REPORT

How should municipal solid waste be treated

– a system study of incineration, material recycling, anaerobic digestion and composting

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Report Summary

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Project title
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Keyword

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Preface

During 2000-2001 we made a system analysis study of waste management to assess different waste management strategies from an environmental, energetical and economic point of view. The study was financed by the Swedish National Energy Administration. I was project leader, but several other researchers made most of the work from other institutes and universities. The final report was in Swedish (Sundqvist et al 2002), because we aimed to reach Swedish municipalities, Swedish authorities and Swedish companies. However, since then I have found that the study also is of international interest. I have presented results in some conferences, workshops, and courses (Sundqvist 2001, 2002, 2004). Because of the international interest I have put together a shorter English version of our report. This report is focused on the method and the results. In the Swedish report there are also several sub-studies and more background data presented.

Jan-Olov Sundqvist
Project Leader

Content

1 Introduction

Waste management in Sweden is rapidly changing. Due to political decisions several actions are taken towards a more sustainable waste management. Producer's responsibility on newsprint, packages, tires, and electric&electronic scrap has been introduced, and the responsibility is connected to recycling targets. From 2000 there is a tax on all waste that is landfilled. From 2001 there is a new national ordinance on landfilling, based on the EU Landfill Directive 1999/31/EC. According to the national Solid Waste Ordinance, landfilling of combustible waste is prohibited from 2001 and landfilling of organic waste is prohibited from 2005. The EU directive on incineration of waste (2000/76/EC) has been implemented into a Waste Incineration Ordinance. All these actions are causing changes in the waste management. As an example it could be mentioned that at the moment, Sweden has 26 incineration plants and about 20 more are planned. Also biological treatment and material recycling is increasing, while landfilling is decreasing.

The Swedish energy system is also in the position of many changes. Today, one nuclear power reactor has been closed down and the government's aim is to close more reactors as renewable energy sources are introduced into the market. The use of fossil fuels is supposed to decline, which demands for other energy sources, of which waste is one.

All this means that the treatment capacity for incineration and biological treatment as well as material recycling has to increase in order to meet the landfill restrictions. This give rise to the question: which treatment options are preferable from an environmental, energy and economic point of view.

A system study has been carried out of how energy, material and plant nutrients in waste are utilised at the best with respect to environment, energy and economy. This paper describes the part of the study that considers management of biodegradable waste. The full study is published (Sundqvist *et al.* 2002) (in Swedish with an English summary). The study has also been presented at some conferences and courses (Sundqvist 2002, Sundqvist 2004).

2 Life Cycle Assessments (LCA)

2.1 LCA

LCA (Life Cycle Assessment) is a process to assess the potential environmental burdens associated with a product, a process or an activity. Characteristic parts in a LCA are identifying and quantifying energy and material flows, and evaluating the environmental impacts associated with these flows. The assessment should encompass the entire life cycle of the studied system (the studied system can be a product, a process or an activity), including material and energy raw ware acquisition, manufacturing, usage and waste treatment.

2.2 The LCA framework

The interest for LCA has increased dramatically since around 1990, resulting in development and increased harmonisation of the methodology. ISO standards have recently been issued (ISO 1997; ISO 1998; ISO 1999; ISO 2000).

The framework outlined here is based on the ISO Standard 14040. According to the standard references a complete LCA consists of the following interrelated components:

1. Goal definition and scoping
2. Inventory analysis
3. Impact assessment
   3.1 Classification
   3.2 Characterisation
   3.3 Valuation or weighting
4. Interpretation

In the goal definition and scoping, the purpose of and the range covered by the study should be defined. This includes definition of system boundaries, data requirements, assumptions and limitations.

In the inventory analysis, the inputs and outputs of the system under study are analysed. The inventory step is described in ISO 14041 (ISO 1998). The system is usually a product through its lifetime, but can also be a service or a process. The inputs to the system are for example energy and raw materials. The outputs from the system are for example products and emissions from processes during raw material acquisition, manufacturing, transportation, usage and waste management. The inventory analysis results in tables of inputs and outputs of the system or systems under study.

