

## 2.1 The conceptual model

The ORWARE model consists of a core system, up- and downstream systems and a compensatory system (Eriksson et al, 2002). The core system describes the waste management system, including collection, treatment, and final disposal of waste generated within a defined geographical area and time-space. Up- and downstream processes are defined as those processes that impact the core system when using materials and energy. For example, production and distribution of diesel fuel used for collection and transportation is defined as upstream processes. Upstream processes also include waste sources and electricity and fuel generation and downstream processes are as example use of organic fertiliser and biogas utilisation (Figure 1).

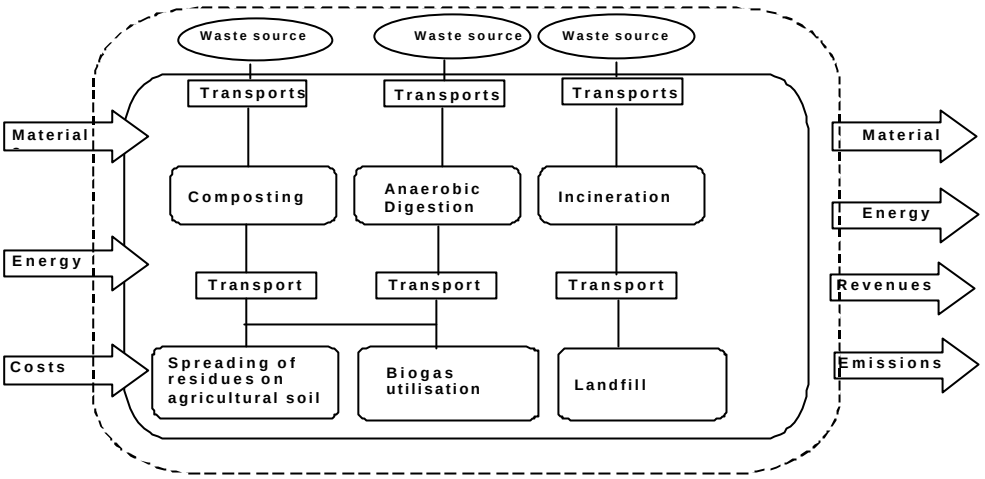


Figure 1. Conceptual model describing the waste management system in the ORWARE model as adapted to Denmark.

From the core system functions or utilities are identified, for example distance travelled by car or bus using biogas or hydrogen as fuel, processed raw materials, organic fertilisers spread to crops, electricity generation etc. The scenarios contribute different amounts of each defined function and the compensatory system supplies the need of a certain function, so that all scenarios use the same amount of functions and thereby are comparable with each other.

All submodels in ORWARE calculate the emissions and use of resources from the specific material treated. Therefore, the submodels do not need an optimal mixture of materials to function properly, but calculates the contribution from each specific material they treat.

## 2.2 The core system

The core system is the physical system studied. In this study the core system describes handling of organic household waste from collection at household level to end use, for example landfilling of ash and slag from incineration and spreading of organic fertilisers.

### 2.2.1 Organic household waste

Household waste consists of different waste fractions, where organic household waste is one of them. The organic fraction of the total household waste is as an average 30 % – 40 % of the total amount of household waste (Sonesson and Jönsson 1996). In Tabel 1 is the most important parameters describing organic household waste are listed. For the full description of the organic waste, see Appendix E. The dry matter content for organic household waste used in the ORWARE model is assumed, as an average, to be 30 % (Jepsen, 2002).

Tabel 1. Key parameters in the ORWARE vector describing organic household waste in kg per kg dry matter (Sonesson and Jönsson 1996 and Sundqvist et al, 1999).

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Total organic carbon (TOC) | 0.434 | Phosphorus | 3.80e- |
| Slowly degradable carbohydrates (C- | 0.029 | Potassium | 9.30e- |
| Easily degradable carbohydrates (C- | 0.097 | Lead (Pb) | 1.00e- |
| Medium degradable carbohydrates | 0.107 | Cadmium | 1.30e-7 |
| Fat (C-fat)[1] | 0.135 | Mercury | 2.80e- |
| Protein (C-protein)[1] | 0.066 | Copper (Cu) | 3.40e- |
| Volatile solids (VS) | 0.8 | Chrome (Cr) | 1.00e- |
| Dioxin | 9.00e- | Nickel (Ni) | 7.00e- |
| Nitrogen (N) | 0.033[2] | Zink (Zn) | 8.00e- |

[1] The sum of the different carbon fractions is TOC
[2] Jepsen (2002)

### 2.2.2 Collection and transportation of waste

There are different types of submodels describing vehicles for different types of transports. For collection of waste, there are back-packer and front-loader models. For transport of primary and secondary waste like fly ash and slag there are three submodels: ordinary truck, truck and trailer and barge for transports at sea. Data on average load, average speed etc. is used as input in all transport submodels. The output is total energy consumption, time consumption and costs. Emissions are calculated from the energy consumption. The transport submodel is further described in Sonesson (1996) and in Sonesson (1998). For more information about transports used in this project, see Appendix D.

### 2.2.3 Incineration

The incineration submodel consists of three parts: pre-treatment, incinerator and air pollution control. The pre-treatment provides baling of the incoming waste, which makes it possible to store waste and to combust it later. In the incinerator, the waste is combusted and the outputs are raw gas, slag and fly ash. The raw gas is led to the air pollution control and the clean gas is released as air emissions. A submodel for flue gas condensing is included which may be used for more efficient energy recovery. Condense water is cleaned before it is emitted. Ash and slag are transported to landfill. The energy recovered in this submodel is district heating and/or electricity.

As for all submodels, site-specific data are used as much as possible. When such data are missing, the attempt has been to use data from 1) comparable facilities, 2) other waste incinerators, or 3) reasonable assumptions. Emission factors are calculated from material balances from each process and are either product related (linearly dependant on the incinerated amount of the substance), process related (dependant on the amount of waste incinerated) or threshold related. The last category is modelled to generate a constant emission level depending on some threshold value, defined as the legislative threshold values are always kept. This approach is realistic for emissions that are normally adjusted within very narrow limits, e.g. $NO_x$. The reason is usually economic; threshold values must be kept, but further reductions would not be economically motivated.

A more detailed description of the waste incineration plant is found in Björklund (1998). Information about waste incineration plant used in this project, see Appendix D.

### 2.2.4 Central composting

In ORWARE, three different types of composting are modelled (Sonesson, 1996). The different types are home composting, windrow composting and reactor composting. The models are based on the assumption that the composts are well managed, i.e. no failures occur that will give rise to high emissions of methane and other products of anaerobic conditions. All leachate water is returned to the compost. The degradation process is the same for all three compost types except for the degradation speed. The emissions are theoretically the same. The different compost submodels generate the same composition of the compost product when processing the same type of waste. When it comes to energy consumption the reactor compost demands most electricity, whereas composting in private households does not need energy at all (just some physical power that is not accounted for). Windrow composting is slightly less energy consuming than the reactor compost. The large scale composting has an option to clean the compost gas from ammonia ($NH_3$) and nitrogen oxides ($NO_x$). The cleaning equipment consists of a condensation step with recycling of condense liquid to the compost process and a bio-filter consisting of mature compost. The nitrogen captured in the filter is returned to the mature compost. The reactor compost submodel also gives a possibility to recover some of the heat released during the degradation. For more information about the compost submodel, see Sonesson 1998. Data and assumptions for this project are described in Appendix D.

### 2.2.5 Anaerobic Digestion

The submodel for anaerobic digestion is suitable for a mesophilic (37 ºC) or thermophilic (55 ºC) process (Dalemo, 1996). The model is based on a real treatment plant in Uppsala, which is a continuous single stage mixed tank reactor (CSTR). The incoming material is cleared from plastic bags and metals and then fragmentised. The separation will result in a loss of organic material. After hygienisation at 70 ºC or 130 ºC, the substrate is brought to the digester. The model automatically calculates the energy needed for hygienisation and digestion as well as need of water for adjustment of the dry matter content (DM). After the digestion step, the substrate passes through a heat exchanger and dewatering equipment.

The amount of gas generated is dependent on the composition of different organic compounds as fat (C-fat), protein (C-prot), cellulose (C-chmd), hemicellulose and lignine (C-chsd), rapidly degradable carbohydrates (C-chfd) and the hydraulic retention time (HRT). The sludge from the digester is either separated into a solid and a liquid phase in the dewatering process or utilised without dewatering. The digestion residue (anaerobic sludge) is stored in large covered lagoons in solid or liquid phase. Liquid from dewatering is either recycled back to reactor or processed elsewhere, for instance pumped to sewage plant, reed bed etc. Electricity is consumed for mixing, pumping and drying. The submodel delivers anaerobic sludge, dried or wet, for spreading and biogas to be combusted. Further description can be found in Dalemo (1999). Data for the model used in this project is described in Appendix D.

### 2.2.6 Landfilling of waste

The landfill submodel is divided into five different landfill types: mixed waste, bio-cell, sludge, fly ash and slag. The submodels are thought to work as Swedish average landfills, and the site-specific adjustments are few. There is a possibility to adjust the efficiency of the landfill gas recovery as well as the

type of leachate treatment used. Energy consumption in form of electricity and diesel oil is accounted for and product outcome is bio-cell. Energy is generated as heat and or electricity from gas-fired engines, see the description of gas utilisation.
Waste landfilled today will cause emissions during a long period of time. A dilemma is how to compare the emissions from the landfill with the instant emissions from the other processes in the system. Just to include instant landfill emissions would be to heavily underestimate the total impact. However, if one tries to estimate the total emissions the uncertainty will be large and the time perspective will not be comparable to other processes. As a compromise the future impact from landfilling has been separated in two time-periods, the definitions of which are a bit different between the different landfill types:

- *Surveyable time:* The time until the most active processes in the landfill has ended and the landfill has reached a pseudo steady state. For mixed waste, sludge and organic waste put in the bio-cell surveyable time is defined to last until the later part of the methane phase. That means a period of about 100 years for mixed waste and 10-20 years for organic waste in a bio-cell. In the case of landfilled incineration ash and slag, the surveyable time corresponds to the time needed for highly soluble substances such as alkaline salts to leak out.
- *Remaining time:* The time until all material has been spread out in the environment through gas emissions, leaking, erosion and possible inland ices. The remaining time includes the emissions in a kind of worst scenario.

Leachate formed in the landfill is collected and treated before emitted to recipient. The landfill submodel uses biological treatment of leachate with chemical precipitation of phosphorus. During surveyable time, 80 % of phosphorus in leachate is precipitated and recycled back to the landfill. The rest of the phosphorus is emitted into recipient. Of nitrogen in leachate, 90 % is emitted as nitrogen gas ($N_2$) to air, and the rest of the nitrogen is emitted to recipient.
The landfill submodel (bio-cell not included) is further described in Björklund (1998), appendix D and the bio-cell in Fliedner (1999). Specific assumptions for this project are described in Appendix D.

### 2.2.7 Gas engine

Biogas from the digester and landfill gas, which is partly collected, is combusted in a stationary gas engine. The energy generated during combustion is utilised as heat and electricity. Landfill gas formed but not collected is partly oxidised into landfill cover the rest is emitted to air mainly as methane ($CH_4$) and carbon dioxide ($CO_2$).
The gas engine generates 38 % electricity and 52 % heat; the remaining 10 % are losses (Jepsen, 2002). Emissions are given in Appendix D.

### 2.2.8 Spreading of organic fertilisers and nitrogen turnover in soil

The submodel for spreading of organic fertiliser is divided into three steps:

1. Calculation of spreading areas and transport distances
2. Transport of residues from treatment plant to centre of spreading areas
3. Spreading of organic fertilisers. The maximum spreading of residues per hectare is determined from its contents of phosphorus and nitrogen.

An ordinary truck performs transportation of residues; see description for the transport submodels above. The distance to and the area of each spreading area are used as input data and the model calculates the total distance and energy consumption.

Two different spreaders are modelled, one for liquid products and one for solid products. The model determines what kind of spreader is needed depending on the dry matter content. The spreading model calculates the emissions from the truck transport and the spreading procedure and energy consumption for the vehicles.

Nitrogen turnover is a down-stream process in the waste treatment flow in ORWARE. It is used as a complement to the organic fertiliser-spreading submodel. Nitrogen in organic fertiliser is assumed to be utilised by plants, organically bound to microorganisms etc. in soil (Dalemo et. al., 1998). The model calculates the emissions of nitrogen compared to use of mineral fertiliser. Thus, relative rather than absolute values are calculated as in the other submodels.

Nitrogen is assumed to exist in three forms: ammonium ($NH_4$), nitrate ($NO_3$) and organically bound (N-org). The model gives emissions from mineralization of organically bound nitrogen during the first year after spreading and the long-term effects of mineralization. The efficiency with which the crops use the organic fertilisers compared to the mineral fertilisers are 100 % for phosphorus, 80 % of the mineral nitrogen and 30 % of the organically bound nitrogen. The emissions of nitrous oxide ($N_2O$), $NO_3$ and ammonia ($NH_3$) depend on the soil condition, spreading conditions and climatic region can be adjusted in the model.

The arable land submodel is further described in Dalemo et al (1998). The sub-models for spreading and nitrogen turnover in soil are further described in Sundqvist et al (2000) and Appendix D.

## 2.3 The compensatory system

In order to fulfil the need of function (utilities) generated from management of waste in the core system. ORWARE supplements the lack of a function from an external source, that all scenarios have the same amount of functions, but from different sources.

### 2.3.1 District heating

Generation of district heating can be included both as an up-stream process to waste management when needed in a waste treatment process, or as a compensatory process if necessary to fulfil a functional unit. Conventional district heating can be generated from biomass, oil or coal. The emissions from coal combustion use the same data source as for electricity production from coal, but with another degree of efficiency, 88 %, compared to degree of efficiency for electrical power generation, se below.

### 2.3.2 Electrical power

Like district heating, electricity generation may be included as both an up-stream process to the waste management system and as a compensatory

process. It is possible to use one single source or a combination, a power mix. The different power sources in the model are biomass, hydropower, wind power, nuclear power, natural gases, oil and coal. Data on Swedish facilities are used except for the coal plant where data is used which describes the emissions from an average coal condense power station in Denmark. The degree of efficiency for condense power is 44 %.

### 2.3.3 Mineral fertiliser

Compensatory production of the mineral fertilisers' nitrogen (N), phosphorus (P) and potassium (K) is done in order to fulfil the functional unit of nutrients spread on arable land. Emissions and use of resources are related to the actual nutrient (emission per kg N, P or K) and not the fertiliser containing the nutrient and thereby directly to the functional unit.

The submodels for compensatory production of mineral fertiliser cover extraction and manufacturing of raw materials and production of nitrogen, phosphorus and potassium fertiliser. The compensatory production of mineral fertiliser includes use of resources and emissions when producing mineral fertilisers. Spreading of mineral fertilisers is not included into compensatory mineral fertilisers.

A life cycle inventory by Davies and Haglund (1999) using western European average data for production of mineral fertilisers are used for estimation the contribution from mineral fertiliser production. Emissions from mineral fertiliser nitrogen is calculated from manufacturing ammonium nitrate (35 % N), Western European average data, phosphorus mineral fertiliser is calculated from Triple superphosphate, TSP (48 % $P_2O_5$), Western European average data and potassium from PK fertiliser (22 % $P_2O_5$, 22 % $K_2O$) Western European average data.

# 3 General conditions for the study

## 3.1 System boundaries

The systems analysis consists of two sets of scenarios and a number of sensitivity analyses. The first set of simulation is five treatment scenarios corresponding to different future waste management option where several treatment technologies are combined. These scenarios were identified and set up by the Danish EPA. The second set of scenarios concerns different waste treatment technologies. Waste is treated either by incineration, central composting or anaerobic digestion. In all scenarios and in the sensitivity analyses, system boundaries for the waste management system are the same. This means that all results for the core system and up- and downstream system are comparable with each other. There are a number of limitations to the scenarios:

- *Limitations in time*: ORWARE calculates the impacts caused by handling and treatment of the amount of waste generated during one year. All emissions occur during this year except for emissions from the landfill and arable land, see Appendix B.
- *Geographical limitations*: Only waste generated in the selected and defined area (Denmark) is included, whereas emissions and use of resources is included wherever they occur and are allocated back to where the waste is generated.
- *Limitations in function*: This involves allocation between core system, up- and down-stream systems and compensatory system. Processes in the compensatory system are, when possible, calculated from a LCA perspective, from cradle to grave (ISO 14040:1977). Thereby extraction, processing, transportation and production of raw materials are included, see Appendix D for each process used in the systems analysis.
- *Limitation of materials treated*: In reality different materials are treated together with the organic household waste, for example large amounts of manure are digested together with the waste.
- *Energy utilisation* is expressed as use of primary energy carriers, the amount of energy raw materials as trees in the forest, oil and coal in deposit etc. that is needed to extract in order to generate the right amount of energy in the process.
- *Use of chemicals in processes* for waste treatment is calculated, but not in a true LCA perspective, cradle to grave.

## 3.2 General assumptions

All specific assumptions for the different submodels are described in Appendix D. Some of the most vital assumptions are however described here.

- The organic waste has a dry matter content of 30 %.
- Collection of waste is based on two general assumptions: the energy fuel consumption is 0.3 GJ/ ton waste and the energy content in diesel oil is 35.6 MJ per l diesel.

- 40 % of the waste to anaerobic digestion is transported 80 km by truck and trailer and 60 % is transported 20 km by truck
- 50 % of the waste to anaerobic digestion is digested in a mesophilic process, 50 % in a thermophile process. Biogas production is set to 125 $nm^3$ per ton of waste treated. Of the incoming waste 35 % is sorted out to incineration.
- The waste to composting is transported 20 km by truck
- 50 % of the waste to composting is put into windrow compost and 50 % into reactor compost. In both composts the carbon-nitrogen ratio has been set to 30, corresponding to an input of carbon-rich material. Differences between the two compost techniques are that the reactor compost uses more electricity and diesel for compost maintenance than the windrow compost. The reactor compost also clean exhaust gases from composting through a combined wet scrubber and compost filter that reduces losses of $NH_3$, $N_2O$ and $CH_4$. Of the incoming waste, 15 % is sorted out to incineration.
- The incineration plant is a CHP plant with 85 % overall efficiency and 0.35 MJ electricity/ MJ heat. No flue gas condensation. The $NO_x$-emission is 200 mg $NO_2$/ MJ fuel.
- Collected biogas is combusted in a gas engine with 90 % degree of efficiency where 38 % of the energy is recovered as electricity and 52 % as district heating.
- Dry spreaders are used when spreading compost. Compost is spread in the spring and harrowed into soil within one hour after spreading. Compost spreading leads to volatilisation of ammonia ($NH_3$) that equals 15 % of ammonium ($NH_4$) content in compost. Liquid spreader is used when spreading of anaerobic sludge. Anaerobic sludge is spread in the spring using a band spreader and harrowed into soil within one hour after spreading. Loss of $NH_3$ is 5 % of $NH_4$-content in anaerobic sludge
- Incineration residues, slag, are recycled to 80 % and 20 % of the slag amount are put on landfill. The recycling is made outside the system and is not accounted for. All ashes are landfilled separately.
- Compensatory heat is produced from coal with 88 % degree of efficiency
- Compensatory power is produced from coal with 44 % degree of efficiency
- Compensatory fertiliser is calculated for western European average data for production of mineral fertiliser nitrogen, phosphorus and potassium.

## 3.3 Mono-treatment scenarios

These scenarios are set up in order to compare specific emissions from three different treatment technologies. All organic waste is directed to one type of treatment; incineration, composting or anaerobic digestion. In each scenario, emissions are expressed for the different stages: collection, transport, treatment and downstream processes (gas utilisation and spreading of organic fertiliser). These scenarios do only cover the core system; compensatory production is not accounted for.

### 3.3.1 Mono-treatment scenario 1: Incineration

All organic household waste is collected and incinerated (Figure 2). All of the ashes from incineration are landfilled. Slag is recycled in an extent of 80 %, therefore only 20 % of the generated slag is landfilled. Emissions from

recycling of slag are not accounted for. Energy recovered from incineration is utilised as electricity.

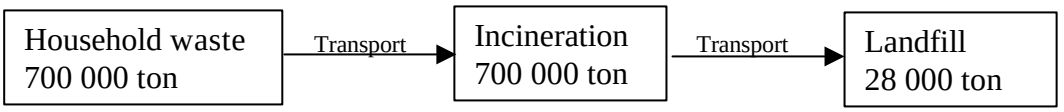


Figure2. Conceptual model for mono-treatment scenario 1: Incineration of all waste.

### 3.3.2 Mono-treatment scenario 2: Anaerobic digestion

All organic household waste is collected and transported to incineration plant. At the incineration plant, the waste is reloaded and transported to anaerobic treatment (50 % mesophile and 50 % termophile digestion), except for 35 %, that is sorted out during bag and metal separation. Anaerobic sludge is transported to arable land and spread as an organic fertiliser. Waste sorted out is incinerated. All ash is landfilled and 80 % of the slag is recycled and 20 % is landfilled. Energy generated during incineration is utilised as electricity. Biogas from anaerobic digestion is combusted in a stationary gas engine. Recovered energy is utilised as electricity and heat.

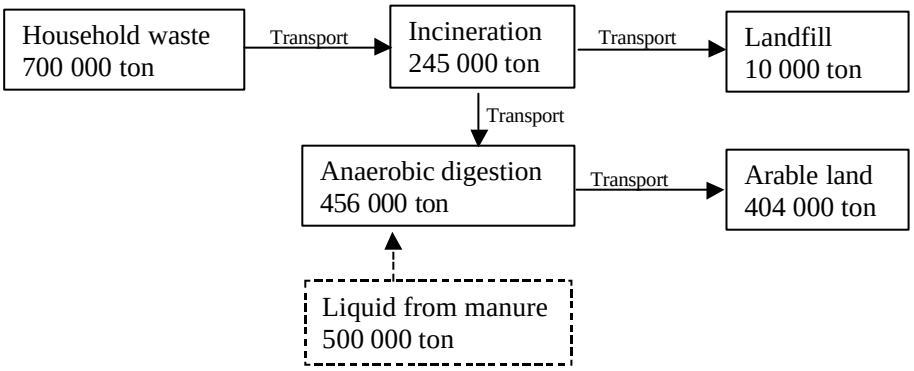


Figure 3. Conceptual model for mono-treatment scenario 2: Anaerobic digestion of all waste.