Impact assessment is a process to characterize and evaluate the influence of the inputs and outputs identified in the inventory analysis. The impact assessment of an environmental LCA should consider the following major categories:

- Resource depletion
- Impacts on human health
- Ecological impacts

Each of these major categories is further divided into several impact sub-categories, see for example ISO 14042 (ISO 1999).

The impact assessment is divided into three steps: classification, characterisation, and weighting. In the classification, the different inputs and outputs are assigned to different impact categories. An analysis and quantification of each impact category is made in the characterisation step. Weighting is the step in which the data of the different specific impact categories are weighted so that they can be compared.

2.3 Some important terms and methods used in LCA

2.3.1 Functional unit

The functional unit is the basis for the calculations in a quantitative life cycle assessment. It is a product, a material or a service for which the environmental loading are quantified. In an absolute LCA the whole life cycle of a specific product, material or service is studied, and the different parts of the life cycle are compared with each other. In this case the functional unit should be, for example, one item of the studied product. On the other hand, in a comparative LCA different products are compared with each other. In that case it is not always relevant to compare the direct products, but more to compare the functions of the products.

The choice of appropriate functional units is of great importance for the LCA. A relevant choice of the functional units is needed for relevant results. For waste management systems it is often preferable to work with several functional units, each one representing an essential utility that is produced from waste. For example, organic degradable waste can be incinerated, anaerobic digested or composted. When incinerated, the product (in Sweden) will be district heating. When anaerobic digested, the products can be district heating, biogas for vehicle or for electricity depending on how the biogas is used. When aerobically digested or composted we also produce a fertiliser. When assessing management of for example organic waste several functional units must be used:
- treatment of a specific amount of waste
- production of a specific amount of district heating energy
- production of a specific amount of electricity
- production of a specific amount of N and P fertiliser (eventually also K fertiliser)
- production of a specific amount of vehicle fuel (for example the amount necessary to drive a buss or a car X km).

In all scenarios and cases the same functional units must be used. If the functional unit is not produced from waste, it has to be produced from another source.

2.3.2 Emission factor

In an LCA the used data is often presented as emission factors and energy factors. Information in databases is often expressed as emission factors. The emission factor gives the emission for a process or sub-process in the life cycle, in relation to an input parameter, for example per weight of product, per weight of a certain element in the product, or related to the energy content of the product. For example, emission of HCl from waste incineration may be expressed as kg HCl emitted per kg Cl in the input to the incinerator. Energy consumption for transport can be presented as MJ fuel (or litres of diesel oil) per kg of transported product and per km transport distance.

2.3.3 System boundaries

The system boundaries define the system that is studied. A LCA is based on the material flows and energy flows over the system boundaries. It is of absolute necessity to have well-defined system boundaries, in order to obtain unambiguous results. Usually the system boundaries can be:
- Geographical boundaries: e.g. disposal of waste generated within a municipality.
- Time boundaries: e.g. the waste generated during one year.
- Functional boundaries: e.g. wastes that can be used for biological treatment.

2.3.4 Allocation

A traditional problem in LCA is how to deal with processes or groups of processes with more than one input and/or output. Some examples are processes or productions with co-products of economic value (multi-output processes), and waste management where several different waste components are treated in the same process with common consumption of raw material and common formation of emissions (multi-input processes). In LCA allocation can be defined as partitioning input or output flows of a unit process to the product system under study (ISO 14040). That means that some proportionate shares the responsibility for environmental impacts caused by processes in a life cycle. General allocation problems in connection with LCA is described in the ISO 14040 – 14043. Allocation problems connected to the waste stages in LCA have been discussed in several reports (e.g. Sundqvist *et al.* 1997; Sundqvist 1999).

3 Economic assessment

Economic assessments have not been subject to standardisation, as life cycle assessments have been for ecological assessments.

Environmental cost is a monetary valuation of the environmental impact caused by the studied system. The calculation of the environmental cost is a part of the weighting step in LCA. There are several principles for valuation the environmental impact.

Life cycle cost is the sum of all financial costs (capital costs and operational costs), from the cradle to the grave for the system under study. Also taxes and fees are included, for example the landfill tax.