### 3.3.3 Mono-treatment scenario 3: composting

All organic household waste is collected and transported to incineration plant. At incineration plant the waste is reloaded and transported to composting (50 % windrow and 50 % reactor), except for 15 %, which is sorted out during bag and metal separation. Compost is transported to arable land and spread as an organic fertiliser. Waste sorted out is incinerated. All ash is landfilled and 80 % of the slag is recycled and 20 % is landfilled. Energy generated during incineration is utilised as electricity.

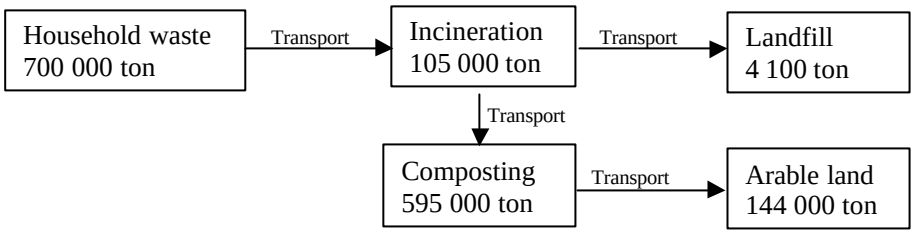


Figure 4. Conceptual model for mono-treatment scenario 1: Composting of all waste.

## 3.4 Multi-treatment scenarios

Five scenarios that reflect the implementation of different treatment technologies available for treatment of organic household waste are simulated. The scenarios describe increased composting and anaerobic digestion in favour of incineration. This is made in a short-term timeframe and a long-term timeframe based on utilisation of organic household waste at a national level.

Table 2. Different treatment methods and amounts treated per year for the five scenarios. Direct waste flows and within parenthesis total waste flows (tons).

| Treatment | Scenario 1 Reference | Scenario 2 2004 Anaerobic digestion | Scenario 3 "Long term" Anaerobic digestion | Scenario 4 2004 Composting | Scenario 5 "long term" Composting |
|---|---|---|---|---|---|
| Incineration | 654 000 (663 700) | 570 000 (609 500) | 370 000 (479 500) | 570 000 (595 500) | 370 000 (425 500) |
| Anaerobic digestion | 14 000 (9 100) | 100 000 (65 000) | 300 000 (195 000) | 30 000 (19 500) | 30 000 (19 500) |
| Central Composting | 32 000 (27 200) | 30 000 (25 500) | 30 000 (25 500) | 100 000 (85 000) | 300 000 (255 000) |
| Sum | 700 000 | 700 000 | 700 000 | 700 000 | 700 000 |
| Landfilling[1] | 26 000 | 24 000 | 19 000 | 23 500 | 16 800 |
| Road constr. | 44 000 | 41 000 | 33 000 | 40 000 | 29 000 |

[1]Landfilling of incineration residues

Numbers within parentheses are higher for incineration and lower for anaerobic digestion and composting. This is explained by that organic waste directed to anaerobic digestion or composting is pre-sorted and the residues are incinerated.

The reference scenario represents waste treatment of today in Denmark. The system is based on incineration of waste with small amounts of composting and anaerobic digestion (Table ). The scenario is used as reference in order to show differences in emissions, environmental impact and turnover of energy when the waste flows are redirected to increased biological treatment.

## 3.5 Sensitivity analysis

- The incineration slag is supposed to be recycled into road construction to 80 % but what are the changes if there is no recycling?
- Organic waste can be source-separated by using either paper bags or plastic bags. The choice will affect the amount of waste rejected from

anaerobic digestion plant in the pre-treatment. Paper bags result in smaller losses than plastic bags. This is studied in a sensitivity analysis.

- The biogas processes are supposed to become better and better as the technology mature. A sensitivity analysis with a higher biogas production is also carried out.
- Arable land can be used as a carbon sink in order to decrease $CO_2$-emissions. The impact of this is studied separately in a sensitivity analysis
- Today new power generation makes it possible to avoid power generation from coal condense power stations. In the future prognoses point at natural gas to be the marginal power production.
- The alternative fuel in district heating is assumed coal but it could also be claimed that the heat from coal is replaced by heat from natural gas. This is changed in the last sensitivity analysis.

# 4 Results

The results are showing environmental impact and use of resources as normalised values. For the multi-scenarios, all impact categories from the reference scenario are given the value 1. The other scenarios reflect the difference between the reference scenario and the other scenarios. The results show the total impact from core, up-/ downstream and compensatory system.

The results from the simulation of mono-scenarios are shown as emission tables in Appendix B. The tables B26-B28 contain emissions to air and water from processes and heavy metals to soil. The Danish EPA primarily uses the mono-scenarios.

Results from sensitivity analysis only show the differences that occur due to changes in the analysis between the scenarios.

Detailed emissions and environmental impact are shown in Appendices A, B and C.

## 4.1 Environmental impact and resource utilisation from multi-treatment scenarios

Environmental impact is calculated by multiplying emissions with different weighting factors (Appendix F). The weighting factors each describe a certain environmental impact categories e.g. global warming potential (GWP), Acidification potential (AP), eutrophication potential (EP) and photochemical oxidants from $NO_x$ and VOC. The resources used are collected into primary energy carriers and non-renewable primary energy carrier. A primary energy carrier is for example coal and oil.

### 4.1.1 Amount of functions generated from multi-treatment scenarios

Depending of which process or mixture of processes that is used to treat the organic household waste, different amount of functions is supplied from each scenario. In this project following functions are identified:

- kg Nitrogen (N-tot) recycled to agricultural soil
- kg Phosphorus (P-tot) recycled to agricultural soil
- kg Potassium (K-tot) recycled to agricultural soil
- MJ or kWh electricity generated from waste treatment
- MJ or kWh heat (as district heating) generated from waste treatment

The amount of functions from each scenario is listed in. Maximum amount of P and K is generated in scenario 5. Maximum amount of N is generated in the scenario 3, electricity in scenario 3 and heat in scenario 1.

Table 3. Amount of functions (nutrients in metric tonnes, energy in TJ) generated from treatment of organic household waste.

| Function<br>Nutrients in tonnes<br>Energy in TJ | Scenario 1<br>Reference | Scenario 2<br>2004<br>Anaerobic digestion | Scenario 3<br>"Long term"<br>Anaerobic digestion | Scenario 4<br>2004<br>Composting | Scenario 5<br>"long term"<br>Composting |
|---|---|---|---|---|---|
| Organic Nitrogen | 130 | 437 | 1 162 | 357 | 854 |
| Comp. Nitrogen | 1 032 | 725 | 0 | 805 | 308 |
| Total Nitrogen | 1 162 | 1 162 | 1 162 | 1 162 | 1 162 |
| Organic | 40 | 97 | 231 | 117 | 311 |
| Comp. Phosphorus | 271 | 214 | 80 | 194 | 0 |
| Total Phosphorus | 311 | 311 | 311 | 311 | 311 |
| Organic Potassium | 99 | 236 | 566 | 287 | 761 |
| Comp. Potassium | 662 | 525 | 195 | 474 | 0 |
| Total Potassium | 761 | 761 | 761 | 761 | 761 |
| Electricity from | 378 | 410 | 483 | 351 | 257 |
| Compensatory | 105 | 73 | 0 | 452 | 226 |
| Electricity | 217 | 216 | 211 | 204 | 165 |
| Total external | 322 | 289 | 211 | 656 | 391 |
| Heat from waste | 1 761 | 1 719 | 1 610 | 1 600 | 1 153 |
| Compensatory heat | 0 | 42 | 151 | 161 | 608 |
| Heat consumption | 2 | 16 | 45 | 5 | 5 |
| Total external heat | 2 | 58 | 196 | 166 | 613 |

The scenario that supplies the largest amount of a function defines the systems need of the function. The other scenarios have to supply the difference between maximum and actual generation from external sources e.g. the compensatory system (Table ).

Nutrients as nitrogen, phosphorus and potassium are supplied from mineral fertilisers, need of heat and electricity assumes to be produced from coal powered plants.

### 4.1.2 Environmental impact from multi-treatment scenarios

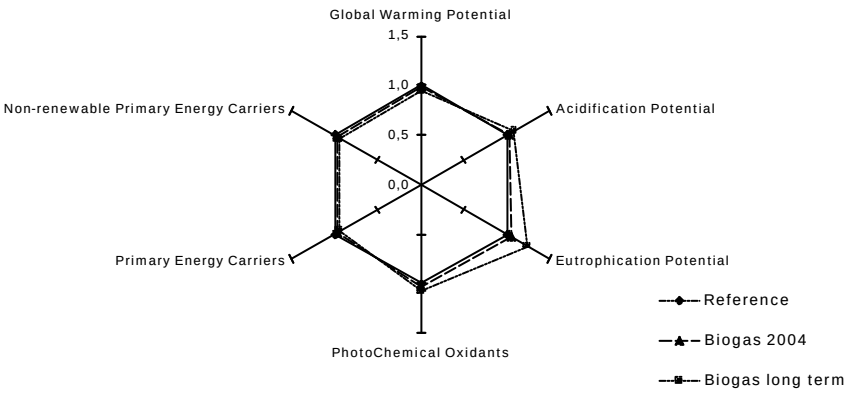


Figure 5. Radar diagram comparing short- and long-term biogas scenarios to the reference scenario. All impacts are normalised values were the reference scenario is given the value 1.

All emissions and use of resources increases when anaerobic digestion is increased on behalf of incineration. Emissions of primarily $NO_x$ have a large contribution to acidification, eutrophication and photochemical oxidants.

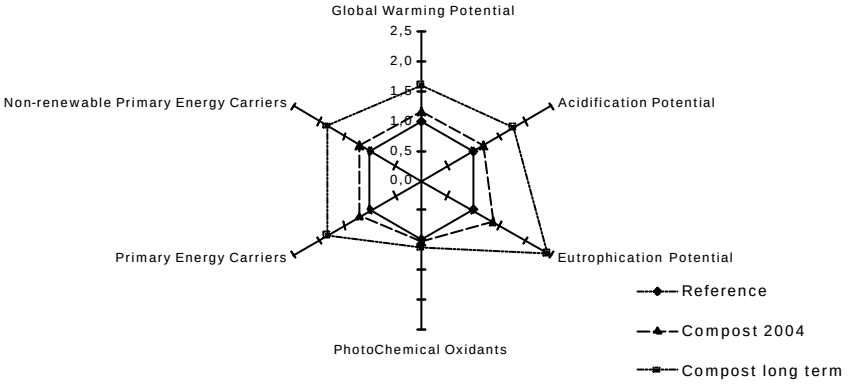


Figure 6. Radar diagram comparing short- and long-term composting scenarios to the reference scenario. All impacts are normalised values were the reference scenario is given the value 1.

All emissions and use of resources increases when a larger part of is composted instead of incinerated.

## 4.2 Environmental impact and resource utilisation from mono-treatment scenarios

Environmental impact from emissions in core system and up- and downstream system is calculated in then same way for mono-treatment scenarios as for multi-treatment scenarios.

Identified utilities are for monotreatment scenarios only quantified, no compensatory production is included.

### 4.2.1 Amount of functions generated from multi-treatment scenarios

By treating all waste in one process, the potential yield of utilities can be determined.

Table 4. Amount of functions generated from mono-treatment scenarios.

| Function | Incineratio | Anaerobic | Compostin |
|---|---|---|---|
| ton Nitrogen | 0 | 2 538 | 1739 |
| ton | 0 | 472 | 678 |
| ton Potassium | 0 | 1 155 | 1 660 |
| TJ electricity | 388 | 643 | 58 |
| TJ heat | 1 840 | 1 460 | 276 |

Incineration of waste yields the highest amounts of heat, although the differences between incineration and anaerobic digestion are approximately 20 %. Anaerobic digestion generates more electricity compared to incineration. No energy is recovered from composting. Both anaerobic digestion and composting generates nutrients that can be utilised as organic

fertiliser. Anaerobic digestion is more effective in recycling N and composting recycles more P and K. The amount of nutrients is partly dependent on the efficiency of pre-treatment especially for P and K.

### 4.2.2 Environmental impact from mono-treatment scenarios

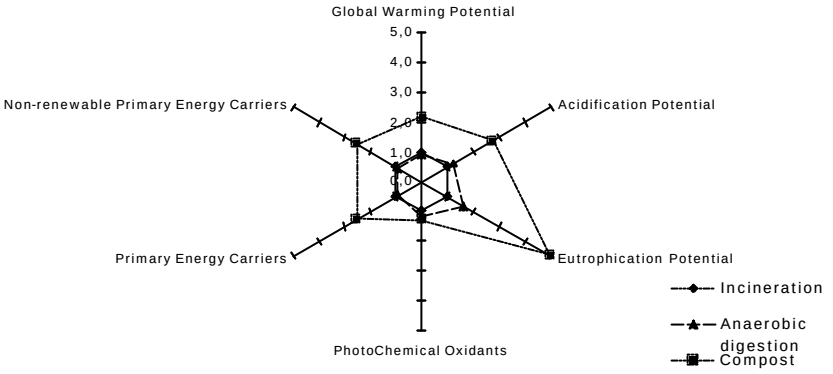


Figure 7. Radar diagram comparing mono-treatment scenarios. All impacts are normalised values were the mono-treatment scenario incineration is given the value 1.

Incineration has the smallest impact on the environment and utilisation of resources followed by anaerobic digestion and composting. With the exception of photochemical oxidants all impacts categories is largest for composting compared with anaerobic digestion.

## 4.3 Sensitivity analysis

### 4.3.1 No recycling of slag from incineration

In this analysis, the recycling of incineration slag with 80 % was set to zero and all slag was disposed of at the slag landfill. There were no differences compared to the original system as the emissions from the slag landfill are small and few and do not affect the impact categories studied here.

### 4.3.2 Paper bags instead of plastic bags

A change from plastic bags to paper bags for the organic household fraction would mean lower reject streams from the pre-treatment could be achieved. Reject to incineration before anaerobic digestion was therefore set to 10 % instead of the original 35 %. The corresponding figures for compost were 5 % instead of 15 %.

All Functional units increase in magnitude, except for district heating which remains the same as in the original scenarios. More waste sent to anaerobic digestion results in higher electrical power generated and more nitrogen to soil while more composting results in higher amounts of the functional units' phosphorus and potassium. Global warming increases for all scenarios and the differences between the reference scenario and the biogas scenarios are

levelled out. Composting becomes less favourable with respect to GWP than before. Acidification and eutrophication increase but the internal order remains the same. The same result is found for photochemical oxidants and consumption of primary energy carriers.

### 4.3.3 Higher biogas production

The biogas production is boosted from 125 $nm^3$ per ton waste to 150 $nm^3$ per ton waste treated. The functional unit heat is almost constant as well as potassium and phosphorus. The functional units' electrical power and nitrogen increase. For GWP the differences are small but the biogas scenarios become better in relation to the reference and composting worse. For the other environmental impact categories, the differences are extremely small and the internal relation is not changed between the scenarios. The consumption of primary energy carriers goes through the same changes as GWP.

### 4.3.4 Carbon sink

As the soil is seen as a carbon sink, just GWP is affected. The results are displayed in Figures 8 and 9.

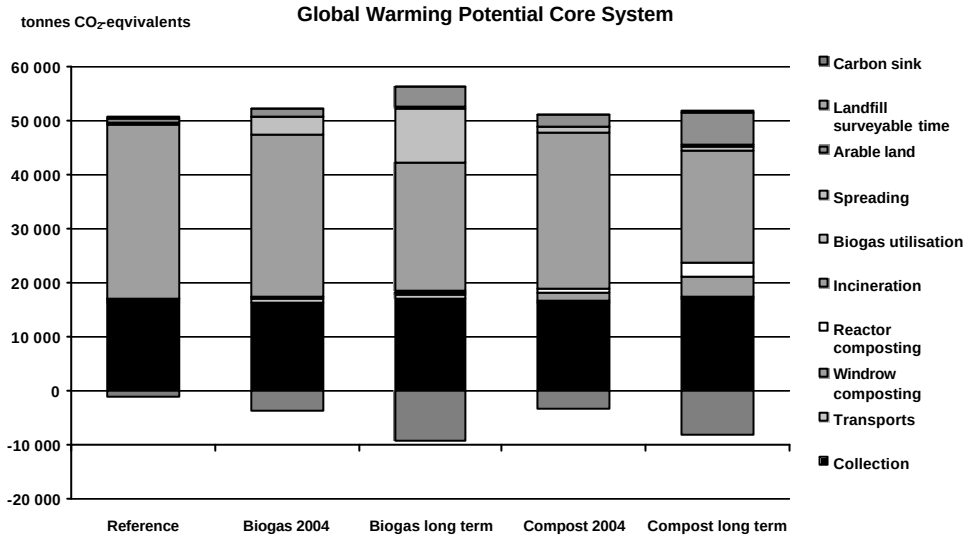


Figure 8. Global Warming Potential from the core system with biological carbon to soil as carbon sinks.

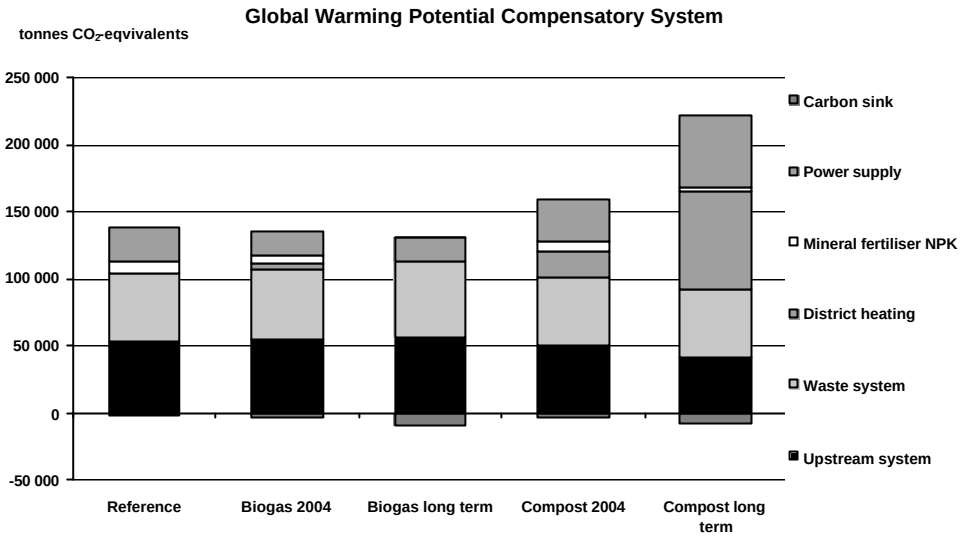


Figure 9. Global Warming Potential from the total system with biological carbon to soil as carbon sinks.

### 4.3.5 Power generation from natural gas instead of coal

When natural gas is used for compensatory power, the contribution to the GWP from the upstream system is cut in half for all scenarios. The use of electricity for the different treatment processes explains this effect on GWP. Contribution from power supply is 50 % of the original value for all scenarios. On the total, the biogas scenarios become less favourable than before compared to the reference scenario and are now in line with or somewhat higher than the reference scenario.

With respect to acidification the contribution from the upstream system is decreased with a factor 10 and the impact from power supply is principally zero for all scenarios. This affects predominantly the composting scenarios, which now become better than before. Scenario Compost 2004 is now comparable to scenario Biogas long term. The difference between the biogas scenarios increases. Also for eutrophication, the upstream system and power supply are heavily decreased. These activities only contribute with a small part of the total impact (the core system dominates), no major changes are observed on the total level. Formation of photochemical-oxidants decreases to approximately 1/3 of the original value for the upstream system and almost disappears for power supply. On the total, scenario Compost long term becomes somewhat lower than scenario Biogas long term.

Consumption of primary energy carriers decreases for all scenarios but less for the reference scenario and the biogas scenarios (100 TJ) and more for the compost scenarios (200 TJ). There is no shift in order between the scenarios.

### 4.3.6 Heat generation from natural gas instead of coal

The last sensitivity analysis is a change of fuel from coal to natural gas for compensatory heat. As the scenarios to a larger and larger extent include compensatory heat, the impact of fuel change affects the scenarios in correspondence to that. The biogas scenarios are somewhat less favourable compared to the reference scenario and scenario Composting long term is most affected. For eutrophication, no changes can be observed because

district heating constitutes such a small part of the total impact in each scenario. The changes are however never so large that the order between the scenarios is changed.

# 5 References


1999/31/EU directive of April 26, on the landfilling of waste, 1999.

2000/76/EU directive of December 4, on the incineration of waste, 2000.

Björklund, A., 1998, Environmental Systems Analysis Waste Management with Emphasis on Substance Flows and Environmental Impact, Licentiate Thesis, Royal Institute of Technology, Department of Chemical Engineering And Technology, Industrial Ecology, Stockholm, Sweden

Björklund, A., 2000, Environmental Systems Analysis of Waste Management. Experiences from Applications of the ORWARE Model, Doctoral Thesis, Department of Chemical Engineering and Technology, Division of Industrial Ecology, Royal Institute of Technology, Stockholm, Sweden

Buhre M, Eriksson Å, (1997). Livscykelanalys för kolkraft, Examensarbete vid Vattenfall Energisystem AB

Dalemo, M., 1996, The Modelling of an Anaerobic Digestion Plant and a Sewage Plant in the ORWARE Simulation Model, Report 213, Department of Agricultural Engineering, SLU, Sweden

Dalemo, M., 1999, Environmental Systems Analysis of Organic Waste Management The ORWARE model and the sewage plant and anaerobic digestion submodels, AGRARIA 146, Doctoral Thesis, SLU, Sweden

Dalemo, M., Sonesson, U., Björklund, A., Mingarini, K., Frostell, B., Jönsson, H., Nybrant, T., Sundqvist, J. -O., Thyselius, L., 1997, ORWARE – A Simulation Tool for Organic Waste Handling Systems. Part 1: Model Description, Resources Conservation and Recycling 21 (1997) 17 – 37

Dalemo, M., Sonesson, U., Jönsson, H., Björklund, A., 1998, Effects of Including Nitrogen Emissions in Environmental Systems Analysis of Waste Management Strategies, Resources Conservation and Recycling 24 (1998) 363-381)

Davies, J., Haglund, C., 1999, Life Cycle Inventory (LCI) of Fertiliser Production – Fertiliser Products Used in Sweden and Western Europe, SIK-report No 654 1999, SIK The Swedish Institute for food and biotechnology, Gothenburg, Sweden

Environmental management – Life Cycle Assessment – Life Cycle Impact Assessment ISO 14042:2000, European standard, European Committee for standardisation, Brussels, Belgium

Environmental management – Life Cycle Assessment – Principles and Framework ISO 14040:1997 European standard, European Committee for standardisation, Brussels, Belgium

Eriksson, O., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J.-O., Granath, J., Carlsson, M., Baky, A., Thyselius, L., 2002, ORWARE – a Simulation Tool for Waste Management, Resources Conservation and Recycling, No 36/ 4 (2002) pp. 287 – 307, Elsevier
Fliedner, A., 1999, Organic Waste Treatment in Biocells - A Computer-based Model-ling Approach In the Context of Environmental Systems Analysis, examensarbete, Avd. för Mark- och vattenresurser och Avd. för Industriellt Miljöskydd, KTH, Stockholm, Sverige (TRITA KET-IM 1999:5)

Gunnarsdotter Beck-Friis, B., 2001, Emissions of Ammonia, Nitrous Oxide and Methane during Composting of Organic Household Waste, Agraria 266, Doctoral Thesis, SLU, Sweden

Hyldebrandt-Larsen, M., 2002, Pers. comm. Danish EPA

Jeppsen, S-E., 2002, Pers. comm. Danish EPA

Nybrant, T., Jönsson, H., Sonesson, U., Frostell, B., Sundqvist, J.-O., Mingarini, K., Thyselius, L., Dalemo, M., 1995, ORWARE ett Verktyg att Jämföra Hanteringssystem för Organiskt Avfall, AFR-report 75, Swedish waste researh council now Swedish Environmental Protection Agency , Stockholm, Sweden

Sonesson, U., 1996, Modelling of the Compost and Transport Process in the ORWARE Simulation Model, Report 214, Swedish University of Agricultural Sciences (SLU), Department of Agricultural Engineering, Uppsala Sweden

Sonesson, U., 1998, Systems Analysis of Waste Management – The ORWARE Model, Transport and Compost Sub-models, Agraria 130, Doctoral Thesis, Swedish University of Agricultural Sciences, Uppsala Sweden

Sonesson, U., Jönsson, H., 1996, Urban Biodegradable Waste Amount and Composition – Case Study Uppsala, Report 201, Department of Agricultural Engineering, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden

Sundqvist, J-O., Baky, A., Björklund, A., Carlsson, M., Eriksson, O., Frostell, B., Granath, J., Thyselius, L., 1999, Systemanalys av energiutnyttjande från avfall . utvärdering av energi, miljö och ekonomi. Fallstudie Uppsala, IVL Rapport 1380.

Sundqvist, J-O., Baky, A., Björklund, A., Carlsson Reich, M., Eriksson, O., Granath, J., Thyselius, L., 2002, .Hur ska hushållsavfallet tas om hand? Utvärdering av olika behandlingsmetoder. IVL Rapport B 1462. Stockholm, Sweden

Uppenberg, S., Brandel, M., Lindfors, L.-G., Marcus, H.-O., Wachtmeister, A., Zetterberg, L., 1999, Miljöfaktabok för bränslen, Institutet för vatten- och Luftvårdsforskning, Stockholm, Sverige (IVL-rapport B 1334)

Uppenberg, S., Lindfors, L.-G., 1999, EPD Produktspecifika utgångspunkter för drivmedel, PSR 1999:6, finns på hemsidan; http://www.smsstandard.se/pdf/epd/psr9906.pdf

Valkeinen, T., 2002, Pers. comm. Danish, VAPO, Finland

Wester, L., 1993, Tabeller och Diagram för energitekniska beräkningar

Åberg, A., 1998, Borlänge Energi, personlig kommunikation

# Environmental impact assessment

## Global Warming Potential

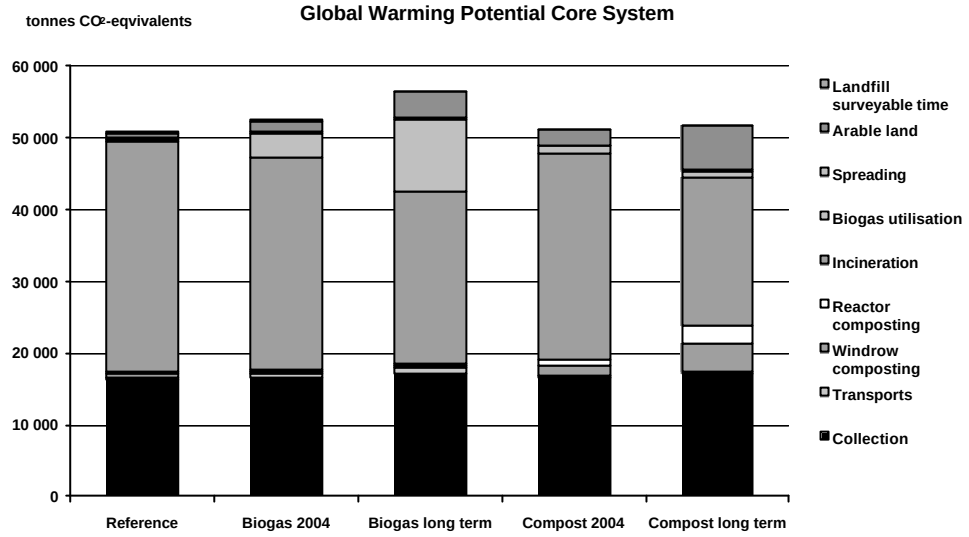


Figure A1. Global warming potential (GWP) for core system.

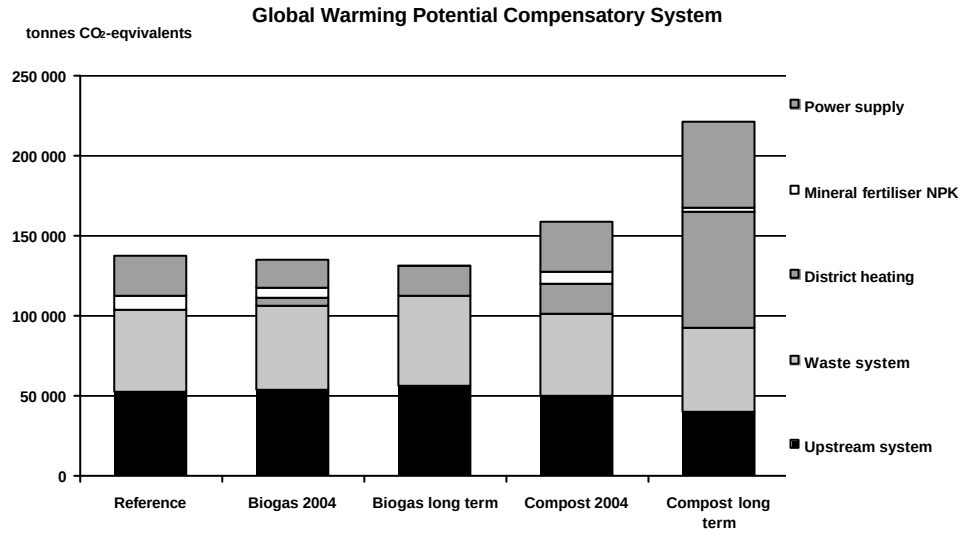


Figure A2. Global warming potentials (GWP) for compensatory system.

## Acidification potential

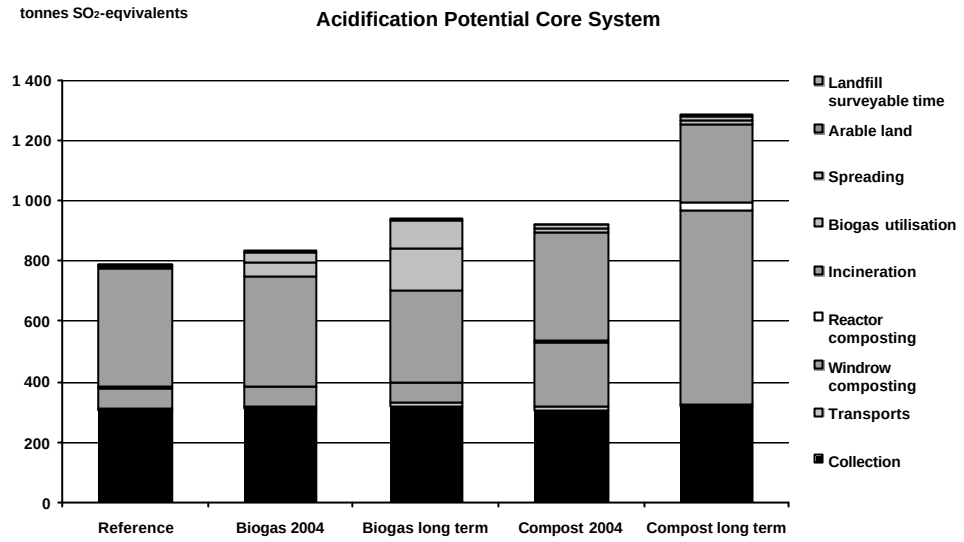


Figure A3. Acidification potentials (AP) for core system.

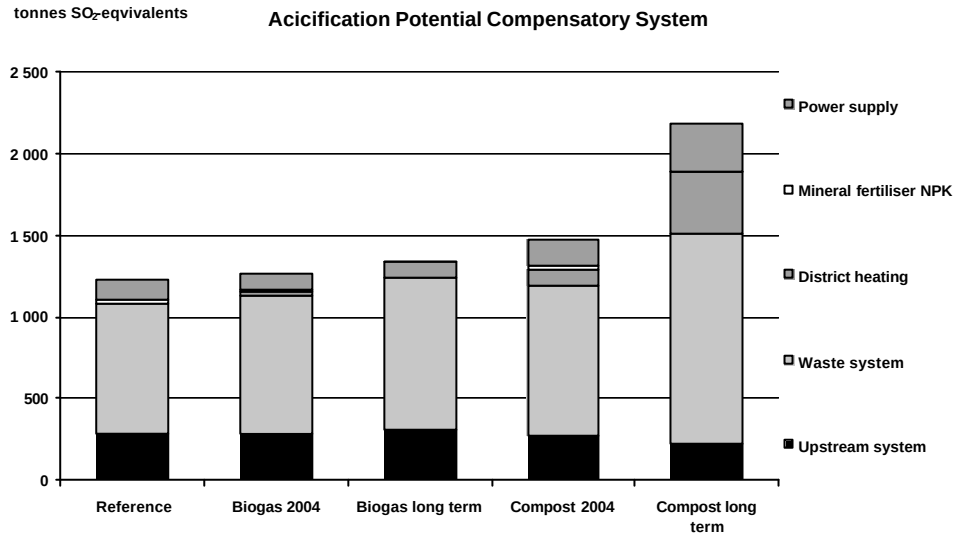


Figure A4. Acidification potentials (AP) for compensatory system.

## Eutrophication Potential

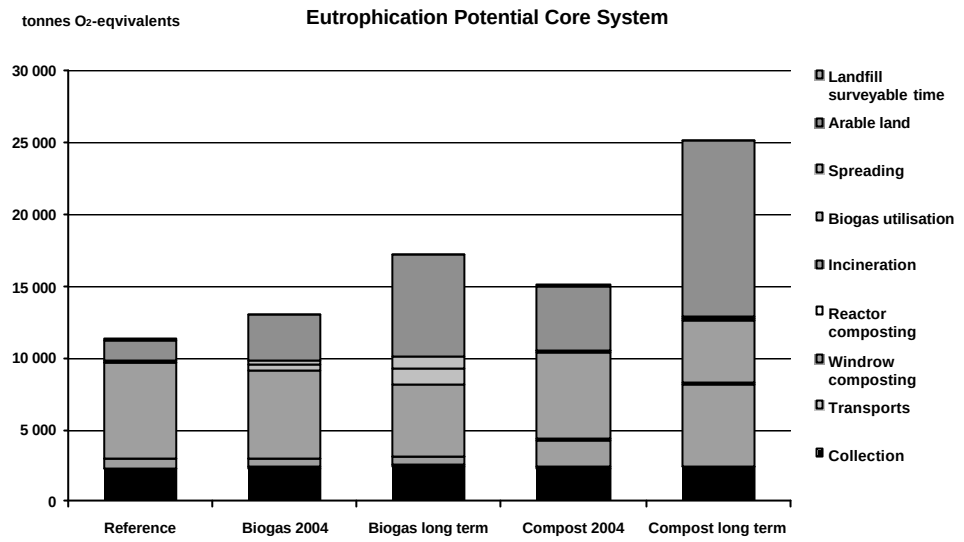


Figure A5. Eutrophication potentials (EP) for core system.

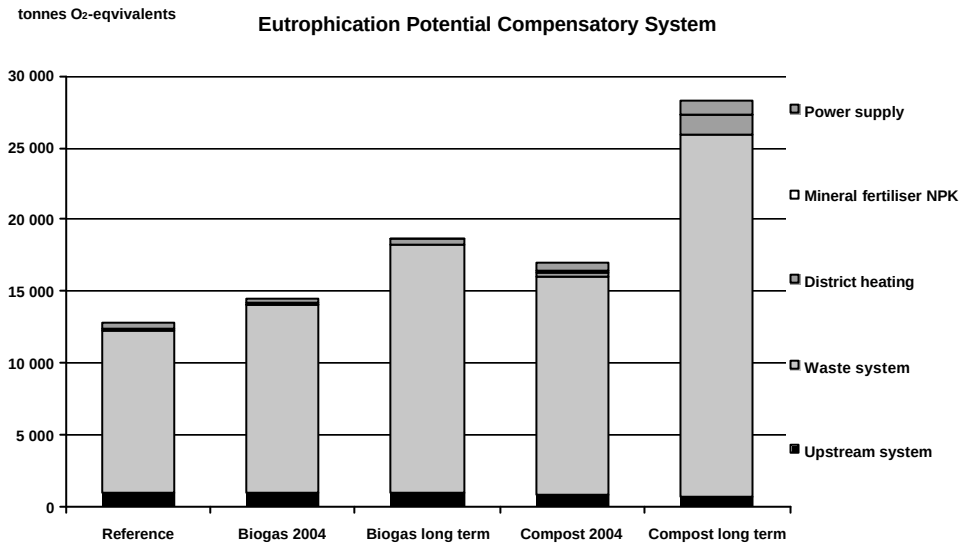


Figure A6. Eutrophication potentials (EP) for compensatory system.

## Formation of Photochemical Oxidants

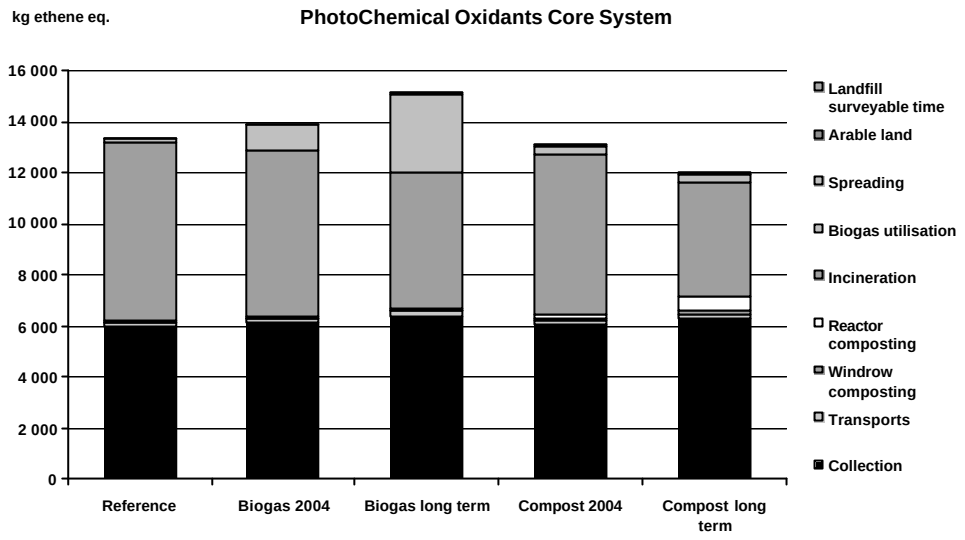


Figure A7. Photochemical oxidants (VOC-$NO_x$) for core and compensatory system.

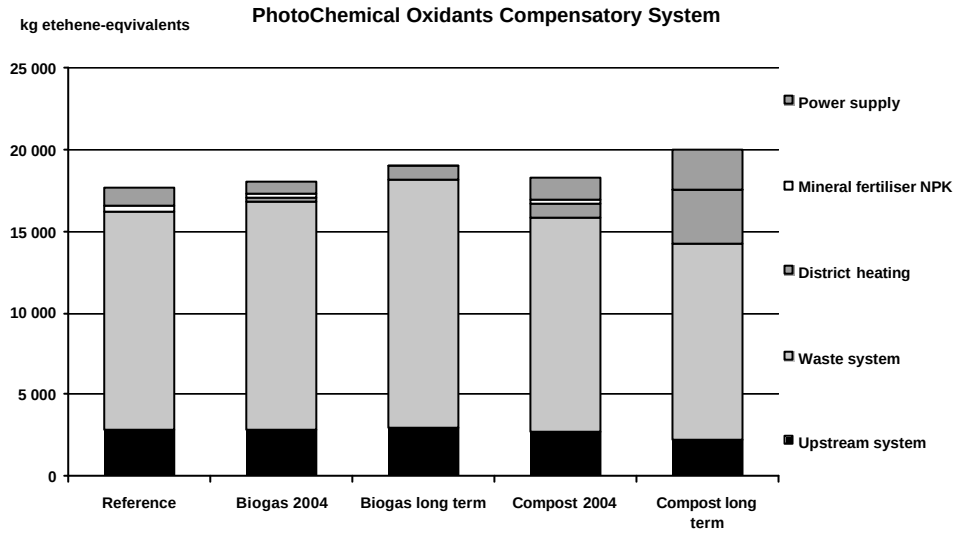


Figure A8. Photochemical oxidants (VOC-$NO_x$) for core and compensatory system.

## Consumption of primary energy carriers

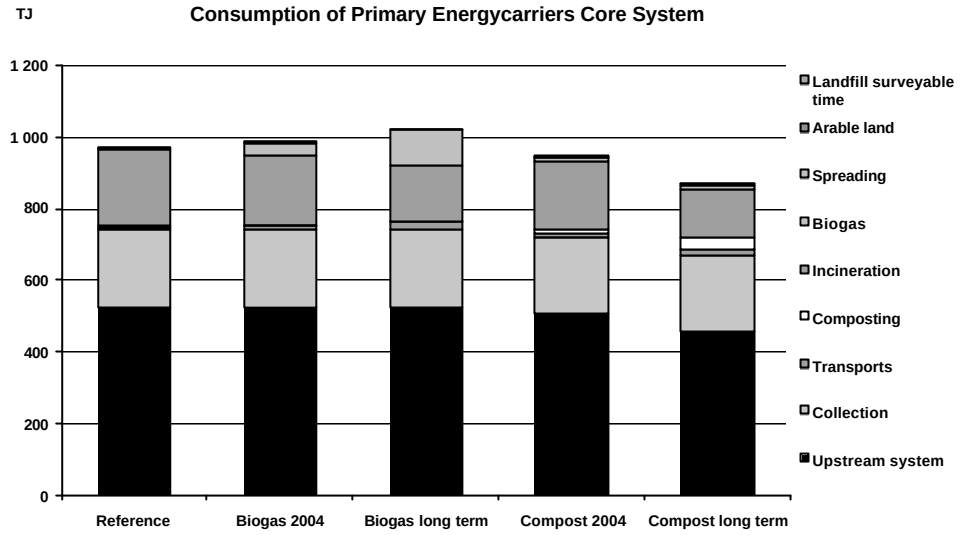


Figure A9. Consumption of primary energy carriers in the waste system, distributed to different processes.

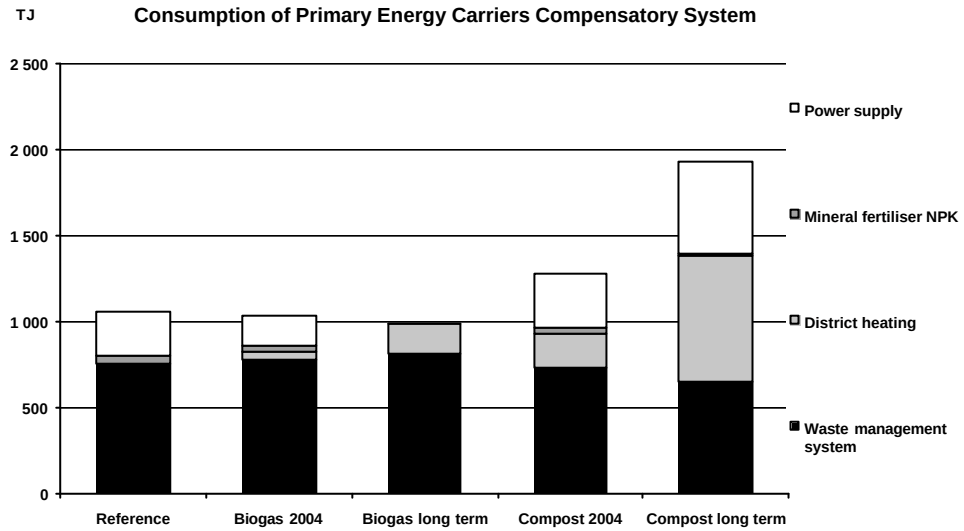


Figure A10. Consumption of primary energy carriers in the total system, distributed amongst processes.

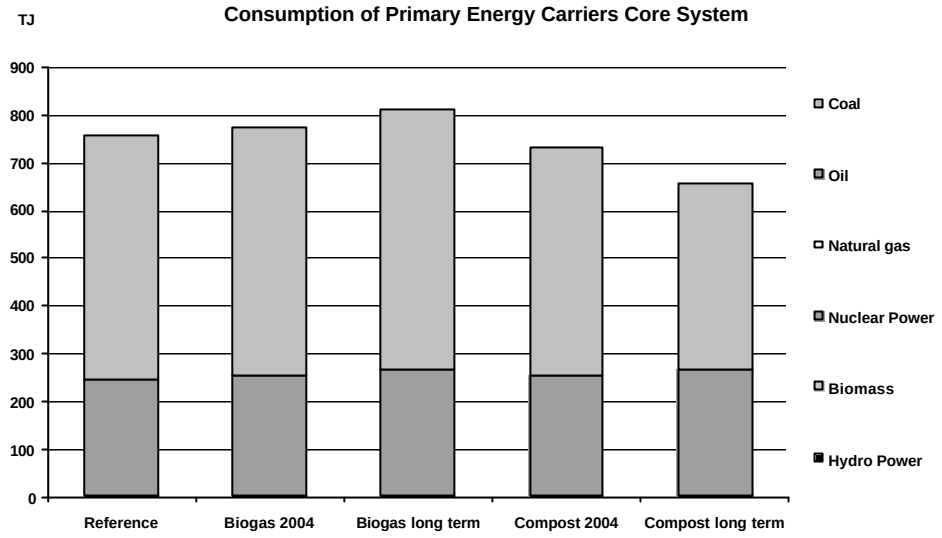


Figure A11. Use of primary energy carriers in the core system.