Welfare costs or societal cost is the sum of environmental cost and life cycle cost (in the life cycle costs the environmental-related taxes and fees are not included).

4 The ORWARE Model

The simulation model ORWARE has been used for assessing waste management schemes for municipal solid waste. The framework of the model has been developed during the past ten years in several research projects. Descriptions of ORWARE can be found in several reports and articles, e.g. (Björklund 1998; Carlsson 1997; Dalemo *et al.* 1997a; Dalemo *et al.* 1997b; Soneson *et al.* 1997, Sundqvist *et al.* 1999, Eriksson *et al.* 2000, Sundqvist *et al.* 2002; Eriksson *et al.* 2002). This paper presents the results from the latest report (Sundqvist *et al. 2002).*

ORWARE is a model for the calculation of substance flows, energy flows, environmental impacts, and costs of waste management. It was first developed for systems analysis of organic waste management, hence the acronym ORWARE (ORganic WAste REsearch), but now the model covers inorganic fractions in municipal waste as well.

ORWARE consists of a number of separate submodels, which may be combined to describe a waste management system. Each submodel describes a process in a real waste management system, e.g. waste collection, waste transport, or a waste treatment facility (e.g. incineration).

4.1 Methods and general description of the model

All submodels in ORWARE calculate the turnover of materials (including the emissions), energy and financial resources in the process. Processes within the waste management system are e.g. waste collection, incineration, anaerobic digestion, composting, material recycling and landfill disposal. Materials turnover is characterised by (1) the supply of waste materials and process chemicals, (2) the output of products and secondary wastes, and (3) emissions to air, water and land. Energy turnover is the use of different energy carriers such as electricity, coal, oil or heat, and recovery of e.g. heat, electricity, hydrogen, or biogas from waste treatment processes. The financial turnover is defined as costs of individual processes. The financial costs are calculated in a life-cycle perspective from the cradle to the grave.

The sub-models may be combined to describe the waste management system in a city or municipality (or other system boundary). Such a conceptual ORWARE model of a complete waste management system is shown in Figure 1.

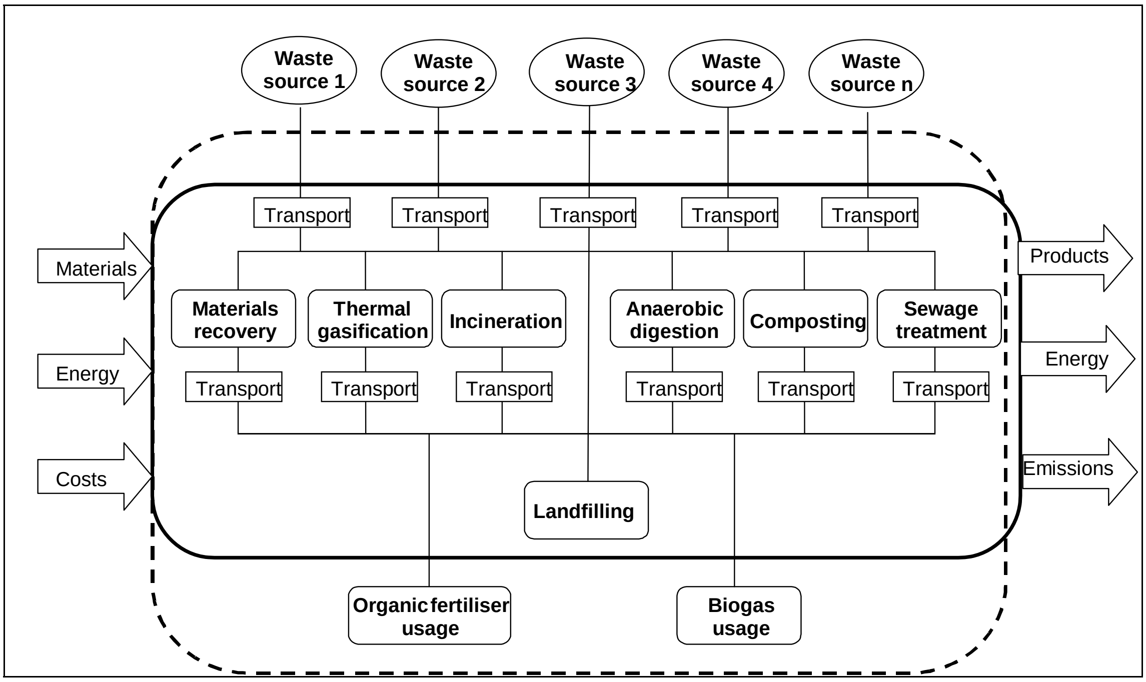


Figure 1. A conceptual model of a complete waste management system comprising different processes described by different submodels (Sundqvist et al, 1999; Sundqvist et al, 2002)