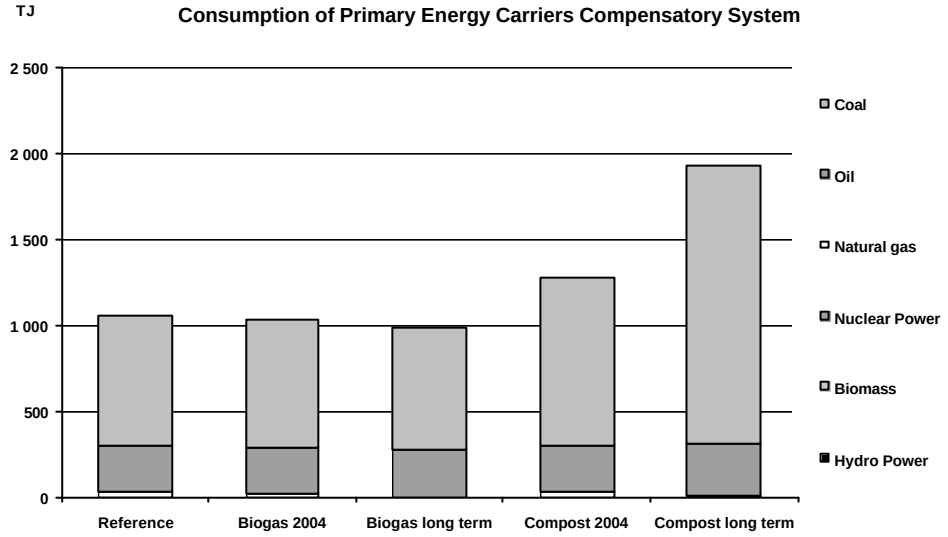


Figure A12. Use of primary energy carriers in the compensatory system.

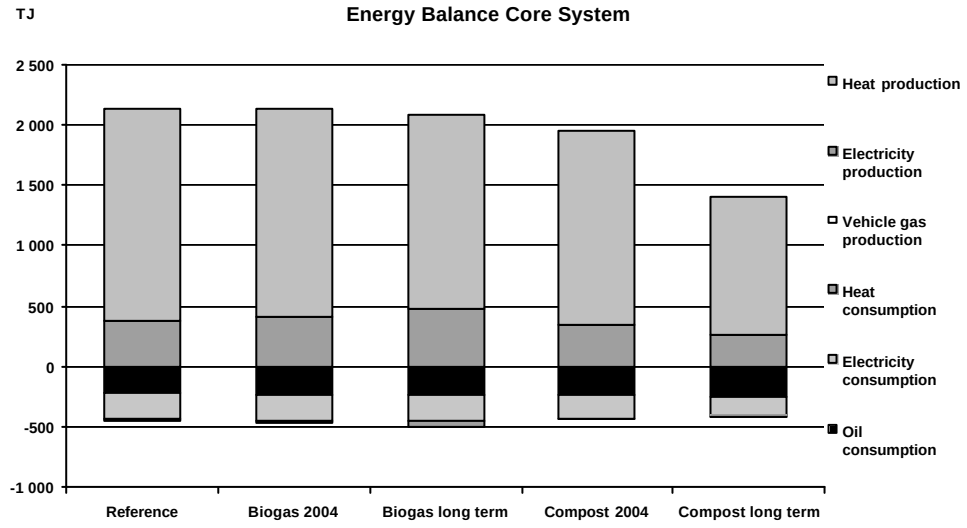


Figure A13. Energy balance for the waste system.

# Emissions from the processes

## Emissions from core system

### Emissions from collection and transportation of wastes

Emissions presented in Table B1 show the total emissions from collection of organic household waste. Collection of organic waste includes following modes of transportation:

- Organic waste from households, collection with collection trucks
- Organic waste from households to anaerobic digestion (60 %), transported with ordinary truck
- Organic waste from households to composting using ordinary truck
- Organic waste from households to anaerobic digestion (40%), transported with truck and trailer

Table B1. Emissions originating from collection of organic waste from households expressed as kg per year.

| Emissio | Reference | Biogas | Biogas long | Compost | Compost long |
|---|---|---|---|---|---|
| $NO_x$ | 375 161 | 381 699 | 397 214 | 380 958 | 394 356 |
| $N_2O$ | 880 | 896 | 932 | 894 | 925 |
| $SO_x$ | 38 353 | 39 022 | 40 608 | 38 946 | 40 316 |
| CO | 62 | 64 | 66 | 63 | 66 |
| VOC | 14 218 | 14 464 | 15 046 | 14 437 | 14 945 |
| $CO_{2\ (fossil)}$ | 15 942 038 | 16 219 842 | 16 879 138 | 16 188 360 | 16 757 709 |
| $CO_{2\ (bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CH_4$ | 215 | 219 | 228 | 219 | 226 |
| Particles | 2 801 | 2 849 | 2 965 | 2 844 | 2 944 |

Transportation of wastes after collection includes the following modes of transportation using truck and trailer:

- Ash from incineration to landfill
- Slag from incineration to landfill
- Digestion residue from anaerobic digester to arable land
- Compost from compost plant to arable land

Table B2. Emissions from Transportation of primary and secondary wastes expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 9 136 | 10 780 | 14 565 | 8 881 | 7 243 |
| $N_2O$ | 21 | 25 | 34 | 21 | 17 |
| $SO_x$ | 934 | 1 102 | 1 489 | 908 | 740 |
| CO | 2 | 2 | 2 | 1 | 1 |
| VOC | 341 | 402 | 544 | 332 | 270 |
| $CO_{2\ (fossil)}$ | 388 206 | 458 074 | 618 939 | 377 405 | 307 789 |
| $CO_{2\ (bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CH_4$ | 5 | 6 | 8 | 5 | 4 |
| Particles | 68 | 80 | 109 | 66 | 54 |

### Emissions from Waste incineration

Emissions from incineration of waste consist of emissions related to the actual incineration plant. Emissions related to use of up-stream electricity are presented under up-stream emission (Appendix D).

Table B3 Emissions from waste incineration plant expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 497 801 | 463 251 | 379 944 | 447 869 | 320 614 |
| $N_2O$ | 103 380 | 95 728 | 77 319 | 92 915 | 66 468 |
| $SO_x$ | 42 589 | 39 437 | 31 853 | 38 278 | 27 383 |
| CO | 996 | 923 | 745 | 895 | 641 |
| VOC | 0 | 0 | 0 | 0 | 0 |
| $CO_{2\ (fossil)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2\ (bio)}$ | 317 240 257 | 293 760 133 | 237 267 800 | 285 127 150 | 203 969 150 |
| $CH_4$ | 0 | 0 | 0 | 0 | 0 |
| Dioxin | 6.65E-05 | 6.11E-05 | 4.80E-05 | 5.97E-05 | 4.26E-05 |
| $NH_3$ | 0.0052 | 0.0049 | 0.0039 | 0.0047 | 0.0034 |
| S-tot (aq) | 13 375 | 12 385 | 10 002 | 12 021 | 8 599 |
| P-tot (aq) | 22 142 | 20 502 | 16 556 | 19 901 | 14 236 |
| K-tot (aq) | 908 138 | 840 880 | 679 062 | 816 202 | 583 875 |
| Pb | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Cd | 0 | 0 | 0 | 0 | 0 |
| Hg | 0.18 | 0.17 | 0.14 | 0.17 | 0.12 |
| Cu | 0.07 | 0.07 | 0.05 | 0.06 | 0.05 |
| Cr | 1.09 | 1.01 | 0.81 | 0.98 | 0.70 |
| Ni | 1.94 | 1.80 | 1.44 | 1.75 | 1.25 |
| Zn | 0.48 | 0.44 | 0.36 | 0.43 | 0.31 |
| Pb (aq) | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 |
| Cd (aq) | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 |
| Hg (aq) | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 |
| Cu (aq) | 0.29 | 0.27 | 0.21 | 0.26 | 0.18 |
| Cr (aq) | 0.55 | 0.50 | 0.41 | 0.49 | 0.35 |
| Ni (aq) | 1.11 | 1.03 | 0.83 | 1.00 | 0.71 |
| Zn (aq) | 2.24 | 2.07 | 1.67 | 2.01 | 1.44 |

### Anaerobic digestion

Emissions from energy input to anaerobic digestion plant and utilisation of biogas for generation of electricity and heat, see up-stream processes for electricity and heat generation (Appendix D).

Table B4. Emissions from anaerobic digestion plant and utilisation of biogas expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 8 141 | 58 153 | 174 459 | 17 446 | 17 446 |
| $N_2O$ | 779 | 5 562 | 16 687 | 1 669 | 1 669 |
| $SO_x$ | 793 | 5 665 | 16 996 | 793 | 1 700 |
| CO | 6 195 | 44 247 | 132 741 | 13 274 | 13 274 |
| VOC | 10 754 | 76 813 | 230 438 | 23 044 | 23 044 |
| $CO_{2\ (fossil)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2\ (bio)}$ | 2 225 087 | 15 893 475 | 47 680 426 | 4 768 043 | 4 768 043 |
| $CH_4$ | 10 655 | 76 105 | 228 314 | 22 831 | 22 831 |

### Composting

Emissions from composting are divided into windrow and reactor composting. Each type of compost process has two tables, emissions from the microbial processes in the compost and emissions from maintenance of compost e.g. use of diesel. For upstream emissions showing use of electricity and manufacturing of diesel for management, see Appendix D.

Table B5. Emissions from microbial activity during compost process expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long |
|---|---|---|---|---|---|
| Windrow | | | | | |
| $NH_3$ | 36 311 | 34 042 | 34 042 | 113 472 | 340 416 |
| $N_2O$ | 240 | 225 | 225 | 749 | 2 248 |
| VOC | 6 | 6 | 6 | 19 | 57 |
| $CO_{2\ (fossil)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2\ (bio)}$ | 4 585 240 | 4 298 663 | 4 298 663 | 14 328 875 | 42 986 625 |
| $CH_4$ | 16 048 | 15 045 | 15 045 | 50 151 | 150 453 |
| Reactor compost | | | | | |
| $NH_3$ | 363 | 340 | 340 | 1 135 | 3 404 |
| $N_2O$ | 24 | 22 | 22 | 75 | 225 |
| VOC | 6 | 6 | 6 | 19 | 57 |
| $CO_{2\ (fossil)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2\ (bio)}$ | 4 585 240 | 4 298 663 | 4 298 663 | 14 328 875 | 42 986 625 |
| $CH_4$ | 8 024 | 7 523 | 7 523 | 25 076 | 75 227 |

Table B6. Emissions from compost management expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long |
|---|---|---|---|---|---|
| Windrow | | | | | |
| $NO_x$ | 608 | 570 | 570 | 1 900 | 608 |
| $N_2O$ | 1 | 1 | 1 | 3 | 8 |
| $SO_x$ | 36 | 34 | 34 | 113 | 340 |
| CO | 67 | 63 | 63 | 210 | 631 |

| | | | | | |
|---|---|---|---|---|---|
| VOC | 24 | 23 | 23 | 76 | 230 |
| $CO_{2\ (fossil)}$ | 15 096 | 14 153 | 14 153 | 47 175 | 141 525 |
| $CO_{2\ (bio)}$ | 0 | 0 | 0 | 0 | 0 |
| Particles | 3 | 2 | 2 | 8 | 25 |
| Reactor compost | | | | | |
| $NO_x$ | 3 060 | 2 869 | 2 869 | 9 563 | 3 060 |
| $N_2O$ | 4 | 4 | 4 | 13 | 38 |
| $SO_x$ | 183 | 171 | 171 | 571 | 1 714 |
| CO | 339 | 318 | 318 | 1 059 | 3 177 |
| VOC | 123 | 116 | 116 | 385 | 1 155 |
| $CO_{2\ (fossil)}$ | 75 983 | 71 234 | 71 234 | 237 448 | 712 342 |
| $CO_{2\ (bio)}$ | 0 | 0 | 0 | 0 | 0 |
| Particles | 13 | 13 | 13 | 42 | 125 |

### Landfill of ash and slag from incineration of waste

Emissions from landfills for waste are expressed as emissions from landfill site during surveyable time (Table B7) and emissions from management of landfill (Table B8).

Table B7. Total potential emissions from landfilling of waste during one year during surveyable time expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NH_3$ | 0 | 0 | 0 | 0 | 0 |
| $N_2O$ | 0 | 22 | 22 | 75 | 225 |
| VOC | 14 096 | 122 | 82 | 72 | 88 |
| $CO_{2\ (fossil)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2\ (bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CH_4$ | 0 | 0 | 0 | 0 | 0 |
| $SO_x$ | 20 450 | 18 937 | 15 294 | 18 380 | 13 149 |
| S-tot (aq) | 8 729 | 8 083 | 6 528 | 7 846 | 5 613 |
| Pb | 0 | 0 | 0 | 0 | 0 |
| Cd | 0 | 0 | 0 | 0 | 0 |
| Hg | 5.41E-04 | 5.01E-04 | 4.04E-04 | 4.86E-04 | 3.48E-04 |
| Cu | 0 | 0 | 0 | 0 | 0 |
| Cr | 0 | 0 | 0 | 0 | 0 |
| Ni | 0 | 0 | 0 | 0 | 0 |
| Zn | 0 | 0 | 0 | 0 | 0 |
| Pb (aq) | 6.32E-03 | 5.83E-03 | 4.67E-03 | 5.67E-03 | 4.06E-03 |
| Cd (aq) | 2.13E-01 | 1.97E-01 | 1.59E-01 | 1.91E-01 | 1.37E-01 |
| Hg (aq) | 8.19E-04 | 7.58E-04 | 6.12E-04 | 7.36E-04 | 5.26E-04 |
| Cu (aq) | 34 | 32 | 25 | 31 | 22 |
| Cr (aq) | 1.15E-02 | 1.06E-02 | 8.55E-03 | 1.03E-02 | 7.38E-03 |
| Ni (aq) | 1.29E-02 | 1.19E-02 | 9.61E-03 | 1.16E-02 | 8.30E-03 |
| Zn (aq) | 6.75E-01 | 6.25E-01 | 5.04E-01 | 6.07E-01 | 4.34E-01 |

Table B8. Emissions from management of landfill expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 1 822 | 2 779 | 2 542 | 6 666 | 17 534 |
| $N_2O$ | 4.28 | 6.52 | 5.96 | 15.64 | 41.14 |
| $SO_x$ | 186 | 284 | 260 | 682 | 1 793 |
| CO | 0.30 | 0.46 | 0.42 | 1.11 | 2.92 |
| VOC | 69 | 105 | 96 | 253 | 665 |
| $CO_{2\ (fossil)}$ | 77 431 | 118 108 | 108 001 | 283 278 | 745 085 |

| | | | | | |
|---|---|---|---|---|---|
| $CO_{2\ (bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CH_4$ | 1.05 | 1.60 | 1.46 | 3.83 | 10.07 |
| Particles | 14 | 21 | 19 | 50 | 131 |

### Spreading of compost and anaerobic sludge and emissions from arable land

Table B9. Emissions from spreading of organic residues on arable land and nitrogen turnover expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 366 | 1 855 | 5 338 | 903 | 1 664 |
| $N_2O$ | 1 474 | 4 225 | 10 771 | 4 155 | 10 500 |
| $SO_x$ | 37 | 190 | 546 | 92 | 170 |
| CO | 0.06 | 0.31 | 0.89 | 0.15 | 0.28 |
| VOC | 14 | 69 | 199 | 34 | 62 |
| $CO_{2\ (fossil)}$ | 15 533 | 78 846 | 226 837 | 38 367 | 70 705 |
| $CO_{2\ (bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CH_4$ | 0.21 | 1.07 | 3.07 | 0.52 | 0.96 |
| $NH_3$ | 2 494 | 16 639 | 49 560 | 5 531 | 6 716 |
| Particles | 2.73 | 13.85 | 39.85 | 6.74 | 12.42 |
| $NO_3$ (aq) | 199 112 | 570 652 | 1 454 644 | 561 451 | 1 419 157 |
| Pb (so) | 106 | 254 | 609 | 308 | 818 |
| Cd (so) | 1 | 3 | 8 | 4 | 11 |
| Hg (so) | 0.3 | 1 | 2 | 1 | 2 |
| Cu (so) | 362 | 864 | 2 071 | 1 048 | 2 782 |
| Cr (so) | 106 | 254 | 609 | 308 | 818 |
| Ni (so) | 75 | 178 | 426 | 216 | 573 |
| Zn (so) | 852 | 2 032 | 4 872 | 2 466 | 6 546 |

## Emissions from up-and down-stream system

### Electricity generation for core system

Table B10. Emissions from utilisation of electricity for incineration in core system expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 223 307 | 205 071 | 161 331 | 200 360 | 143 163 |
| $SO_x$ | 134 166 | 123 210 | 96 930 | 120 379 | 86 014 |
| CO | 1 081 | 993 | 781 | 970 | 693 |
| Particles | 3 950 | 3 628 | 2 854 | 3 544 | 2 533 |
| VOC | 582 | 534 | 420 | 522 | 373 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 21 875 552 | 20 089 120 | 15 804 320 | 19 627 680 | 14 024 480 |
| $CH_4$ | 19 030 | 17 476 | 13 748 | 17 074 | 12 200 |
| $N_2O$ | 3.5.E-01 | 3.2.E-01 | 2.6.E-01 | 3.2.E-01 | 2.3.E-01 |
| Pb | 5.8.E-01 | 5.3.E-01 | 4.2.E-01 | 5.2.E-01 | 3.7.E-01 |
| Cd | 1.5.E-03 | 1.4.E-03 | 1.1.E-03 | 1.4.E-03 | 9.9.E-04 |
| Hg | 8 | 8 | 6 | 8 | 5 |
| Cu | 6.1.E-01 | 5.6.E-01 | 4.4.E-01 | 5.5.E-01 | 3.9.E-01 |
| Cr | 4.5.E-01 | 4.1.E-01 | 3.2.E-01 | 4.0.E-01 | 2.9.E-01 |
| Ni | 5.1.E-01 | 4.6.E-01 | 3.7.E-01 | 4.5.E-01 | 3.2.E-01 |
| Zn | 7.5.E-01 | 6.9.E-01 | 5.4.E-01 | 6.8.E-01 | 4.8.E-01 |
| Pb (aq) | 6.84E-09 | 6.28E-09 | 4.94E-09 | 6.14E-09 | 4.38E-09 |
| Cd (aq) | 7.28E-10 | 6.69E-10 | 5.26E-10 | 6.54E-10 | 4.67E-10 |
| Hg (aq) | 8.35E-09 | 7.67E-09 | 6.03E-09 | 7.49E-09 | 5.35E-09 |
| Cu (aq) | 7.26E-09 | 6.67E-09 | 5.25E-09 | 6.52E-09 | 4.66E-09 |
| Cr (aq) | 1.07E-07 | 9.81E-08 | 7.72E-08 | 9.59E-08 | 6.85E-08 |
| Ni (aq) | 7.31E-07 | 6.71E-07 | 5.28E-07 | 6.56E-07 | 4.68E-07 |
| Zn (aq) | 2.29E-06 | 2.11E-06 | 1.66E-06 | 2.06E-06 | 1.47E-06 |

Table B11. Upstream emission for electricity utilised during anaerobic digestion expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 2 691 | 19 225 | 57 674 | 5 767 | 5 767 |
| $SO_x$ | 1 617 | 11 551 | 34 652 | 3 465 | 3 465 |
| CO | 13 | 93 | 279 | 28 | 28 |
| Particles | 48 | 340 | 1 020 | 102 | 102 |
| VOC | 7 | 50 | 150 | 15 | 15 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 263 662 | 1 883 297 | 5 649 891 | 564 989 | 564 989 |
| $CH_4$ | 229 | 1 638 | 4 915 | 491 | 491 |
| $N_2O$ | 4.26E-03 | 3.05E-02 | 9.14E-02 | 9.14E-03 | 9.14E-03 |
| Pb | 6.94E-03 | 4.96E-02 | 1.49E-01 | 1.49E-02 | 1.49E-02 |
| Cd | 1.87E-05 | 1.33E-04 | 4.00E-04 | 4.00E-05 | 4.00E-05 |
| Hg | 1.01E-01 | 7.20E-01 | 2.16 | 2.16E-01 | 2.16E-01 |
| Cu | 7.35E-03 | 5.25E-02 | 1.57E-01 | 1.57E-02 | 1.57E-02 |
| Cr | 5.38E-03 | 3.84E-02 | 1.15E-01 | 1.15E-02 | 1.15E-02 |
| Ni | 6.09E-03 | 4.35E-02 | 1.31E-01 | 1.31E-02 | 1.31E-02 |
| Zn | 9.09E-03 | 6.49E-02 | 1.95E-01 | 1.95E-02 | 1.95E-02 |
| Pb (aq) | 8.24E-11 | 5.89E-10 | 1.77E-09 | 1.77E-10 | 1.77E-10 |
| Cd (aq) | 8.78E-12 | 6.27E-11 | 1.88E-10 | 1.88E-11 | 1.88E-11 |
| Hg (aq) | 1.01E-10 | 7.19E-10 | 2.16E-09 | 2.16E-10 | 2.16E-10 |
| Cu (aq) | 8.75E-11 | 6.25E-10 | 1.88E-09 | 1.88E-10 | 1.88E-10 |
| Cr (aq) | 1.29E-09 | 9.20E-09 | 2.76E-08 | 2.76E-09 | 2.76E-09 |
| Ni (aq) | 8.81E-09 | 6.29E-08 | 1.89E-07 | 1.89E-08 | 1.89E-08 |
| Zn (aq) | 2.76E-08 | 1.97E-07 | 5.92E-07 | 5.92E-08 | 5.92E-08 |

No electricity is used during windrow composting, therefore no emission for upstream utilisation of electricity.

Table B12. Up-stream emission for electricity utilised during reactor composting expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 2 574 | 2 413 | 2 413 | 8 043 | 24 130 |
| $SO_x$ | 1 546 | 1 450 | 1 450 | 4 833 | 14 498 |
| CO | 12 | 12 | 12 | 39 | 117 |
| Particles | 46 | 43 | 43 | 142 | 427 |
| VOC | 7 | 6 | 6 | 21 | 63 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 252 144 | 236 385 | 236 385 | 787 950 | 2 363 850 |
| $CH_4$ | 219 | 206 | 206 | 685 | 2 056 |
| $N_2O$ | 4.08E-03 | 3.82E-03 | 3.82E-03 | 1.27E-02 | 3.82E-02 |
| Pb | 6.63E-03 | 6.22E-03 | 6.22E-03 | 2.07E-02 | 6.22E-02 |
| Cd | 1.78E-05 | 1.67E-05 | 1.67E-05 | 5.58E-05 | 1.67E-04 |
| Hg | 9.65E-02 | 9.04E-02 | 9.04E-02 | 3.01E-01 | 9.04E-01 |
| Cu | 7.03E-03 | 6.59E-03 | 6.59E-03 | 2.20E-02 | 6.59E-02 |
| Cr | 5.14E-03 | 4.82E-03 | 4.82E-03 | 1.61E-02 | 4.82E-02 |
| Ni | 5.83E-03 | 5.46E-03 | 5.46E-03 | 1.82E-02 | 5.46E-02 |
| Zn | 8.69E-03 | 8.15E-03 | 8.15E-03 | 2.72E-02 | 8.15E-02 |
| Pb (aq) | 7.88E-11 | 7.39E-11 | 7.39E-11 | 2.46E-10 | 7.39E-10 |
| Cd (aq) | 8.40E-12 | 7.87E-12 | 7.87E-12 | 2.62E-11 | 7.87E-11 |
| Hg (aq) | 9.62E-11 | 9.02E-11 | 9.02E-11 | 3.01E-10 | 9.02E-10 |
| Cu (aq) | 8.37E-11 | 7.85E-11 | 7.85E-11 | 2.62E-10 | 7.85E-10 |
| Cr (aq) | 1.23E-09 | 1.15E-09 | 1.15E-09 | 3.85E-09 | 1.15E-08 |
| Ni (aq) | 8.42E-09 | 7.89E-09 | 7.89E-09 | 2.63E-08 | 7.89E-08 |
| Zn (aq) | 2.64E-08 | 2.48E-08 | 2.48E-08 | 8.26E-08 | 2.48E-07 |

## *Appendix C*

## Heat generation for core system

Table B13. Upstream emission for heat utilised during anaerobic digestion expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 2 574 | 16 502 | 47 630 | 5 252 | 5 252 |
| $SO_x$ | 1 547 | 9 914 | 28 617 | 3 156 | 3 156 |
| CO | 12 | 80 | 231 | 25 | 25 |
| Particles | 46 | 292 | 843 | 93 | 93 |
| VOC | 7 | 43 | 124 | 14 | 14 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 252 186 | 1 616 529 | 4 665 974 | 514 527 | 514 527 |
| $CH_4$ | 219 | 1 406 | 4 059 | 448 | 448 |
| $N_2O$ | 0 | 0 | 0 | 0 | 0 |
| Pb | 0 | 0 | 0 | 0 | 0 |
| Cd | 0 | 0 | 0 | 0 | 0 |
| Hg | 0 | 1 | 2 | 0 | 0 |
| Cu | 0 | 0 | 0 | 0 | 0 |
| Cr | 0 | 0 | 0 | 0 | 0 |
| Ni | 0 | 0 | 0 | 0 | 0 |
| Zn | 0 | 0 | 0 | 0 | 0 |
| Pb (aq) | 7.88E-11 | 5.05E-10 | 1.46E-09 | 1.61E-10 | 1.61E-10 |
| Cd (aq) | 8.40E-12 | 5.38E-11 | 1.55E-10 | 1.71E-11 | 1.71E-11 |
| Hg (aq) | 9.62E-11 | 6.17E-10 | 1.78E-09 | 1.96E-10 | 1.96E-10 |
| Cu (aq) | 8.37E-11 | 5.37E-10 | 1.55E-09 | 1.71E-10 | 1.71E-10 |
| Cr (aq) | 1.23E-09 | 7.89E-09 | 2.28E-08 | 2.51E-09 | 2.51E-09 |
| Ni (aq) | 8.42E-09 | 5.40E-08 | 1.56E-07 | 1.72E-08 | 1.72E-08 |
| Zn (aq) | 2.64E-08 | 1.70E-07 | 4.89E-07 | 5.40E-08 | 5.40E-08 |

## Upstream emissions from utilisation of diesel for collection transports and management

Table B14. Upstream emission for diesel utilised during collection of waste expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 21 943 | 22 326 | 23 233 | 22 282 | 23 066 |
| $SO_x$ | 7 836 | 7 972 | 8 296 | 7 957 | 8 237 |
| CO | 431 | 438 | 456 | 438 | 453 |
| Particles | 215 | 219 | 228 | 219 | 226 |
| VOC | 7 540 | 7 672 | 7 983 | 7 657 | 7 926 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 754 015 | 767 155 | 798 338 | 765 666 | 792 594 |
| $CH_4$ | 431 | 438 | 456 | 438 | 453 |
| $N_2O$ | 0 | 0 | 0 | 0 | 0 |
| Pb | 0.79 | 0.81 | 0.84 | 0.81 | 0.83 |
| Cd | 0.19 | 0.20 | 0.21 | 0.20 | 0.20 |
| Hg | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 |
| Cu | 0 | 0 | 0 | 0 | 0 |
| Cr | 0.19 | 0.19 | 0.20 | 0.19 | 0.20 |
| Ni | 9.09 | 9.25 | 9.63 | 9.23 | 9.56 |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pb (aq) | 2.20 | 2.24 | 2.33 | 2.23 | 2.31 |
| Cd (aq) | 0.30 | 0.31 | 0.32 | 0.31 | 0.32 |
| Hg (aq) | 0 | 0 | 0 | 0 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| Cu (aq) | 1.38 | 1.40 | 1.46 | 1.40 | 1.45 |
| Cr (aq) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ni (aq) | 1.70 | 1.73 | 1.80 | 1.73 | 1.79 |
| Zn (aq) | 4.72 | 4.80 | 5.00 | 4.79 | 4.96 |

Table B15. Upstream emission for diesel utilised during transportation expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 534 | 631 | 852 | 519 | 424 |
| $SO_x$ | 191 | 225 | 304 | 185 | 151 |
| CO | 10 | 12 | 17 | 10 | 8 |
| Particles | 5 | 6 | 8 | 5 | 4 |
| VOC | 184 | 217 | 293 | 179 | 146 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 18 361 | 21 666 | 29 274 | 17 850 | 14 558 |
| $CH_4$ | 10 | 12 | 17 | 10 | 8 |
| $N_2O$ | 0 | 0 | 0 | 0 | 0 |
| Pb | 1.93E-02 | 2.28E-02 | 3.08E-02 | 1.88E-02 | 1.53E-02 |
| Cd | 4.72E-03 | 5.57E-03 | 7.53E-03 | 4.59E-03 | 3.74E-03 |
| Hg | 5.77E-04 | 6.81E-04 | 9.20E-04 | 5.61E-04 | 4.58E-04 |
| Cu | 0 | 0 | 0 | 0 | 0 |
| Cr | 4.65E-03 | 5.48E-03 | 7.41E-03 | 4.52E-03 | 3.69E-03 |
| Ni | 2.21E-01 | 2.61E-01 | 3.53E-01 | 2.15E-01 | 1.76E-01 |
| Zn | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Pb (aq) | 5.35E-02 | 6.31E-02 | 8.53E-02 | 5.20E-02 | 4.24E-02 |
| Cd (aq) | 7.34E-03 | 8.67E-03 | 1.17E-02 | 7.14E-03 | 5.82E-03 |
| Hg (aq) | 0 | 0 | 0 | 0 | 0 |
| Cu (aq) | 3.36E-02 | 3.97E-02 | 5.36E-02 | 3.27E-02 | 2.67E-02 |
| Cr (aq) | | | | | |
| Ni (aq) | 4.14E-02 | 4.89E-02 | 6.61E-02 | 4.03E-02 | 3.29E-02 |
| Zn (aq) | 4.72 | 4.80 | 5.00 | 4.79 | 4.96 |

Table B16. Upstream emission for diesel utilised during windrow compost management expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 21 | 19 | 19 | 65 | 195 |
| $SO_x$ | 7 | 7 | 7 | 23 | 70 |
| CO | 0.4 | 0.4 | 0.4 | 1.3 | 3.8 |
| Particles | 0.2 | 0.2 | 0.2 | 0.6 | 1.9 |
| VOC | 7 | 7 | 7 | 22 | 67 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 714 | 669 | 669 | 2 231 | 6 694 |
| $CH_4$ | 0.4 | 0.4 | 0.4 | 1.3 | 3.8 |
| $N_2O$ | 0 | 0 | 0 | 0 | 0 |
| Pb | 7.51E-04 | 7.04E-04 | 7.04E-04 | 2.35E-03 | 7.04E-03 |
| Cd | 1.84E-04 | 1.72E-04 | 1.72E-04 | 5.74E-04 | 1.72E-03 |
| Hg | 2.24E-05 | 2.10E-05 | 2.10E-05 | 7.01E-05 | 2.10E-04 |
| Cu | 0 | 0 | 0 | 0 | 0 |
| Cr | 1.81E-04 | 1.69E-04 | 1.69E-04 | 5.65E-04 | 1.69E-03 |
| Ni | 8.61E-03 | 8.07E-03 | 8.07E-03 | 2.69E-02 | 8.07E-02 |
| Zn | 0 | 0 | 0 | 0 | 0 |
| Pb (aq) | 2.08E-03 | 1.95E-03 | 1.95E-03 | 6.50E-03 | 1.95E-02 |
| Cd (aq) | 2.86E-04 | 2.68E-04 | 2.68E-04 | 8.92E-04 | 2.68E-03 |
| Hg (aq) | 0 | 0 | 0 | 0 | 0 |
| Cr (aq) | 0 | 0 | 0 | 0 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| Cu (aq) | 1.31E-03 | 1.23E-03 | 1.23E-03 | 4.09E-03 | 1.23E-02 |
| Ni (aq) | 1.61E-03 | 1.51E-03 | 1.51E-03 | 5.04E-03 | 1.51E-02 |
| Zn (aq) | 4.47E-03 | 4.19E-03 | 4.19E-03 | 1.40E-02 | 4.19E-02 |

Table B17. Upstream emission for diesel utilised during reactor compost management expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 105 | 98 | 98 | 327 | 981 |
| $SO_x$ | 37 | 35 | 35 | 117 | 350 |
| CO | 2 | 2 | 2 | 6 | 19 |
| Particles | 1 | 1 | 1 | 3 | 10 |
| VOC | 36 | 34 | 34 | 112 | 337 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 3 594 | 3 369 | 3 369 | 11 231 | 33 692 |
| $CH_4$ | 2 | 2 | 2 | 6 | 19 |
| $N_2O$ | 0 | 0 | 0 | 0 | 0 |
| Pb | 3.78E-03 | 3.54E-03 | 3.54E-03 | 1.18E-02 | 3.54E-02 |
| Cd | 9.24E-04 | 8.66E-04 | 8.66E-04 | 2.89E-03 | 8.66E-03 |
| Hg | 1.13E-04 | 1.06E-04 | 1.06E-04 | 3.53E-04 | 1.06E-03 |
| Cu | 0 | 0 | 0 | 0 | 0 |
| Cr | 9.10E-04 | 8.53E-04 | 8.53E-04 | 2.84E-03 | 8.53E-03 |
| Ni | 4.33E-02 | 4.06E-02 | 4.06E-02 | 1.35E-01 | 4.06E-01 |
| Zn | 0.E+00 | 0.E+00 | 0.E+00 | 0.E+00 | 0.E+00 |
| Pb (aq) | 1.05E-02 | 9.82E-03 | 9.82E-03 | 3.27E-02 | 9.82E-02 |
| Cd (aq) | 1.44E-03 | 1.35E-03 | 1.35E-03 | 4.49E-03 | 1.35E-02 |
| Hg (aq) | 0 | 0 | 0 | 0 | 0 |
| Cu (aq) | 6.58E-03 | 6.17E-03 | 6.17E-03 | 2.06E-02 | 6.17E-02 |
| Cr (aq) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Ni (aq) | 8.11E-03 | 7.60E-03 | 7.60E-03 | 2.53E-02 | 7.60E-02 |
| Zn (aq) | 2.25E-02 | 2.11E-02 | 2.11E-02 | 7.03E-02 | 2.11E-01 |

Table B18. Upstream emission for diesel utilised during landfill management expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 107 | 98 | 78 | 96 | 68 |
| $SO_x$ | 38 | 35 | 28 | 34 | 24 |
| CO | 2 | 2 | 2 | 2 | 1 |
| Particles | 1 | 1 | 1 | 1 | 1 |
| VOC | 37 | 34 | 27 | 33 | 23 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 3 662 | 3 371 | 2 671 | 3 287 | 2 350 |
| $CH_4$ | 2 | 2 | 2 | 2 | 1 |
| $N_2O$ | 0 | 0 | 0 | 0 | 0 |
| Pb | 3.85E-03 | 3.54E-03 | 2.81E-03 | 3.46E-03 | 2.47E-03 |
| Cd | 9.42E-04 | 8.67E-04 | 6.87E-04 | 8.45E-04 | 6.04E-04 |
| Hg | 1.15E-04 | 1.06E-04 | 8.39E-05 | 1.03E-04 | 7.38E-05 |
| Cu | 0 | 0 | 0 | 0 | 0 |
| Cr | 9.27E-04 | 8.53E-04 | 6.76E-04 | 8.32E-04 | 5.95E-04 |
| Ni | 4.42E-02 | 4.06E-02 | 3.22E-02 | 3.96E-02 | 2.83E-02 |
| Zn | 0 | 0 | 0 | 0 | 0 |
| Pb (aq) | 1.07E-02 | 9.82E-03 | 7.78E-03 | 9.58E-03 | 6.85E-03 |
| Cd (aq) | 1.46E-03 | 1.35E-03 | 1.07E-03 | 1.31E-03 | 9.40E-04 |
| Hg (aq) | 0 | 0 | 0 | 0 | 0 |
| Cu (aq) | 6.71E-03 | 6.17E-03 | 4.89E-03 | 6.02E-03 | 4.30E-03 |
| Cr (aq) | 0 | 0 | 0 | 0 | 0 |
| Ni (aq) | 8.27E-03 | 7.61E-03 | 6.03E-03 | 7.42E-03 | 5.30E-03 |
| Zn (aq) | 2.29E-02 | 2.11E-02 | 1.67E-02 | 2.06E-02 | 1.47E-02 |

## *Appendix C*

Table B19. Upstream emission for diesel utilised during spreading of organic fertilisers expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 21 | 109 | 312 | 53 | 97 |
| $SO_x$ | 8 | 39 | 111 | 19 | 35 |
| CO | 0 | 2 | 6 | 1 | 2 |
| Particles | 0 | 1 | 3 | 1 | 1 |
| VOC | 7 | 37 | 107 | 18 | 33 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 735 | 3 729 | 10 729 | 1 815 | 3 344 |
| $CH_4$ | 0 | 2 | 6 | 1 | 2 |
| $N_2O$ | 0 | 0 | 0 | 0 | 0 |
| Pb | 7.72E-04 | 3.92E-03 | 1.13E-02 | 1.91E-03 | 3.52E-03 |
| Cd | 1.89E-04 | 9.59E-04 | 2.76E-03 | 4.67E-04 | 8.60E-04 |
| Hg | 2.31E-05 | 1.17E-04 | 3.37E-04 | 5.70E-05 | 1.05E-04 |
| Cu | 0 | 0 | 0 | 0 | 0 |
| Cr | 1.86E-04 | 9.44E-04 | 2.72E-03 | 4.59E-04 | 8.47E-04 |
| Ni | 8.86E-03 | 4.50E-02 | 1.29E-01 | 2.19E-02 | 4.03E-02 |
| Zn | 0 | 0 | 0 | 0 | 0 |
| Pb (aq) | 2.14E-03 | 1.09E-02 | 3.13E-02 | 5.29E-03 | 9.75E-03 |
| Cd (aq) | 2.94E-04 | 1.49E-03 | 4.29E-03 | 7.26E-04 | 1.34E-03 |
| Hg (aq) | 0 | 0 | 0 | 0 | 0 |
| Cu (aq) | 1.35E-03 | 6.83E-03 | 1.96E-02 | 3.32E-03 | 6.12E-03 |
| Cr (aq) | 0 | 0 | 0 | 0 | 0 |
| Ni (aq) | 1.66E-03 | 8.42E-03 | 2.42E-02 | 4.10E-03 | 7.55E-03 |
| Zn (aq) | 4.60E-03 | 2.33E-02 | 6.71E-02 | 1.14E-02 | 2.09E-02 |

## Emissions from compensatory system

### Electrical power

Table B20. Emissions from electrical power generation expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 76 462 | 52 991 | 0 | 95 485 | 163 906 |
| $SO_x$ | 76 125 | 52 758 | 0 | 95 065 | 163 185 |
| CO | 1 217 | 844 | 0 | 1 520 | 2 609 |
| Particles | 4 434 | 3 073 | 0 | 5 538 | 9 506 |
| NMVOC | 22 063 | 15 291 | 0 | 27 552 | 47 295 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 24 693 632 | 17 113 751 | 0 | 30 837 463 | 52 934 322 |
| $CH_4$ | 21 407 | 14 836 | 0 | 26 734 | 45 890 |
| $N_2O$ | 0.25 | 0.18 | 0 | 0.32 | 0.54 |
| Pb | 0.65 | 0.45 | 0 | 0.81 | 1.39 |
| Hg | 0.04 | 0.03 | 0 | 0.05 | 0.08 |
| Cu | 0.68 | 0.47 | 0 | 0.86 | 1.47 |
| Cr | 0.50 | 0.35 | 0 | 0.63 | 1.08 |
| Ni | 0.57 | 0.39 | 0 | 0.71 | 1.22 |
| Zn | 0.85 | 0.59 | 0 | 1.06 | 1.82 |
| Pb (aq) | 0.0077 | 0.0053 | 0 | 0.010 | 0.02 |
| Cd (aq) | 0.00082 | 0.00057 | 0 | 0.001 | 0.002 |
| Hg (aq) | 0.0094 | 0.0065 | 0 | 0.012 | 0.02 |
| Cu (aq) | 0.0082 | 0.0057 | 0 | 0.010 | 0.02 |
| Ni (aq) | 0.82 | 0.57 | 0 | 1.03 | 1.76 |
| Zn (aq) | 2.59 | 1.79 | 0 | 3.23 | 5.55 |

## *Appendix C*

## District heating

Table B21. Emissions from heat generation in compensatory system expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 0 | 15 323 | 54 734 | 58 369 | 220 771 |
| $SO_x$ | 0 | 15 256 | 54 494 | 58 113 | 219 800 |
| CO | 0 | 244 | 871 | 929 | 3 515 |
| Particles | 0 | 889 | 3 174 | 3 385 | 12 803 |
| NMVOC | 0 | 4 421 | 15 794 | 16 842 | 63 703 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 0 | 4 948 611 | 17 676 736 | 18 850 668 | 71 298 958 |
| $CH_4$ | 0 | 4 290 | 15 324 | 16 342 | 61 811 |
| $N_2O$ | 0 | 3.24E-02 | 1.16E-01 | 1.23E-01 | 4.67E-01 |
| Pb | 0 | 1.30E-01 | 4.63E-01 | 4.94E-01 | 1.87E+00 |
| Hg | 0 | 7.44E-03 | 2.66E-02 | 2.84E-02 | 1.07E-01 |
| Cu | 0 | 1.37E-01 | 4.90E-01 | 5.23E-01 | 1.98E+00 |
| Cr | 0 | 1.01E-01 | 3.60E-01 | 3.84E-01 | 1.45E+00 |
| Ni | 0 | 1.14E-01 | 4.07E-01 | 4.34E-01 | 1.64E+00 |
| Zn | 0 | 1.70E-01 | 6.07E-01 | 6.47E-01 | 2.45E+00 |
| Pb (aq) | 0 | 1.54E-03 | 5.51E-03 | 5.88E-03 | 2.22E-02 |
| Cd (aq) | 0 | 1.64E-04 | 5.87E-04 | 6.26E-04 | 2.37E-03 |
| Hg (aq) | 0 | 1.88E-03 | 6.73E-03 | 7.17E-03 | 2.71E-02 |
| Cu (aq) | 0 | 1.64E-03 | 5.85E-03 | 6.24E-03 | 2.36E-02 |
| Ni (aq) | 0 | 1.65E-01 | 5.88E-01 | 6.27E-01 | 2.37E+00 |
| Zn (aq) | 0 | 5.19E-01 | 2 | 1.98E+00 | 7.5 |

## Mineral fertiliser, nitrogen

Table B22. Emissions from manufacturing nitrogen mineral fertilisers expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 4 816 | 3 384 | 0 | 1 438 | 1 438 |
| $SO_x$ | 4 347 | 3 054 | 0 | 3 391 | 1 298 |
| CO | 1 239 | 870 | 0 | 966 | 370 |
| PAH | 0 | 0 | 0 | 0 | 0 |
| NMVOC | 1 280 | 899 | 0 | 998 | 382 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 2 931 304 | 2 059 732 | 0 | 2 286 695 | 875 431 |
| $CH_4$ | 2 921 | 2 052 | 0 | 2 279 | 872 |
| $N_2O$ | 15 100 | 10 611 | 0 | 11 780 | 4 510 |
| Pb | 1.37 | 0.96 | 0 | 1.07 | 0.41 |
| Cd | 0.23 | 0.16 | 0 | 0.18 | 0.07 |
| Hg | 0.01 | 0.01 | 0 | 0.01 | 0.00 |
| Cu | 1.62 | 1.14 | 0 | 1.26 | 0.48 |
| Cr | 1.76 | 1.24 | 0 | 1.38 | 0.53 |
| Ni | 5.27 | 3.71 | 0 | 4.11 | 1.58 |
| Zn | 1.81 | 1.27 | 0 | 1.41 | 0.54 |