At the top of the conceptual model in Figure 1 there are different waste sources, followed by different transport and treatment processes. The dashed line in the Figure defines the boundaries of the waste management core system, where wastes are treated and different products are formed.

Another important topic is the “from-cradle-to-grave”-perspective. Both upstream processes (“cradle”) and down-stream processes (“grave”) are considered. Examples of up-stream and down-stream processes are:

- If electricity is consumed in a process, the environmental impact and resources consumption from the production is included as an up-stream process. If the electricity is produced from coal condense power also the landfilling of coal ash is included as a down-stream process.
- If oil is consumed in a process, the environmental impact and resource consumption related to the production and distribution of the oil are included.

4.2 Life Cycle Assessment in ORWARE

The substance flow analysis carried out in ORWARE generates data on emissions from the system. The individual emissions are aggregated into different environmental impact categories, according to LCA practice (see for example ISO 14042 Life Cycle Impact Assessment). The following impact categories are assessed: global warming, acidification, eutrophication and photooxidant formation. Also ecotoxicity and human toxicity have been studied, but the models for weighting different toxic emissions are not fully developed so the results have to be considered carefully.

The system boundaries are of three different types: time, space and function. In an analysis of a certain system, the temporal system boundaries vary between different studies (depends on scope of the study) and also between different submodels. Most of the process data used are annual averages, but for the landfill model as well as the arable land model also long-term impacts are included (Björklund 1998; Sundqvist *et al.* 1999).

There is a geographical boundary delimiting the waste management system as shown in Figure 1, whereas emissions and resource depletion are included regardless of where they occur. The system boundaries in ORWARE are chosen with a LCA perspective, thus including in principle all important processes that are connected to the life cycle of the waste management system. We have included environmental impact and resource consumption for up-stream and down-stream processes. Construction, demolition and final disposal of capital equipment are not included regarding energy consumption and emissions but are included for economy. This is according to common LCA practice. A literature survey was made about energy input during the construction phase and compared to the energy input and output during the whole life cycle (Sundqvist *et al.* 2002). It was found that the energy consumption and environmental impact from the construction phase can be neglected. However if only processes with low energy turnover are studied, the energy consumption from construction may be of importance, e.g. when comparing composting and landfilling (without gas recovery).

The studied system works with several functional units. The major function of the waste management system is to treat the waste. The waste management system can produce different products (functions) from the waste:

- energy: district heating, electricity and biogas (the biogas can be used as vehicle fuel or as an energy source for electricity and district heating).
- fertilisers: a digestion residue or compost containing e.g. nitrogen (N) and phosphorus (P).
- plastic granules from recycling of plastic packages.
- cardboard from recycling of cardboard packages.

Each of these waste products has an alternative virgin raw material source with a production process that has been included in the studied system. All studied systems produce the same amount of “products” (see also Figure 2):

- energy (district heating, electricity, and vehicle fuel

- fertilisers (N- and P-fertilisers),
- plastic granules
- cardboard pulp

This alternative system outside the waste system, which produces the same products as the waste management system, is called the compensatory system. The approach with the compensatory system enables a quantitative comparison of environmental, economic and energy parameters between the use of waste as raw material and the use of virgin raw materials.

Compensatory systems also have up-stream and down-stream processes. For electricity, the up-stream process includes production of the fuel used for production of electricity, and the down-stream process is disposal of waste from the energy generation. Therefore, each treatment alternative in ORWARE has its own unique design of the core system as well as different compensatory systems.