### Mineral fertiliser. phosphorus

Table B23. Emissions from manufacturing phosphorus mineral fertilisers expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 4 959 | 3 931 | 1 458 | 3 553 | 0 |
| $SO_x$ | 10 200 | 8 086 | 2 999 | 7 308 | 0 |
| CO | 1 150 | 911 | 338 | 824 | 0 |
| PAH | 0 | 0 | 0 | 0 | 0 |
| NMVOC | 1 755 | 1 392 | 516 | 1 258 | 0 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 833 091 | 660 398 | 244 906 | 596 904 | 0 |
| $CH_4$ | 1 536 | 1 218 | 452 | 1 101 | 0 |
| $N_2O$ | 78 | 62 | 23 | 56 | 0 |
| Pb | 0.25 | 0.20 | 0.07 | 0.18 | 0 |
| Cd | 0.12 | 0.10 | 0.04 | 0.09 | 0 |
| Hg | 0.02 | 0.01 | 0.01 | 0.01 | 0 |
| Cu | 0.30 | 0.24 | 0.09 | 0.21 | 0 |
| Cr | 0.06 | 0.05 | 0.02 | 0.04 | 0 |
| Ni | 2.69 | 2.13 | 0.79 | 1.92 | 0 |
| Zn | 0.27 | 0.21 | 0.08 | 0.19 | 0 |

### Mineral Fertiliser, Potassium

Table B24. Air emissions from manufacturing potassium mineral fertilisers expressed as kg per year.

| Emission | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| $NO_x$ | 457 | 362 | 134 | 327 | 0 |
| $SO_x$ | 684 | 542 | 201 | 490 | 0 |
| CO | 111 | 88 | 32 | 79 | 0 |
| PAH | 0 | 0 | 0 | 0 | 0 |
| NMVOC | 145 | 115 | 43 | 104 | 0 |
| $CO_{2(bio)}$ | 0 | 0 | 0 | 0 | 0 |
| $CO_{2(fossil)}$ | 88 043 | 69 792 | 25 882 | 63 082 | 0 |
| $CH_4$ | 119 | 94 | 35 | 85 | 0 |
| $N_2O$ | 7 | 6 | 2 | 5 | 0 |
| Pb | 0.017 | 0.013 | 0.005 | 0.012 | 0 |
| Cd | 0.008 | 0.006 | 0.002 | 0.006 | 0 |
| Hg | 0.001 | 0.001 | 0.000 | 0.001 | 0 |
| Cu | 0.022 | 0.018 | 0.007 | 0.016 | 0 |
| Cr | 0.004 | 0.003 | 0.001 | 0.003 | 0 |
| Ni | 179 | 142 | 53 | 128 | 0 |
| Zn | 0.020 | 0.016 | 0.006 | 0.014 | 0 |

# *Appendix C*

Emissions from mono-treatments

## Incineration

Table B25. Emissions from mono-treatment – incineration, kg per ton waste collected.

| Emission | Collectio | Transport | Treatmen | Spreadin | Up- |
|---|---|---|---|---|---|
| $CO_{2(fossil)}$ | 2.26E+01 | 5.54E-01 | 0 | 0 | 3.40E+01 |
| $CO_{2(bio)}$ | 0 | 0 | 4.77E+02 | 0 | 0 |
| $CH_4$ | 3.05E-04 | 7.49E-06 | 0 | 0 | 2.93E-02 |
| NMVOC | 2.01E-02 | 4.87E-04 | 0 | 0 | 1.19E-02 |
| CO | 8.85E-05 | 2.17E-06 | 1.50E-03 | 0 | 2.26E-03 |
| Dioxin | 0 | 0 | 1.00E-10 | 0 | 0 |
| Dioxin | 0 | 0 | 4.01E-11 | 0 | 0 |
| $NH_3$ | 0 | 0 | 1.38E-07 | 0 | 0 |
| $NO_x$ | 5.31E-01 | 1.30E-02 | 7.49E-01 | 0 | 3.68E-01 |
| $NO_3$ (aq) | 0 | 0 | 1.67E-03 | 0 | 0 |
| $N_2O$ | 1.25E-03 | 3.06E-05 | 1.56E-01 | 0 | 3.69E-06 |
| $SO_x$ | 5.43E-02 | 1.33E-03 | 6.41E-02 | 0 | 2.14E-01 |
| Pb | 0 | 0 | 1.92E-08 | 0 | 2.02E-06 |
| Cd | 0 | 0 | 1.42E-09 | 0 | 2.85E-07 |
| Hg | 0 | 0 | 2.78E-07 | 0 | 1.26E-05 |
| Cu | 0 | 0 | 1.08E-07 | 0 | 9.18E-07 |
| Cr | 0 | 0 | 1.64E-06 | 0 | 1.42E-05 |
| Ni | 0 | 0 | 2.93E-06 | 0 | 1.40E-05 |
| Zn | 0 | 0 | 7.23E-07 | 0 | 1.45E-06 |
| Particles | 3.97E-03 | 9.74E-05 | 2.49E-02 | 0 | 6.27E-03 |
| Pb (aq) | 0 | 0 | 4.07E-08 | 0 | 3.20E-06 |
| Cd (aq) | 1.48E-08 | 3.64E-10 | 3.55E-07 | 0 | 4.40E-07 |
| Hg (aq) | 0 | 0 | 9.64E-09 | 0 | 1.26E-14 |
| Cu (aq) | 0 | 0 | 5.18E-05 | 0 | 2.01E-06 |
| Cr (aq) | 0 | 0 | 8.38E-07 | 0 | 1.61E-13 |
| Ni (aq) | 0 | 0 | 1.69E-06 | 0 | 2.48E-06 |
| Zn (aq) | 1.24E-04 | 3.03E-06 | 4.38E-06 | 0 | 1.34E-05 |
| Pb (so) | 0 | 0 | 0 | 0 | 0 |
| Cd (so) | 0 | 0 | 0 | 0 | 0 |
| Hg (so) | 0 | 0 | 0 | 0 | 0 |
| Cu (so) | 0 | 0 | 0 | 0 | 0 |
| Cr (so) | 0 | 0 | 0 | 0 | 0 |
| Ni (so) | 0 | 0 | 0 | 0 | 0 |
| Zn (so) | 0 | 0 | 0 | 0 | 0 |

## Anaerobic digestion

Table B26. Emissions from mono-treatment – Anaerobic digestion, kg per ton wastes collected.

| Emissio | Collectio | Transport | Treatmen | Spreadin | Up- |
|---|---|---|---|---|---|
| $CO_{2(fossil)}$ | 2.59E+01 | 1.36E+00 | 0 | 7.40E-01 | 4.69E+01 |
| $CO_{2(bio)}$ | 0 | 0 | 3.54E+02 | 0 | 0 |
| $CH_4$ | 3.50E-04 | 1.84E-05 | 7.61E-01 | 1.00E-05 | 4.04E-02 |
| NMVOC | 2.31E-02 | 1.19E-03 | 7.68E-01 | 6.50E-04 | 1.45E-02 |
| CO | 1.01E-04 | 5.32E-06 | 4.43E-01 | 2.90E-06 | 3.01E-03 |
| Dioxine | 0 | 0 | 3.51E-11 | 0 | 0 |
| Dioxine | 0 | 0 | 1.40E-11 | 0 | 0 |
| $NH_3$ | 0 | 0 | 5.62E-08 | 1.65E-01 | 0 |
| $NO_x$ | 6.09E-01 | 3.20E-02 | 9.14E-01 | 1.74E-02 | 5.04E-01 |
| $NO_3$ (aq) | 0 | 0 | 6.80E-04 | 4.42E+00 | 0 |
| $N_2O$ | 1.43E-03 | 7.50E-05 | 1.19E-01 | 3.27E-02 | 1.70E-06 |
| $SO_x$ | 6.22E-02 | 3.27E-03 | 8.28E-02 | 1.78E-03 | 2.93E-01 |
| Pb | 0 | 0 | 7.38E-09 | 0 | 2.59E-06 |
| Cd | 0 | 0 | 5.73E-10 | 0 | 3.44E-07 |
| Hg | 0 | 0 | 1.13E-07 | 0 | 1.75E-05 |
| Cu | 0 | 0 | 4.38E-08 | 0 | 1.27E-06 |
| Cr | 0 | 0 | 6.59E-07 | 0 | 1.26E-06 |
| Ni | 0 | 0 | 1.16E-06 | 0 | 1.70E-05 |
| Zn | 0 | 0 | 2.94E-07 | 0 | 1.57E-06 |
| Particles | 4.55E-03 | 2.39E-04 | 8.70E-03 | 1.30E-04 | 8.61E-03 |
| Pb (aq) | 0 | 0 | 1.57E-08 | 0 | 3.86E-06 |
| Cd (aq) | 1.70E-08 | 8.92E-10 | 1.43E-07 | 0 | 5.30E-07 |
| Hg (aq) | 0 | 0 | 3.93E-09 | 0 | 1.74E-14 |
| Cu (aq) | 0 | 0 | 2.10E-05 | 0 | 2.43E-06 |
| Cr (aq) | 0 | 0 | 3.36E-07 | 0 | 2.23E-13 |
| Ni (aq) | 0 | 0 | 6.71E-07 | 0 | 3.13E-06 |
| Zn (aq) | 1.42E-04 | 7.44E-06 | 1.78E-06 | 0 | 1.55E-05 |
| Pb (so) | 0 | 0 | 0 | 1.78E-03 | 0 |
| Cd (so) | 0 | 0 | 0 | 2.31E-05 | 0 |
| Hg (so) | 0 | 0 | 0 | 4.97E-06 | 0 |
| Cu (so) | 0 | 0 | 0 | 6.04E-03 | 0 |
| Cr (so) | 0 | 0 | 0 | 1.78E-03 | 0 |
| Ni (so) | 0 | 0 | 0 | 1.24E-03 | 0 |
| Zn (so) | 0 | 0 | 0 | 1.42E-02 | 0 |

## Composting

Table B27. Emissions from mono-treatment – composting, kg per ton wastes collected.

| Emission | Collectio | Transport | Treatmen | Spreadin | Up- |
|---|---|---|---|---|---|
| $CO_{2(fossil)}$ | 2.54E+01 | 2.06E-01 | 0 | 1.62E-01 | 6.30E+00 |
| $CO_{2(bio)}$ | 0 | 0 | 3.58E+02 | 0 | 0 |
| $CH_4$ | 3.44E-04 | 2.79E-06 | 5.02E-01 | 2.18E-06 | 5.08E-03 |
| NMVOC | 2.27E-02 | 1.81E-04 | 3.83E-04 | 1.42E-04 | 1.37E-02 |
| CO | 9.96E-05 | 8.09E-07 | 2.25E-04 | 6.34E-07 | 1.02E-03 |
| Dioxine | 0 | 0 | 1.50E-11 | 0 | 0 |
| Dioxine | 0 | 0 | 6.01E-12 | 0 | 0 |
| $NH_3$ | 0 | 0 | 2.27E-02 | 5.93E-03 | 0 |
| $NO_x$ | 5.98E-01 | 4.86E-03 | 1.12E-01 | 3.80E-03 | 8.99E-02 |
| $NO_3$ | 0 | 0 | 2.50E-04 | 4.29E+00 | 0 |
| $N_2O$ | 1.40E-03 | 1.14E-05 | 2.48E-02 | 3.17E-02 | 5.53E-07 |
| $SO_x$ | 6.12E-02 | 4.96E-04 | 9.61E-03 | 3.89E-04 | 4.32E-02 |
| Pb | 0 | 0 | 2.89E-09 | 0 | 1.56E-06 |
| Cd | 0 | 0 | 2.13E-10 | 0 | 3.49E-07 |
| Hg | 0 | 0 | 4.17E-08 | 0 | 1.93E-06 |
| Cu | 0 | 0 | 1.62E-08 | 0 | 1.38E-07 |
| Cr | 0 | 0 | 2.46E-07 | 0 | 4.44E-07 |
| Ni | 0 | 0 | 4.39E-07 | 0 | 1.65E-05 |
| Zn | 0 | 0 | 1.08E-07 | 0 | 1.70E-07 |
| Particles | 4.47E-03 | 3.62E-05 | 3.73E-03 | 2.84E-05 | 1.28E-03 |
| Pb (aq) | 0 | 0 | 6.11E-09 | 0 | 3.95E-06 |
| Cd (aq) | 1.67E-08 | 1.36E-10 | 5.33E-08 | 0 | 5.42E-07 |
| Hg (aq) | 0 | 0 | 1.45E-09 | 0 | 1.89E-15 |
| Cu (aq) | 0 | 0 | 7.76E-06 | 0 | 2.44E-06 |
| Cr (aq) | 0 | 0 | 1.26E-07 | 0 | 4.09E-08 |
| Ni (aq) | 0 | 0 | 2.54E-07 | 0 | 3.06E-06 |
| Zn (aq) | 1.39E-04 | 1.13E-06 | 6.57E-07 | 0 | 2.23E-02 |
| Pb (so) | 0 | 0 | 0 | 2.55E-03 | 0 |
| Cd (so) | 0 | 0 | 0 | 3.32E-05 | 0 |
| Hg (so) | 0 | 0 | 0 | 7.14E-06 | 0 |
| Cu (so) | 0 | 0 | 0 | 8.67E-03 | 0 |
| Cr (so) | 0 | 0 | 0 | 2.55E-03 | 0 |
| Ni (so) | 0 | 0 | 0 | 1.79E-03 | 0 |
| Zn (so) | 0 | 0 | 0 | 2.04E-02 | 0 |

# Distribution of metals and dioxin

Table C1. Distribution of lead (Pb) expressed as kg per year.

| Lead, Pb | Reference | Biogas 2004 | Biogas long | Compost 2004 | Compost long |
|---|---|---|---|---|---|
| Core system | | | | | |
| Sources | 2 173 | 2 167 | 2 153 | 2 166 | 2 147 |
| Air | 0.013 | 0.012 | 0.009 | 0.011 | 0.008 |
| Soil | 106 | 254 | 609 | 308 | 818 |
| Water | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 |
| Left in landfill | 551 | 510 | 411 | 495 | 354 |
| Left in material | 1 515 | 1 403 | 1 133 | 1 362 | 974 |
| External system | | | | | |
| Air | 2 | 2 | 1 | 3 | 4 |
| Water | 77 | 69 | 55 | 155 | 386 |
| Soil | 0 | 0 | 0 | 0 | 0 |
| Left in landfill | 0 | 0 | 0 | 0 | 0 |
| Left in material | 0 | 0 | 0 | 0 | 0 |
| Sum external | 79 | 70 | 56 | 157 | 390 |

Table C2. Distribution of cadmium (Cd) expressed as kg per year

| Cadmium, Cd | Reference | Biogas 2004 | Biogas long | Compost 2004 | Compost long |
|---|---|---|---|---|---|
| Core system | | | | | |
| Sources | 29 | 29 | 29 | 29 | 28 |
| Air | 0.00094 | 0.00087 | 0.00070 | 0.00085 | 0.00061 |
| Soil | 1 | 3 | 8 | 4 | 11 |
| Water | 0.24 | 0.22 | 0.18 | 0.21 | 0.15 |
| Left in landfill | 24 | 22 | 18 | 22 | 16 |
| Left in material | 3 | 3 | 2 | 3 | 2 |
| External system | | | | | |
| Air | 0.36 | 0.26 | 0.04 | 0.27 | 0.08 |
| Water | 0.15 | 0.14 | 0.10 | 0.29 | 0.69 |
| Soil | 0 | 0 | 0 | 0 | 0 |
| Left in landfill | 0 | 0 | 0 | 0 | 0 |
| Left in material | 0 | 0 | 0 | 0 | 0 |
| Sum external | 0.50 | 0.40 | 0.14 | 0.56 | 0.77 |

Table C3. Distribution of Mercury (Hg) expressed as kg per year.

| Mercury, Hg | Reference | Biogas 2004 | Biogas long | Compost 2004 | Compost long |
|---|---|---|---|---|---|
| Core system | | | | | |
| Sources | 6 | 6 | 6 | 6 | 6 |
| Air | 0.18 | 0.17 | 0.14 | 0.17 | 0.12 |
| Soil | 0.3 | 1 | 2 | 1 | 2 |
| Water | 0.006 | 0.0059 | 0.0048 | 0.0058 | 0.0041 |
| Left in landfill | 5 | 5 | 4 | 5 | 3 |
| Left in material | 0 | 0.04 | 0.03 | 0.04 | 0.03 |
| External system | | | | | |
| Air | 0.07 | 0.06 | 0.03 | 0.10 | 0.19 |
| Water | 0.37 | 0.33 | 0.26 | 0.74 | 1.79 |
| Soil | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Left in landfill | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Left in material | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sum external | 0.44 | 0.39 | 0.29 | 0.84 | 1.98 |

Table C4. Distribution of copper (Cu) expressed as kg per year.

| Copper, Cu | Reference | Biogas 2004 | Biogas long term | Compost | Compost long |
|---|---|---|---|---|---|
| Core system | | | | | |
| Sources | 7 160 | 7 158 | 7 154 | 7 158 | 7 153 |
| Air | 0.07 | 0.07 | 0.05 | 0.06 | 0.05 |
| Soil | 362 | 864 | 2071 | 1048 | 2782 |
| Water | 34 | 32 | 26 | 31 | 22 |
| Left in landfill | 1 612 | 1 493 | 1 205 | 1 449 | 1 037 |
| Left in material | 5 151 | 4 770 | 3 853 | 4 630 | 3 312 |
| External system | | | | | |
| Air | 3 | 2 | 0.59 | 3 | 4 |
| Water | 82 | 73 | 58 | 164 | 410 |
| Soil | 0 | 0 | 0 | 0 | 0 |
| Left in landfill | 0 | 0 | 0 | 0 | 0 |
| Left in material | 0 | 0 | 0 | 0 | 0 |
| Sum external | 84 | 75 | 59 | 167 | 414 |

Table C5. Distribution of Chrome (Cr) expressed as kg per year.

| Chrome, Cr | Reference | Biogas 2004 | Biogas long term | Compost 2004 | Compost long term |
|---|---|---|---|---|---|
| Core system | | | | | |
| Sources | 2 167 | 2 162 | 2 148 | 2 160 | 2 143 |
| Air | 1.1 | 1.0 | 0.8 | 1.0 | 0.7 |
| Soil | 106 | 254 | 609 | 308 | 818 |
| Water | 0.56 | 0.52 | 0.41 | 0.50 | 0.36 |
| Left in landfill | 847 | 784 | 632 | 761 | 544 |
| Left in material | 1 212 | 1 122 | 907 | 1 089 | 779 |
| External system | | | | | |
| Air | 2 | 2 | 0.38 | 2 | 3 |
| Water | 60 | 54 | 43 | 121 | 302 |
| Soil | 0 | 0 | 0 | 0 | 0 |
| Left in landfill | 0 | 0 | 0 | 0 | 0 |
| Left in material | 0 | 0 | 0 | 0 | 0 |
| Sum external | 63 | 56 | 43 | 123 | 306 |

Table C6. Distribution of Nickel (Ni) expressed as kg per year.

| Nickel, Ni | Reference | Biogas 2004 | Biogas long term | Compost | Compost long |
|---|---|---|---|---|---|
| Core system | | | | | |
| Sources | 1 497 | 1 495 | 1 490 | 1 494 | 1 487 |
| Air | 1.9 | 1.8 | 1.4 | 1.7 | 1.2 |
| Soil | 75 | 178 | 426 | 216 | 573 |
| Water | 1.1 | 1.0 | 0.8 | 1.0 | 0.7 |
| Left in landfill | 393 | 363 | 293 | 353 | 252 |
| Left in material | 1 027 | 951 | 768 | 923 | 660 |
| External system | | | | | |
| Air | 187 | 148 | 54 | 135 | 4 |
| Water | 69 | 61 | 49 | 138 | 345 |
| Soil | 0 | 0 | 0 | 0 | 0 |
| Left in landfill | 0 | 0 | 0 | 0 | 0 |
| Left in material | 0 | 0 | 0 | 0 | 0 |
| Sum external | 256 | 209 | 103 | 273 | 349 |

Table C7. Distribution of Zink (Zn) expressed as kg per year.

| Zink, Zn | Reference | Biogas 2004 | Biogas long term | Compost | Compost long |
|---|---|---|---|---|---|
| Core system | | | | | |
| Sources | 16949 | 16937 | 16908 | 16934 | 16896 |
| Air | 0.5 | 0.4 | 0.4 | 0.4 | 0.3 |
| Soil | 852 | 2032 | 4872 | 2466 | 6546 |
| Water | 3 | 3 | 2 | 3 | 2 |
| Left in landfill | 9843 | 9113 | 7358 | 8846 | 6328 |
| Left in material | 6252 | 5789 | 4676 | 5619 | 4020 |
| External system | | | | | |
| Air | 3 | 2 | 0.7 | 3 | 5 |
| Water | 101 | 90 | 72 | 202 | 506 |
| Soil | 0 | 0 | 0 | 0 | 0 |
| Left in landfill | 0 | 0 | 0 | 0 | 0 |
| Left in material | 0 | 0 | 0 | 0 | 0 |
| Sum external | 104 | 92 | 73 | 206 | 511 |

Table C8. Distribution of dioxin expressed as kg per year.

| Dioxin | Reference | Biogas 2004 | Biogas long term | Compost | Compost long |
|---|---|---|---|---|---|
| Core system | | | | | |
| Sources | 1.89E-05 | 1.89E-05 | 1.89E-05 | 1.89E-05 | 1.89E-05 |
| Air | 6.65E-05 | 6.11E-05 | 4.80E-05 | 5.97E-05 | 4.26E-05 |
| Soil | 9.58E-07 | 2.29E-06 | 5.48E-06 | 2.77E-06 | 7.36E-06 |
| Water | 2.66E-05 | 2.44E-05 | 1.92E-05 | 2.39E-05 | 1.71E-05 |
| Left in landfill | 3.38E-02 | 3.11E-02 | 2.44E-02 | 3.03E-02 | 2.17E-02 |
| Left in material | 2.66E-03 | 2.44E-03 | 1.92E-03 | 2.39E-03 | 1.71E-03 |
| External system | | | | | |
| Air | 1.42E-06 | 1.07E-06 | 1.60E-08 | 1.06E-06 | 1.97E-07 |
| Water | 0 | 0 | 0 | 0 | 0 |
| Soil | 0 | 0 | 0 | 0 | 0 |
| Left in landfill | 0 | 0 | 0 | 0 | 0 |
| Left in material | 0 | 0 | 0 | 0 | 0 |
| Sum external | 1.42E-06 | 1.07E-06 | 1.60E-08 | 1.06E-06 | 1.97E-07 |

# ORWARE submodels

## Collection and Transports

Models for trucks with and without trailer are used for calculating energy consumption, emissions and cost for transport of materials from one place to another. The difference between these trucks and the collection trucks is that loading and unloading is assumed an insignificant part of the transport and is therefore left out of the model. Otherwise, sub-models are identical in their structure differing only in the input data concerning fuel consumption, loading capacity etc. The model structure is shown in Figure D1

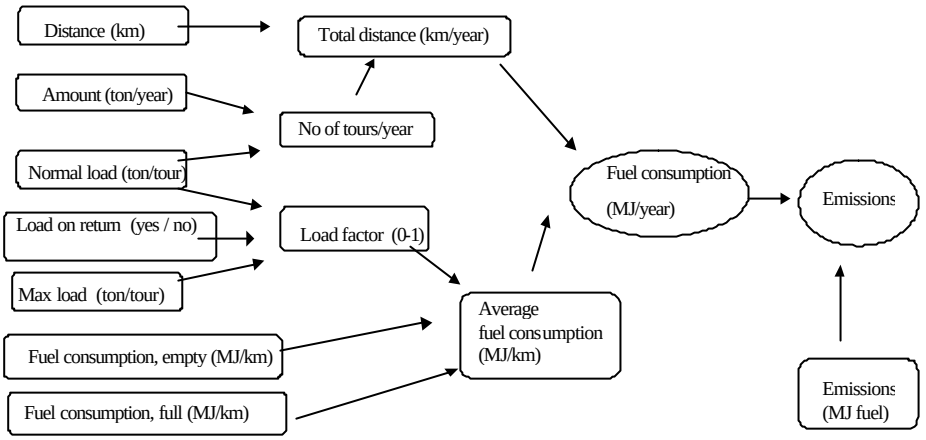


Figure D1. Model structure for transport models.