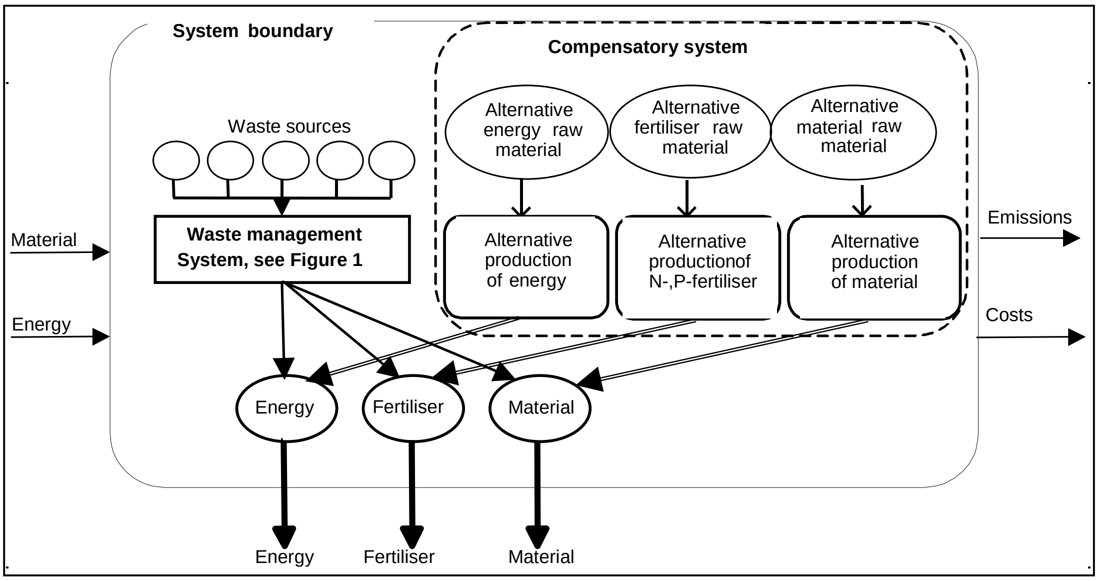


Figure 2. The studied system: the waste management system (as in Figure 1) and the compensatory system with alternative production of energy, material and fertiliser (Sundqvist et al, 1999; Sundqvist et al, 2002)

The total system that is analysed consists of the following parts:

- the waste management system with different submodels i.e. the core system of the waste management system
- the compensatory system
- key flows of material and energy connected to up-stream and down-stream systems

4.3 Overview of some sub-models in ORWARE

4.3.1 Collection and transports

The transport sub-model has been described in Dalemo *et al.* (1997). The transport sub-model is divided into three blocks: "garbage truck", "ordinary truck", and "truck and trailer". They have the same structure while the parameters differ. From different demographic data the model first calculates the transport distance. For each transport block there is specific fuel consumption (MJ per km). The emissions are calculated from the fuel consumption by emission factors.

4.3.2 Incineration

The original incineration model has been described in Dalemo *et al.* (1997) and Björklund (1998). Since then the model has been updated (Sundqvist *et al.* 1999; and Sundqvist *et al.* 2002). The incineration plant that is modelled is a modern plant that with good margins fulfils the requirements in the EU waste incineration directive. The emission data is based on emissions from a real incineration plant. The plant has an advanced flue gas cleaning system, including a flue gas condensation step where energy is recovered by heating pumps. The incineration plant produces district heating.

4.3.3 Landfill

There are several landfill models for different kind of wastes. In this study we have used:
- Municipal solid waste landfill
- Landfills for ashes and slag. There are separate models for
  - Bottom ash and slag from waste incineration
  - Fly ash and flue gas cleaning waste from waste incineration
  - Ash and slag from biofuel combustion (in the compensatory system)

There is also a "biocell" model and a sewage sludge landfill model, but they are not used in the current study.

The landfill models are described in detail in earlier reports (Björklund 1998; Fliedner 1999). Some basic theory of how landfilling can be handled in LCA is given in e.g. Sundqvist (1999).

The landfilled waste undergoes different degradation processes, similar to anaerobic digestion. The degradation occurs rather slowly. The time aspects in our landfill model for organic materials are based on the two time horizons:

- the **surveyable time** period, which is the time until some kind of pseudo-steady-state is obtained. For a conventional municipal solid waste landfill this corresponds to the end of the methane production phase, which is estimated to be of the magnitude of one century.

- the **hypothetical, infinite time** period, which is the period until the landfilled material is completely released to the environment.

In this paper, only the emissions during the surveyable time period are presented.

In a municipal solid waste landfill close to 100 % of sugar, starch, hemicellulose, fats, and proteins and about 70 % of the cellulose are degraded during the surveyable period. Plastics are degraded to 3 % and humus and lignin are assumed to be undegradable. Landfill gas, consisting of mainly methane, carbon dioxide and water is produced during the degradation. We have assumed that 50 % of the theoretically produced landfill gas is recovered (during the surveyable time period) and used as a fuel in a gas engine producing electricity and heat. The rest of the landfill gas will migrate to the ambient air. During the passage through the landfill cover about 15 % of the methane gas is oxidised into carbon dioxide. The remaining methane gas is emitted as a greenhouse gas. The leachate water is treated in a local treatment plant, reducing COD-, N- and P-emissions to water.

4.3.4 Anaerobic digestion

The original anaerobic digestion model has been described in earlier reports (Dalemo 1996; Dalemo *et al.* 1997). Since then the model has been adapted to a thermofile process.

The incoming domestic food wastes are packed in plastic bags. In a bag separator the bags are cut and emptied and separated from the degradable material. Slaughterhouse wastes are hygienised at 70 or 130^{0}C before digestion. The water content is adjusted to about 85 % and the waste is fed into the digestion reactor. The hydraulic residence time in the reactor is 20 days.

The study addressed two ways to use the biogas:

1. The gas is upgraded to 97 % CH_4 and compressed to 250 bars. The gas is then used as fuel for busses.
2. The gas is combusted in a gas engine, where both electricity and heat (for district heating) is produced.

The digestion residue or digestate is spread on agricultural land, thus substituting chemical P and N fertiliser. During the spreading a lot of ammonia can be released. A new, improved spreading technology was modelled where the digestate is worked down in the soil simultaneously with the spreading.

4.3.5 Composting

In the study, open windrow composting was modelled. About 50 – 75 % of the organic material is degraded into carbon dioxide, water and compost. The degradation rate is different for different organic compounds. During the process ammonia is released to air. In a separate study the emissions from ”closed” compost or reactor compost were estimated, where the exhaust gases are treated to separate out ammonia. The compost is spread on agricultural land, thus substituting chemical N- and P- fertiliser.

4.3.6 Plastic recycling

70 % of the plastic packages are sorted out by the households and are collected at special “recycling stations” by a bring system (each recycling station serves about 1000 – 1500 inhabitants. The plastic waste is transported to a primary separation plant where about 40 % are rejected. The reject is transferred to an incineration plant. The plastic fraction is washed and milled, and processed to granules. These granules are supposed to substitute virgin plastic granules. It was assumed that 1 kg of recycled plastic granules can substitute 1 kg of virgin plastic granules.

4.3.7 Cardboard recycling

70 % of the cardboard packages are sorted out by the households and are collected at special "recycling stations" by a bring system (each recycling station serves about 1000 – 1500 inhabitants. The cardboard waste is transported to a cardboard mill where recycled cardboard pulp is produced. About 20 % of the input is rejected during the process. After discussing quality aspects with the pulp mill we have assumed that 1.15 kg of recycled cardboard pulp can substitute 1.0 kg of virgin cardboard pulp.