The number of loads required per year in the transport model is calculated from the amount of material to be transported and the normal load capacity for the specific type of material. The number of loads together with the distance between source and destination gives total drive distance per year. This total drive distance in turn is used for two purposes:

1. To calculate total fuel consumption using average fuel consumption per km
2. By using average speed, the total drive time per year is obtained which in turn gives the number of trucks required paving the ground for fixed cost calculation. The total drive time is also used for calculation of variable costs (e.g. salary etc.) that are functions of time consumed for transport.

Normal load and max load together with information about whether the truck is loaded on return or not gives basis for load factor i.e. what part of the max load is the actual average load. This load factor and data about fuel consumption both during max load and empty load gives average full consumption. The total fuel consumption is used together with emissions per MJ of fuel consumed to calculate emissions per year.

The structure of model provides it flexibility in different ways. Materials with lower density result in more number of loads with low average fuel consumption.
It is simple to change many parameters so that changes in prices etc can be made. The biggest drawback lies in the assumption of the average speed, which regulates the drive time and in turn much of the cost calculations.

Average speed should reflect the speed during the transport of the material during one year, including loading, unloading and the working days spent for maintenance etc. These parameters are difficult to estimate. Therefore, currently the average speed is calculated by dividing normal drive distances per year for long distances by the number of working hours per year. Table D1 shows input data in transport models, Table D2 shows emission data per MJ.

Table D1. Input data for transport models.

| Input data | Value |
|---|---|
| Max load, truck | 12 ton |
| Max load, truck and trailer | 35 ton |
| Average speed | 30 km/h [1] |
| Fuel consumption truck, empty | 2 litre / 10 km |
| Fuel consumption truck, full load | 3.5 litre / 10 km |
| Fuel consumption trailer, empty | 3 litre / 10 km |
| Tyre wear | 0.027 g tyre / MJ consumed fuel |
| Fuel consumption truck and trailer, full load | 5 litre / 10 km |

[1]Corresponding to a use of a truck for 1 760 hours per year and an annual drive distance of about 500 km.

Table D2. Air emissions from trucks.

| Emission | g/MJ |
|---|---|
| $CO_2$ – | 74 |
| $CH_4$ | 0.001 |
| VOC | 0.066 |
| PAH | 0.000002 |
| CO | 0.00029 |
| $NO_x$ | 0.53 |
| $N_2O$ | 0.0026 |
| $SO_x$ | 0.093 |
| Particles | 0.013 |

## Input data for collection and transports sub-model in current study

The organic waste in Denmark is supposed to be collected and transported to incineration plant. At the incineration plant waste is sorted out to incineration, composting or to anaerobic digestion. Load and distances driven during collection and transportation of waste are shown in Table D3.

Input data parameters for collection:

- Fuel consumption: 0.3 GJ/ton waste (Hyldebrandt-Larsen, 2002)
- Energy content in diesel oil: 35.6 MJ/l diesel, (Hyldebrandt-Larsen, 2002)

Table D3. Loads and distances for transports.

| Type of load | From | To | Load1 | Distance |
|---|---|---|---|---|
| Waste (40 | Incineration | Anaerobic | 20 (35) | 80 |
| Waste (60 | Incineration | Anaerobic | 8 (12) | 20 |
| Waste | Incineration | Composting | 8 (12) | 10 |
| Reject | Anaerobic | Landfill | 10 (35) | 40 |
| Reject | Composting | Landfill | 25 (35) | 40 |
| Ash | Incineration | Landfill | 25 (35) | 40 |
| Slag | Incineration | Landfill | 10 (35) | 40 |
| Sludge | Anaerobic | Arable land | 10 (35) | 5 |
| Compost | Composting | Arable land | 25 (35) | 15 |

[1] Normal load (Max load)

All vehicles are assumed empty during return transport, therefore when calculating emissions the actual distances are twice that are shown in Table D3. Using information from Table D4 the actual fuel consumption for collection and transportation can be calculated.

Table D4. Fuel consumption for different trucks.

| Truck data | Value | Unit |
|---|---|---|
| Ordinary truck | | |
| Maximum load | 12 | ton |
| Average speed | 30 | km/ h |
| Fuel consumption, fully | 35 | l/ 100 |
| Fuel consumption, empty | 20 | l/ 100 |
| Truck and trailer | | |
| Maximum load | 35 | ton |
| Average speed | 30 | km /h |
| Fuel consumption, fully | 35 | l/ 100 |
| Fuel consumption, empty | 30 | l/ 100 |

## Incineration

The data used for calculations is from 1996. Currently there are two varieties of the model, one describing the incinerator in Uppsala operated by Vattenfall and the second model for Fortums (former Birka Energy's) incinerator at Högdalen in Stockholm. The model for Stockholm has been modified and further developed compared to the one described in Björklund (1998), appendix F. The changes made are shown in a recent project report to the Swedish Energy Administration (Sundqvist et al., 2002). In both cases, the models are site specific and use emission and data for mass flows measured at these facilities. The model is built up of three parts: pre-treatment, incineration chamber and flue gas cleaning. Figure D2 gives a schematic diagram of the structure valid for both models.

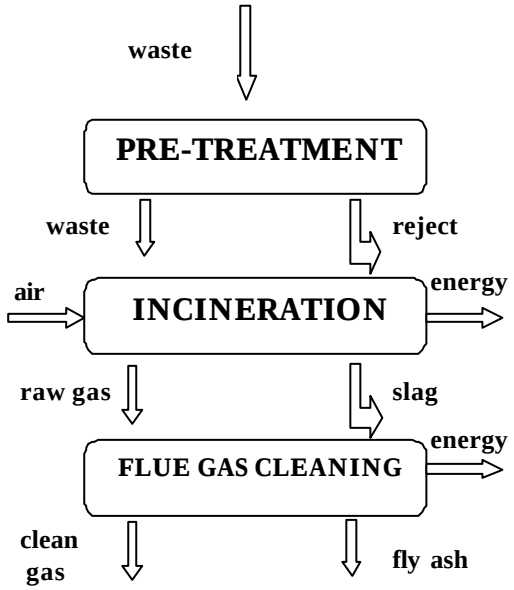


Figure D2. Structure of the incineration model.

### Pre-treatment

In pre-treatment, some parts of the incoming waste are separated for compression, wrapping and enclosing in a plastic. This possibility of wrapping can be utilised at times when the amount of incoming waste is much more than the capacity of the incinerator. This situation is often in the summer time where parts of the incineration facility are closed for maintenance. To avoid landfilling of combustible waste from the same municipality or waste from another municipality for landfilling somewhere else, the wrapping alternative is preferred.
In terms of modelling this would mean 2 kg of plastic per ton of waste and electricity consumption of 14.5 MJ/ton waste. This data for wrapping is obtained from Åberg (1998).

### Incineration

In the incineration chamber mixed waste is incinerated where an impure flue gas or raw gas is built up. Non-combustible part is separated in the form of slag. The raw gas is then taken to flue-gas cleaning facility where gas cleaning is performed with calculation of associated energy recovery, see figure A2. As part of the raw gas cleaning, condensation equipment and a water treatment facility to treat the condensed water are included. The gas cleaning part gives one stream of fly ash and another stream of clean gas.

### Flue gas cleaning

Separation of pollutants and partitioning of substances is carried out in the model to the largest extent using a material balance. This is related to either the amount of a specific incoming substance or the total amount of incoming waste. It is logical to relate certain emissions to the prevailing permissible values e.g. for $NO_X$, which is linearly dependent on the energy content of the waste. A material balance is not applied for such substances in the model.

During incineration in both sub-models, different components are partitioned as follows:

- How much of the heavy metals in the incoming waste ending up in the slag and raw gas are calculated first. Then calculation is done on how much of the metals in the raw gas go to the fly ash, sludge and wastewater and emissions to air. The fly ash and sludge are mixed together to give a stabilised cement-like material. Emissions to water and air are proportional to the amount of metals in the waste. Emissions to air for all heavy metals except mercury are less than 0.5 % of incoming amount. The ash and sludge resulting from the flue gas cleaning part and the slag from the incineration chamber are transported to a waste landfill site.
- Nitrogen oxide ($NO_x$) and nitrous oxide ($N_2O$) emission are calculated based in energy content. This depends on the fact that permissible amount of $NO_x$ emissions is given in units of kg $NO_x$/ MJ.
- Calculations of sulphur oxides ($SO_x$) are done in the same way as for nitrogen oxides.
- Dioxin emission is calculated from the amount of waste incinerated.
- Heat production in the model is calculated as heat from the energy content of the waste based on its composition. The energy recovery is calculated using the effective heating value and the moisture content of

the waste. In the flue gas condenser, about 70 % of the theoretically available heat of the steam are recovered.
- The number and amount of chemical additives varies based on the facility.

### Input data to the incineration model in this study

The basis for the model is waste incineration facility at Högdalen in Stockholm with a latest performance data from the environmental report of the facility for the year 2000. Baling of waste is not included and there is no flue gas condensation. Rest products from the facility like ash and slag are landfilled. Of the slag generated, 80 % is recycled in road construction and 20 % is landfilled. In Table D5 the parameters of incineration are described.

Table D5. Performance parameters for incineration process.

| Parameter | Value | Unit |
|---|---|---|
| Total efficiency | 85 | % of lower heat value |
| Electricity consumption | 0.32 | MJ/kg waste |
| $NO_X$ - emission to air | 200 | mg $NO_2$/MJ waste |
| $N_2O$ - emission to air | 0.01 | kg N-$N_2O$/kg N in |
| $NH_3$ - emission to air | 0.11 | mg $NH_3$/MJ waste |
| Dioxin formation | 0.2 | ng dioxin/$m^3$ flue gas |
| CO – emission | 3.29 | mg CO/MJ waste |
| Particles/Dust | 0.50 | mg particles /MJ |
| $SO_2$-separation in flue gas | 95 | % |
| HCl- separation in flue gas | 99.8 | % |
| Alpha value for heat power | 0.35 | MJ el/MJ heat |

## Compost

In the ORWARE model three different types of composts is modelled:
- Large scale reactor compost with or without compost gas cleaning
- Large scale windrow compost with or without compost gas cleaning
- Small scale home composting

Microbial degradation processes occurring during composting are assumed same for the three compost techniques. Emissions during composting are theoretically the same for all types of composts. The model assumes that the composting process works under optimum conditions.
The compost model assumes that:

- The compost is well aerated during the whole process
- The compost is allowed to fully mature
- Dry matter content in matured compost is 50 %
- The time-factor is not regarded, only the processes from the beginning to the end of the compost process and not how long time it takes to decompose organic material

Organic matter is degraded during the compost process. Heat $CO_2$, and some methane ($CH_4$) are released and the mature compost consists of mainly humus-like substances. Different organic substances decompose to different degrees according to Table D6.

Table D6. Degradation of organic compounds during composting (Sonesson, 1996).

| Substance | % turned into | % turned into |
|---|---|---|
| C-chsd (lignin) | 30 | 70 |
| C-chmd (cellulose) | 90 | 5[1] |
| C-chfd (starch, | 80 | 20 |
| C-fat | 60 | 40 |
| C-protein | 65 | 35 |

[1] After composting, there is a small residue of undegraded C-chmd. It is assumed that 5 % of incoming C-chmd is undegraded.

Depending on C/N-ratio in compost part of the nitrogen is volatilised as gas, primarily as $NH_3$, but also as $N_2O$ and $N_2$. The model calculates that of the total amount of nitrogen lost as gaseous emission 98 % is volatilised as $NH_3$, 0,5 % as $N_2O$ and 1,5 % as $N_2$ (Gunnarsdotter Beck-Friis, 2001).

Heavy metals are considered as inert material and the total amount fed into the compost equals the amount in matured compost. Because of degradation of organic compounds the concentration of metals on dry matter basis increases.

### Input data to the compost model in this study

50 % of the waste to compost is put in windrow compost, 50 % in reactor compost. In both composts the carbon-nitrogen ratio has been set to 30, corresponding to an input of carbon-rich material. Differences between the two compost techniques are that the reactor compost has a higher use of electricity and diesel for running and maintenance of compost and that compost exhaust gases are cleaned in a bio-filter according to Table D7.

Generally a carbon-nitrogen of 30 is sufficient for reactor composting. In windrow composting is the carbon-nitrogen ratio probably higher than 30. Therefore are the nitrogen losses from windrow composting somewhat overestimated.

Table D7. Performance parameters for the compost process.

| Type of compost | Value | Unit |
|---|---|---|
| Open windrow | | |
| Electricity | 0 | MJ/kg |
| Diesel consumption | 0.0015[1] | MJ/kg |
| Compost gas | No | |
| Reduction of $NH_3$ | 0 | % |
| Reduction of $N_2O$ | 0 | % |
| Reduction of $CH_4$ | 0 | % |
| Reactor compost | | |
| Electricity | 0.180[1] | MJ/kg |
| Diesel consumption | 0.0755[1] | MJ/kg |
| Compost gas | Yes | |
| Reduction of $NH_3$ | 99[1] | % |
| Reduction of $N_2O$ | 90 | % |
| Reduction of $CH_4$ | 50 | % |

[1] Valkainen (2002)

## Anaerobic digestion

The original submodel for anaerobic digestion is described in Dalemo (1996).
Incoming material to anaerobic digestion can be pre-treated by utilising bag- and metal separation, hygienisation at 70 °C or by sterilisation at 130 °C. During bag and metal separation parts of the material that clings to the bags are sorted out with the separated metal. If plastic bags are used the model assumes that 25 % of the waste clings to the plastic bags. When using paper bags the losses are only 1 % e.g. only losses from metal separation.
Hygienisation is calculated as energy used for heating the material from ambient temperature to hygienisation or sterilisation temperature according to the formula: $E = m * c_p * \Delta T$

The actual energy requirements are assumed to be 20 % higher than the calculated due to energy losses. Ambient temperature is assumed to be 10 °C as an yearly average temperature.

The anaerobic sub-model in ORWARE describes continuous single stage mixed tank reactor (CSTR) in steady state working under meso- or termophile conditions, 37 °C and 55 °C. After digestion the anaerobic sludge passes through a heat exchanger, where 50 % of the energy content (heat) is recovered. The exchanged heat is used for preheating the incoming material.

The anaerobic sludge can be dewatered, dried or not treated at all. Dewatered sludge has a dry matter content of 25 – 35 % and dried sludge 98 %. Dried sludge is turned into pellets and incinerated or as organic fertiliser, primarily phosphorus.
The anaerobic sludge is stored in covered storage for reducing ammonia ($NH_3$) losses. Covered storage also gives the possibility to gather methane that is formed during storage.

The amount of biogas from anaerobic digestion depends of the incoming materials composition of organic carbon. The model is assuming degradation of organic Substances according to first order kinetics
$D = D_0/(1 + (1/k*HRT)$ where
D = Degradation ratio
$D_0$ = Maximum degradation ratio
k = first order rate constant
HRT = Hydraulic retention time

Different organic substances are decomposed at different rates. To be able to calculate the degradation ratio for a mixture of waste substances, degradation is calculated from degradation of different organic compounds shown in table A 4.8.

Table D8. Performance parameters for the anaerobic digestion process.

| Organic substances | $D_0$ | K ($days^{-1}$) | % $CH_4$ |
|---|---|---|---|
| C-chsd (lignin) | 0 | 0.001 | 50 |
| C-chmd (cellulose) | 1-1.77* C-chsd | 0.18 | 50 |
| C-chfd (starch. | 1.0 | 0.23 | 50 |
| C-fat | 0.8 | 0.13 | 69 |
| C-protein | 0.95 | 0.13 | 78 |

Energy for pumping and mixing of material etc. of different materials requires approximately 5 % of produced energy. Heat requirement in the

digester is calculated from a mechanistic approach. Heat consumption depends on the temperature of the digested material and losses through the digester reactor during digestion. It is assumed that 50% of the heat in material leaving the digester can reused through a heat exchanger reducing the temperature from digester temperature to ambient temperature, thus reducing the need of heat.

### Input data to the anaerobic digestion model in this study

- 50 % of the waste to anaerobic digestion is digested in a mesophilic process, 50 % in a thermofilic process.
- Biogas production is set to 125 $nm^3$ per ton waste treated.
- Dry matter (DM) content in digestion chamber is set to 13 %. The incoming waste is therefore diluted using fresh water
- No recycling of anaerobic sludge to incoming waste
- 35 % of the incoming waste is sorted out to incineration.
- No dewatering of anaerobic sludge prior to spreading
- All anaerobic sludge is utilised as organic fertiliser

### Landfilling of waste

Five different types of landfills are modelled; biocell (Fliedner, 1999), landfills for mixed waste, sludge, ash and slag (Björklund, 1998). The models are supposed to reflect Swedish average landfills and therefore site-specific modification of the models is limited.

Waste that is put into landfill today will continue to give out emissions for long time in the future. One dilemma is, thus, how to compare such emissions from landfills with more immediate emissions from other processes in the system. To include only the immediate emissions from landfills would be illogical representation of the total load. On the other hand to try to estimate the total emission brings about considerable magnitude of uncertainty and even so the time perspective becomes incomparable with the other processes. As a compromise, future impacts of landfills have been divided into two periods that have some differences for the different types of landfills (see Figure D3):

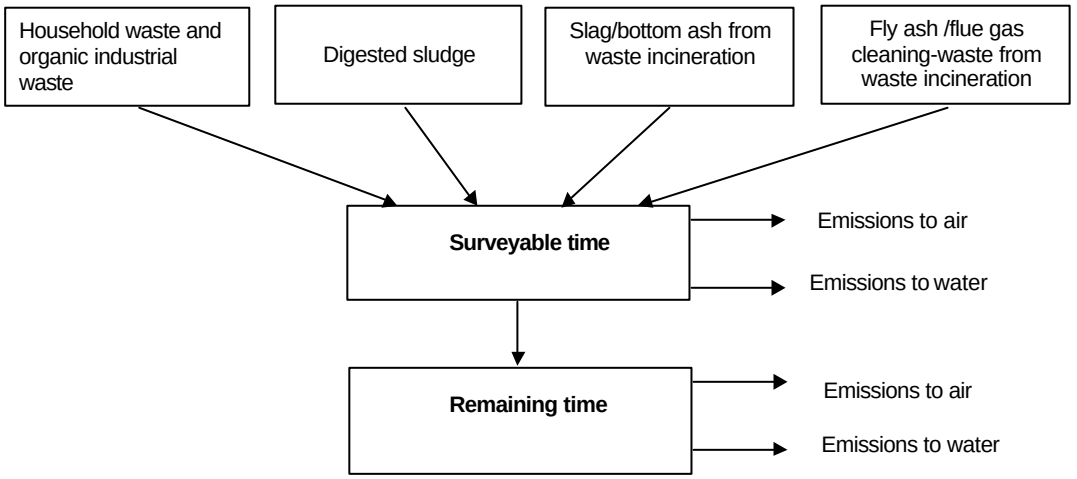


Figure D3. Material flow structure in the landfilling model.

*Surveyable time (ST):* During this time most of the reactive processes in landfills is subsided and the landfill apparently reaches a stationary condition. For mixed waste and sludge as well as bio-cell, the surveyable time is defined as the end of the methane generation phase. For slag and ash landfills the leakage of soluble salts defines the surveyable time. The surveyable time is consequently a functional measure of time and varies from case to case but generally it is in the order of 100 years.

*Remaining, infinite time (RT):* This time period covers until all the material in the landfill is spread out in the environment through the formation of gas, leakage, erosion and eventual inland icing. This infinite time embodies emissions in the worst scenario.

Calculations are based on the amount of waste to landfill during one year. The emission during the surveyable time is an average yearly emission under corresponding time from a landfill where the same amount of waste is put into landfill year after year. When emissions under this surveyable time are calculated, the emissions that will occur during the remaining time are also calculated. During assessment and discussions attention is paid only to those emissions under the surveyable time. In the sub-models for landfill of mixed waste and sludge, the following processes occur:

- Degradation of organic material gives emissions composed of mainly methane. Sugar, starch and fat are considered 100 % degradable, cellulose 70 % while lignin and plastic as non-degradable. The composition of the gas varies depending on composition of the organic material. In most of the cases, the gas contains 50 – 60 % $CH_4$ and the rest mainly $CO_2$.
- Leakage of heavy metals is small during the surveyable time, in the range 0.1 to 0.001 % of the amount to landfill.
- Nutrient leaks in the form of phosphorous (2 % of amount landfilled, 15 % for sludge) and nitrogen (90 % of the amount to landfill).
- For organic pollutants, there is lack of knowledge concerning their long-term fate in landfills. During the surveyable time, it is possible that such substances are formed, degraded, converted to gas, vaporised, leak out or adsorbed to the material in landfill. A very simplified estimate for every substance studied.
- The gas can be collected during the surveyable time with an efficiency of 50 % of the gas formed. The collected gas can be flared out or combusted in a gas motor. The remaining gas makes its way to the outer layer of the landfill where 15 % of the methane is oxidised to carbon dioxide.