5 Earlier ORWARE studies

In the first stage of the study (Sundqvist *et al*, 1999; Eriksson et al 2002b), three different municipalities with very different characteristics were studied:

- Stockholm, the capital of Sweden, is a big city with an incineration plant and a system for district heating. There is no arable land within the municipality borders (arable land is needed for spreading of the organic fertiliser produced from biological treatment of the organic waste). The source-separated wastes are collected in "recycling stations", each one serving 1000 – 1500 inhabitants, while the rest waste is collected at the households. Stockholm City has app. 750 000 inhabitants.
- Uppsala is a relatively big municipality, also with an incineration plant and a system for district heating. Arable land can be found close to the city area. The source-separated wastes are collected in "recycling stations", each one serving 1000 – 1500 inhabitants, while the rest waste is collected at the households. Uppsala municipality has app. 186 000 inhabitants.
- Älvdalen is a municipality with a rather low population living on a large area. Älvdalen has no incineration plant and no system for district heating. There is hardly any agricultural land within the municipality. Älvdalen municipality has 8 100 domiciled inhabitants plus a great number of tourists from season to season. In Älvdalen some of the most famous Swedish ski-centres are located which means that during short time periods, tourists produce large amounts of waste with a low degree of source separation. In Älvdalen the source separated wastes and the rest fraction is collected at a central place in each village. As an average, there are about 135 people in each village.

The results showed that the same conclusions could be drawn in all three municipalities. The ranking between different waste management options was the same. The following conclusions were drawn for all three municipalities:

1. The study showed that decreased amounts of waste to landfilling, and increased amounts to energy recovery and material recycling were positive, from an environmental and energy point of view, as well as from a welfare economic and a life cycle cost point of view. This means that landfilling of energy-rich waste should be avoided as far as possible. The negative results for landfilling depended on both environmental impact from the landfill (especially greenhouse gases), and a low recovery of resources, which gave rise to more energy consumption, environmental impact and costs in the compensatory system.
2. The waste management system in all three municipalities should be based on incineration, even if the waste had to be transported to a regional facility. Once the waste is collected,

longer regional transports are of little significance (from an energetical, environmental and economic point of view), as long as the transports are carried out in an efficient way.

3. When comparing materials recycling and incineration, and biological treatment and incineration, no unambiguous conclusions could be drawn. There are benefits and drawbacks associated with all these waste management options:
    - Materials recycling of plastic containers was comparable to incineration from a welfare economic aspect, but gives less environmental impact and lower energy use – on condition that the recycled plastic replaces virgin plastic.
    - Materials recycling of cardboard was comparable to incineration concerning welfare economy and energy, but has both environmental advantages and disadvantages.
    - Anaerobic digestion of easy degradable waste gave a higher welfare economic cost than incineration, and had both environmental advantages and disadvantages. Conclusions regarding energy use depended upon how the biogas was used.
    - Composting of easy degradable waste was comparable to anaerobic digestion from a welfare economic aspect, but gave higher energy use and environmental impact than both anaerobic digestion and incineration.

6 System study

Data presented in this section is from the final report (Sundqvist *et al.* 2002).

6.1 Objectives

The objectives of the second stage were to study how general the results from the first stage were, and to identify parameters that could shift the results.

6.2 System boundaries

Based on the results in the first stage, the second stage was based on a hypothetical municipality, where different parameters were varied more systematically in sensitivity analyses. The chosen hypothetical municipality was based on Uppsala, which has 186,000 inhabitants and consist of a city area, a “suburban” area, and a rural area. The municipality has a waste incineration facility and a district heating system. All transport distances and similar demographic data were taken from the Uppsala case study, but were varied in the sensitivity analysis.

Domestic waste and similar waste from business and industry were studied. The total amount of waste is app. 69,000 tonnes/year. In all scenarios newsprint paper (75 %), glass packages (70 %) and metal packages (50 %) are sorted out and recycled “outside” the studied system (is not included in the 69,000 tons of waste). The remaining paper, glass and metal are present in the waste studied.

The time frame studied was one year. The waste amount corresponds to one year’s generation of waste in the studied municipality.

Important assumptions are the choices of upstream and compensatory energy sources. In this study, the electricity has been assumed to be produced by combined heat and power plants (CHP). CHP has been judged to be the so-called base load marginal technology, in which new investments are made. A change in electricity generation or consumption in the studied waste management system (including the compensatory system) is supposed to affect the base load technology.

The design of the district heating systems is special for each municipality. There are about 100 separate district heating systems in Sweden. The fuel that competes with waste can be peat, wood chips, oil or coal, depending on several factors such as the heat demand, when the demand is raised, the prices for different fuels, existing combustion facilities, etc. Biofuel (wood chips) was chosen to be the compensatory heat, because biofuel seems to be the most common fuel for district heating today. In the sensitivity analysis also oil was studied as compensatory heat.