The bio-cell model that handles only easy degradable organic waste is based on the landfill for mixed household waste. However, it gives considerably faster degradation (i.e. the surveyable time refers to a shorter time) and more effective gas collection than in conventional landfills (65 % of formed gas). Furthermore a leakage water of higher quality is formed. In this connection, a bio-cell is considered something between conventional landfill and digestion chamber.
The main feature of ash and slag landfills is leakage of heavy metals. Metals in the ash leak out in the range of 1 to 10 % of the amount in during surveyable time. Metals in the slag have less tendency to leach out, the leakage correspond to 0,1 to 5 % of amount in landfill under the surveyable time. No gas is extracted from such landfills.

The leakage treatment model can be connected to all of the landfill submodels. The model reflects a biological treatment with a chemical precipitation. About 80 % of the phosphorus leaking out under the surveyable time are collected and recycled back to the landfill (it then leaks out during the remaining time). Furthermore 90% of the nitrogen leakage is partitioned

as nitrogen gas with the rest going out with the leakage water. No metal partitioning is modelled. Working machines consume 40 MJ of diesel oil per ton material to landfill for all landfill sub-models. Table D9 depicts input data for landfill sub-model.

Table D9. Parameters in landfill model during the surveyable time.

| Parameter | Value | Unit |
|---|---|---|
| degradation of sugar, starch, fat | 100 | % of landfilled amount |
| degradation of cellulose | 70 | % of landfilled amount |
| degradation of lignin and plastic | 0 | % of landfilled amount |
| Leakage of phosphorus | 2 | % of landfilled amount |
| Leakage of nitrogen | 90 | % of landfilled amount |
| Leakage of heavy metals, MSW and | 0.1 – | % of landfilled amount |
| Leakage of heavy metals, incineration | 1 - 10 | % of landfilled amount |
| Leakage of heavy metals, incineration | 0.1 - 5 | % of landfilled amount |
| treatment efficiency, N in leakage | 90 | % of leak water |
| treatment efficiency, P in leakage water | 0.8 | % of leak water |
| Gas collection, mixed waste and | 50 | % of generated gas |
| Gas collection, biocell | 65 | % of generated gas |
| Soil oxidation, methane | 15 | % of methane leakage |
| Diesel consumption, all landfills | 40 | MJ/ton landfilled |

The gas (methane) recovered from landfills can be used as a fuel in a gas motor that can supply electricity and heat. The energy from gas motor is calculated using the energy content of the methane gas. If the gas is flared out, the emissions are calculated according to Table D11, with a zero energy recovery. When it is recovered, 30 % is electricity and 60 % heat but this also varies from case to case.

### Input data to the landfill model in this study

In this study, when the industrial waste is landfilled, 50 % of the landfill gas produced is assumed collected (this is the same as for landfilling of organic waste). Around 90% of this collected gas is used for heat production in a gas motor. Treatment of leakage water (nitrogen and phosphorus) is supposed to be part of both types of landfilling (landfilling of industrial waste and landfilling of ashes and slag). Whenever results for landfilling are shown, they refer only to the emissions during the surveyable time.

#### Gas engine

Biogas formed during anaerobic digestion and from landfilling of organic waste can be used for different purposes. It can be used as:

- Vehicle fuel in cars and busses
- Combusted in a stationary gas engine for generation of electricity and heat
- Torched, only applied to landfill gas. The gas is combusted in a stationary gas engine, but no energy is recovered

### Biogas as vehicle fuel

Before biogas can be utilised as vehicle fuel, it has to be upgraded to a higher fuel quality compared to the original biogas. Methane content is after upgrading 97 % and the amount of $CO_2$ is less than 3 %. Up grading of biogas to vehicle fuel quality is done in two steps:

1. Stripping of $CO_2$
2. Compression of cleaned biogas to 250 bars pressure

Both steps require an input of electricity amounting to 3 % of the energy produced.

### Utilisation of biogas in a stationary gas engine for heat and power generation

Energy from combustion of biogas in a stationary gas-engine equals to the energy content of the produced biogas. If the energy is utilised as electricity and heat, 30 % of the energy in the biogas can be utilised as electricity and 60 % as heat. The remaining 10 % are assumed lost during combustion. Other emissions from a stationary gas engine are shown in Table D10.

Table D10. Emissions from combustion of methane gas in a stationary gas motor (mg/MJ gas).

| Substance | Emission [mg/ MJ |
|---|---|
| $CH_4$ | 100 |
| VOC | 160 |
| CO | 250 |
| $NO_x$ | 200 |
| Particles | 0 |

### Input data to the anaerobic digestion model in this study

- All biogas is combusted in a stationary gas engine
- Energy is utilised as electricity and no heat is recovered. In this study 38 % of the energy in the biogas is utilised as electricity and 52 % as heat.
- Emissions factors for stationary gas engine are adapted to Danish data stating that Cleaning of sulphur emitted as sulphur dioxide is cleaned to 400 mg/$m^3$ gas. New emission factors are shown in Table D11.

Table D11. Emissions from incineration of methane gas from landfilling in a stationary gas motor (mg/MJ gas).

| Substance | Emissio |
|---|---|
| $CH_4$ | 430 |
| VOC | 4 |
| CO | 250 |
| $NO_x$ | 100 |
| Particles | 0 |

Spreading of organic material on arable land and emissions from nitrogen turnover in the soil

The submodel for spreading of organic fertiliser and nitrogen turnover in soil has four different parts:

- Calculation of transportation from treatment plant to satellite storage in field
- Calculation of area needed to spread organic fertiliser
- Spreading of organic fertiliser
- Nitrogen turnover in soil

### Calculation of transportation from treatment plant to satellite storage in field

Calculation of transport distances from treatment plant to arable land uses the acreage needed over longer time-period than one year. This acreage is different to the actual acreage available because more than one years yield is spread of organic fertiliser on each hectare. It is actually the average transport distance over a number of years that are calculated.

### Calculation of area needed to spread organic fertiliser

Need of acreage for spreading of organic fertiliser is calculated for each fertiliser spread. The different organic fertilisers' need of acreage is then added together to a total need of acreage. This total area needed is then used for calculating the transport distances from storage to spreading. This calculates the total need of area inside a geographically defined area. In reality, is not the total acreage available because of different reasons. By multiplying the available area with a factor, that represents some kind of acceptance of spreading organic fertiliser, the total transport distance is calculated.

### Spreading of organic fertiliser

Emissions from spreading of organic fertilisers are emissions from transport from storage on site to field and vehicle emissions during spreading. Ammonia volatilisation during spreading is also calculated.

Using dry or liquid spreader can do spreading. The model chooses appropriate spreader based on the organic fertiliser dry matter content. For dry matter content up to 10 % organic fertiliser are spread with liquid spreader. Dry spreader is used when dry matter content is above 10 %.

Table D12. Data concerning dry and liquid spreaders.

| Spreader | Value | Unit |
|---|---|---|
| Dry spreader | | |
| Empty weight | 6 000 | kg |
| Loading capacity | 3 750 | kg |
| Speed during transportation to and | 15 | km/hou |
| Speed during spreading | 5 | km/hou |
| Liquid spreader | | |
| Empty weight | 4 000 | kg |
| Tank volume | 8 000 | l |
| Working width | 12 | m |
| Speed during transportation to and | 15 | km/ h |
| Speed during spreading | 4 | km/ h |

For each organic fertiliser spread, the model calculates the distance from field storage to field and time and energy when spreading. Emissions per MJ fuel used for tractor pulling spreader are assumed same as for transportation. Ammonia volatilisation is a function of type of spreader, spreading technique etc. (Table D12).

Table D13. Emissions of ammonia as a fraction of ammonium content in relation to spreading time, type of solid manure, and application technique, when spread in cereal crop (Dalemo, 1998).

| Time of | Spreading technique | Solid | Slurry | Urine (%) |
|---|---|---|---|---|
| Spring | Broad cast + harrowing within 1 h | 15 | 10 | 8 |
| Spring | Broad cast + harrowing within 12 h | 50 | 20 | 20 |
| Spring | Band spreading + harrowing within | | 5 | 7 |
| Spring | Band spreading + harrowing within | | 20 | 10 |
| Early summer | Band spreading | | 7 | 10 |
| Early autumn | Broad cast + harrowing within 1 h | 20 | 5 | 15 |
| Early autumn | Band spreading + harrowing within | | 3 | 10 |
| Late autumn | Broad cast + harrowing within 1 h | 10 | 5 | 10 |

## Nitrogen turnover in soil

The nitrogen turnover sub-model in ORWARE is a complement to the spreading sub-model. It is assumed that nitrogen in soil is available as $NH_4$, $NO_3$ and organically bound nitrogen. The sub-model calculates emissions from mineralization or organic nitrogen during first year after spreading and long-time effects from mineralization and immobilisation of nitrogen from nitrogen pool (Figure D4).

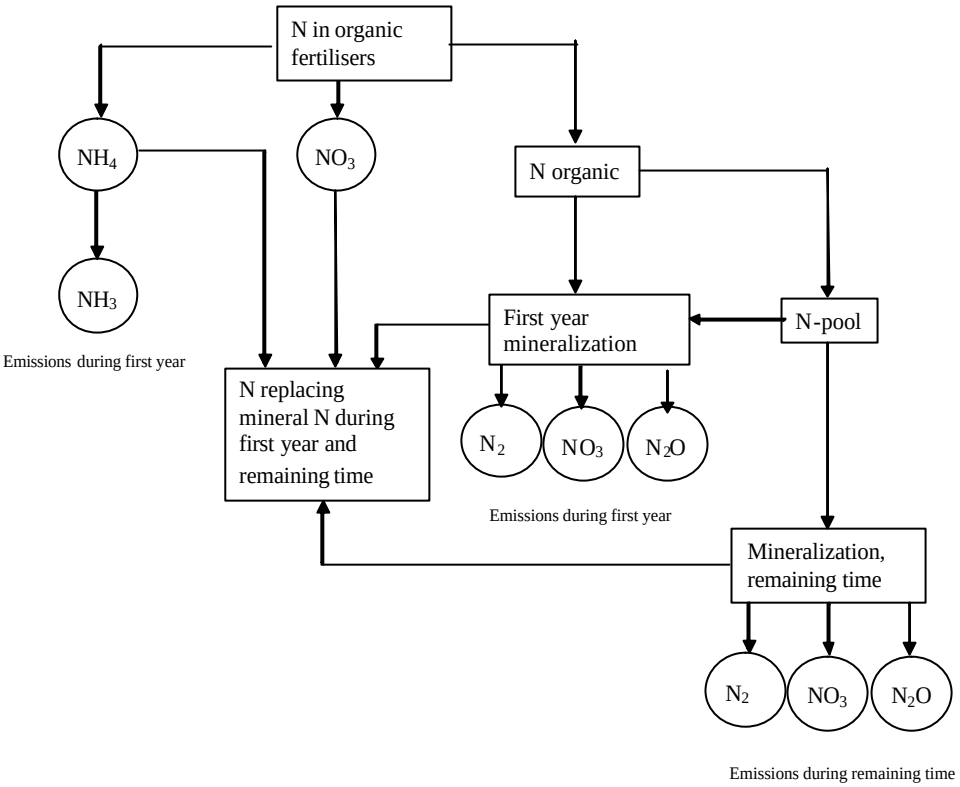


Figure D4. Nitrogen turnover model in ORWARE (Sundqvist et al, 1999).

The nitrogen turnover sub-model gives the relation between organic fertiliser and mineral fertiliser. It is assumed that nitrogen in organic fertilisers is utilised by plants as 80 % of $NH_4$ and $NO_3$. Organic nitrogen is utilised to 30 % during first year after spreading compared to mineral fertiliser.

Phosphorus and potassium is utilised by the plants. All metals remain in soil after spreading.

## Input data to the spreading and nitrogen turnover models model in this study

- Transport distances between treatment plant and arable land is calculated as a normal transport according to transportation sub-model in ORWARE. It is assumed that organic compost and anaerobic sludge is transported with truck and trailer to arable land. No return transport is assumed.
- Calculation of acreage is based on nitrogen and phosphorus content in compost and anaerobic sludge.

- Dry spreaders spread compost.
- Anaerobic sludge is spread using liquid spreaders.

### Compensatory district heating and power supply

For both electricity and heat combustion of coal is used. The same origin of data is then used for both electricity and heat combustion there is just a change of degree of efficiency between the two. In this study data from combustion of coal at the condense power plant at Fyn in Denmark is used. This plant is supposed to reflect an average type of coal condense power production plant, Uppenberg et al (1999). The coal, in the form of powder, is combusted in one older and one newer block where the newer one is equipped with semi-dry sulphur cleaning and low-$NO_x$ burner while the older block lacks of such equipment.

In Table D14 and B15 resource consumption and emission factors for power production from coal combustion is shown. Data in Uppenberg (1999) relies on the LCA for coal power (Buhre et al 1997). Uppenberg (1999) show data per MJ fuel. Coal condense power has 44 % degree of efficiency and heat and power has 88 % degree of efficiency.

Table D14. Resource consumption for combustion of coal.

| Energy resource (MJ/MJ | Extractio | Use | Sum |
|---|---|---|---|
| Renewable | | | |
| Hydro power | 0 | 9.5E-05 | 9.5E-05 |
| Bio-fuel | 0 | 0 | 0 |
| Non renewable | | | |
| Nuclear power | 0 | 1.6E-04 | 1.6E-04 |
| Natural gas | 0 | 9.24E-04 | 9.24E-04 |
| Oil | 2.32E-02 | 4.19E-03 | 2.74E-02 |
| Coal | 2.07E-02 | 5.72E-04 | 2.1E-02 |

Table D15. Emission factors for combustion of coal expressed as g per MJ fuel.

| Emission to | Extractio | Use | Sum |
|---|---|---|---|
| $NO_x$ | 6.27E-02 | 0.257 | 0.32 |
| $SO_2$ | 4.84E-02 | 0.284 | 0.33 |
| CO | 5.03E-03 | 6.23E-05 | 5.09E-03 |
| HC (NMVOC) | 1.88E-03 | 8.62E-04 | 2.74E-03 |
| $CO_2$ fossil | 4.3 | 99 | 1.03E-02 |
| $N_2O$ | 4.17E-07 | 6.45E-07 | 1.06E-06 |
| $CH_4$ | 8.94E-02 | 1.53E-04 | 8.96E-02 |
| Particles | 6.65E-03 | 1.19E-02 | 1.86E-02 |

### Mineral fertiliser

Mineral fertilisers calculate the emissions for nitrogen (N), phosphorus (P) and potassium (K) needed to fulfil the functional unit N, P and K spread on arable land. N, P and K are calculated from Davies and Haglund (1999) using western European average data for production of mineral fertilisers. Emissions from mineral fertiliser nitrogen are calculated from spreading of Ammonium nitrate (35 % N), Western European average data. Emissions from production of phosphorus mineral fertiliser are calculated from Triple

superphosphate, TSP (48 % $P_2O_5$), Western European average data and Potassium from PK fertiliser (22 % $P_2O_5$, 22 % $K_2O$) Western European average data.

Table D16. Resource consumption for production of mineral fertiliser N, P and K expressed as MJ per kg NPK.

| Resources | N-tot | P-tot | K-tot |
|---|---|---|---|
| Diesel (train) | 4.37E-01 | 9.12E+00 | 5.98E-01 |
| El. European | 3.76E-01 | 8.40E+0 | 2.57E-01 |
| Fuel, ship 2-stroke | 3.14E-02 | 1.10E+00 | 2.85E-02 |
| Hard coal | 3.95E+00 | 0 | 0 |
| Natural gas > 100 | 3.17E+01 | 0 | 0 |
| Oil, heavy | 4.33E+00 | 1.20E+01 | 3.14E-01 |
| Steam | 0 | 0 | 5.45E-01 |

Table D17. Emission factors for production of mineral fertiliser N, P and K expressed as g per kg N, P and K.

| Emissions | Nitrogen | Phosphorus | Potassium |
|---|---|---|---|
| Cd | 2.19E-04 | 4.46E-04 | 1.19E-05 |
| Cr | 1.71E-03 | 2.10E-04 | 5.78E-06 |
| Cu | 1.57E-03 | 1.10E-03 | 3.37E-05 |
| Hg | 1.43E-05 | 6.83E-05 | 2.12E-06 |
| Ni | 5.11E-03 | 9.93E-03 | 2.70E-04 |
| Pb | 1.33E-03 | 9.31E-04 | 2.54E-05 |
| Zn | 1.75E-03 | 9.88E-04 | 2.96E-05 |
| $CH_4$ | 2.83E+00 | 5.68E+00 | 1.80E-01 |
| CO | 1.20E+00 | 4.25E+00 | 1.67E-01 |
| $CO_2$ | 2.84E+03 | 3.08E+03 | 1.33E+02 |
| N2O-N | 9.31E+00 | 1.83E-01 | 6.84E-03 |
| Dioxin | 6.40E-10 | 2.62E-09 | 8.20E-11 |
| NMVOC | 1.24E+00 | 6.49E+00 | 2.19E-01 |
| $NH_3$-N | 0 | 1.20E-03 | 3.44E-05 |
| $NO_2$-N | 4.11E+00 | 0 | 0 |
| $NO_x$-N | 1.42E+00 | 5.58E+00 | 2.10E-01 |
| N-tot | 1.48E+01 | 5.76E+00 | 2.17E-01 |
| PAH | 3.20E-04 | 6.01E-06 | 5.94E-06 |
| $SO_2$-S | 2.20E+00 | 1.92E+01 | 5.26E-01 |
| SO3-S | 0 | 5.31E-01 | 1.38E-02 |
| S-tot | 2.20E+00 | 1.97E+01 | 5.40E-01 |
| Cd (aq) | 7.77E-06 | 3.76E-05 | 1.20E-06 |
| Cr (aq) | 8.51E-06 | 2.10E-04 | 6.57E-06 |
| Cu (aq) | 2.80E-06 | 5.82E-05 | 2.42E-06 |
| Ni (aq) | 6.20E-05 | 2.43E-04 | 7.65E-06 |
| Pb (aq) | 5.80E-05 | 2.74E-04 | 8.69E-06 |
| COD (aq) | 1.72E-03 | 3.51E-02 | 1.45E-03 |
| P-tot (aq) | 3.43E-06 | 3.30E+00 | 8.64E-02 |
| $SO_4$-S (aq) | 2.34E-01 | 2.33E+00 | 7.18E-02 |
| S-tot (aq) | 2.34E-01 | 2.33E+00 | 7.18E-02 |
| BOD (aq) | 6.86E-05 | 1.09E-03 | 4.50E-05 |

# Household waste composition

Table E1. High heat values (MJ per kg), annual amount of substances in the organic waste (kg wet weight) and composition of organic household waste (kg per kg dry weight).

| Parameter | High heat | Organic household | Organic household |
|---|---|---|---|
| C-tot biological | 0 | 91 140 000 | 0,434 |
| C-lignin | 40.89 | 6 090 000 | 0.029 |
| C-cellulose | 37.51 | 22 470 000 | 0.107 |
| C-sugar | 39.57 | 20 370 000 | 0.097 |
| C-fat | 51.25 | 28 350 000 | 0.135 |
| C-protein | 45.07 | 13 860 000 | 0.066 |
| VS | 0 | 168 000 000 | 0.8 |
| VOC | 50.10 | 420 | $2.00*10^{-06}$ |
| CHX | 35.00 | 2 | $1.00*10^{-08}$ |
| PAH | 0 | 105 | $5.00*10^{-07}$ |
| Phenols | 0 | 5 775 | $2.75*10^{-05}$ |
| PCB | 0 | 9 | $4.35*10^{-08}$ |
| Dioxin | 0 | 0 | $9.00*10^{-14}$ |
| N tot | 0 | 6 930 000 | 0.033 |
| S tot | 0 | 504 000 | $2.40*10^{-03}$ |
| P tot | 0 | 798 000 | $3.80*10^{-03}$ |
| Cl | 0 | 819 000 | $3.90*10^{-03}$ |
| K | 0 | 1 953 000 | $9.30*10^{-03}$ |
| Ca | 0 | 5 880 000 | 0.028 |
| Pb | 0 | 2 100 | $1.00*10^{-05}$ |
| Cd | 0 | 27 | $1.30*10^{-07}$ |
| Hg | 0 | 6 | $2.80*10^{-08}$ |
| Cu | 0 | 7 140 | $3.40*10^{-05}$ |
| Cr | 0 | 2 100 | $1.00*10^{-05}$ |
| Ni | 0 | 1 470 | $7.00*10^{-06}$ |
| Zn | 0 | 16 800 | $8.00*10^{-05}$ |
| DM-content (kg/ kg | 0 | | 0.30 |

[1] Wester, 1993
[2] Sonesson et al, 1996

Table E2. Energy values of organic household waste.

| Parameter | Value | Unit |
|---|---|---|
| Low heating | 3.7 | MJ/kg |
| | 12.5 | MJ/kg TS |
| High heating | 5.7 | MJ/kg |
| | 18.9 | MJ/kg TS |

# Characterisation factors for environmental impact categories

Table F1. Characterisation factors for Global Warming Potential, GWP 100, expressed as kg $CO_2$ per kg emission (Uppenberg and Lindfors, 1999).

| Emissio | GWP |
|---|---|
| $CO_{2\ (fossil)}$ | 1 |
| $CO_{2(bio)}$ | 0 |
| $CH_4$ | 21 |
| $N_2O$ | 310 |

Table F2. Characterisation factors for Acidification Potential, AP, expressed as kg $SO_2$ per kg emission (Uppenberg and Lindfors, 1999).

| Emissio | Acidificatio |
|---|---|
| $SO_x$ | 1 |
| Cl | 0,88 |
| $NO_x$ | 0.7 |
| $NH_3$ | 1.88 |

Table F3. Characterisation factors for Eutrophication Potential, EP, expressed as kg $O_2$ per kg emission (Uppenberg and Lindfors, 1999).

| Emission | Eutrophicatio |
|---|---|
| $NH_3$ | 16 |
| $NO_x$ | 6 |
| $NO_3$ (aq) | 4.4 |
| $NH_4$ | 15 |
| COD | 1 |
| P-tot (aq) | 140 |

Table F4. Characterisation factors for photochemical expressed as kg ethene per kg emission (Lindfors et al. 1995).

| Emissio | VOC |
|---|---|
| VOC | 0.416 |
| CO | 0.03 |
| $CH_x$ | 0.02 |
| $CH_4$ | 0.006 |