The studied parameters are according to Table 1 (see also Tables 2 and 3 for weighting factors).

Table 1. Impact categories that have been studied

Environmental impact:	Global Warming Potential
	Acidification Potential
	Eutrophication Potential
	Photooxidant formation, divided into
	- VOC
	- NO_X
	(Ecotoxicity)*
	(Human toxicity)*
Energy consumption	Total consumption of primary energy carriers
	Consumption of non-renewable primary energy carriers
Economy	Financial life cycle costs
	Environmental costs (by three different methods for valuation of emissions and energy resources)
	Welfare economy (which is the sum of the two above)

* the results from the ecotoxicity and human toxicity assessment are uncertain and is not referred in this paper.

The weighting factors used for characterisation and valuation is presented in Tables 2 and 3. The impact category "photooxidant formation" is divided into two sub-classes: NO_X and VOC, which are obtained from the inventory result.

Table 2. Environmental impact categories studied and weighting factors used

	Global warming	Acidification	Eutrophication	Photooxidant formation	
	kg CO_2-equiv. /kg	*kg SO_2-equiv./kg*	*kg O_2-demand/kg*	*NO_X kg NO_X/kg*	*VOC kg ethene-eq./kg*
CO_2 (fossil) (to air)	1				
N-NO_X (to air)		0,7	6	1	
N-N_2O (to air)	310				
S-SO_2 (to air)		1			
CH_4 (to air)	21				0,006
N-NH_3 (to air)		1,88	16		
HCl (to air)		0,88			
N-NH_4 (to water)			15		
N-NO_3 (to water)			4,4		
COD (to water)			1		
P (to water)			140		
VOC (to air)					0,416
CO (to air)					0,03

Table 3. Economic weighting factors used in the study

	Economic weighing ORWARE *SEK/kg**	Economic weighing EPS 2000 *SEK/kg**	Economic weighing EcoTax´99 *SEK/kg**
CO_2 (fossil) (to air)	0,4	0,92	0,40
Particles (dust) (to air)		306	31,5
N-NO_X (to air)	54	18	34,50
N-N_2O (to air)	124	326	88000
S-SO_2 (to air)	34	27,80	53,30
CH_4 (to air)	8,4	23	3,40
N-NH_3 (to air)			46,80
HCl (to air)	68		
N-NH_4 (to water)	47	-3,60	54,50
N-NO_3 (to water)			15,8
COD (to water)	3	0,01	3,80
P (to water)	439	0,50	
VOC (to air)	1,49	18	121
CO (to air)	0,11	2,80	0,60
Pb (to air)	310 000	24735	7 800 000
Pb (to water)	310 000		96 400
Pb (to land)	310 000		3700
Cd (to air)	1 123 000	87	3 730 000
Cd (to water)	1 123 000		617 000
Cd (to land)	1 123 000	46	30 000
Hg (to air)	232 000	522	3 910 000
Hg (to water)	232 000		20
Hg (to land)	232 000	1649	1300
Cu (to air)	0	0	3 910 000
Cu (to water)	0	0	20
Cu (to land)	0	0	1300
Cr (to air)	0	170	599 000
Cr (to water)	0	0	570
Cr (to land)	0	0	
Ni (to air)	0	0	551 000
Ni (to water)	0	0	3 380
Ni (to land)	0	0	3 400
Zn (to air)	0	360	120 000
Zn (to water)	0	0	6,70
Zn (to land)	0	0	3 100
Consumption of biomass	0	0,34	0
Consumption of crude oil	0	4,30	11,70
Consumption of coal	0	0,42	0,16
Consumption of natural gas	0	9,35	8,83

6.3 Scenarios

The wastes included in the study are shown in Table 3.

Table 3. Amount and composition of waste (tons/year)

	Detached houses	Flats	Rural houses	Domestic waste, sum	Waste from business*	**Total waste**
Degradable waste	5 642	9 490	2 655	17 787	5 645	**23 432**
Non-combustible residue	549	924	258	1 732	1 408	**3 140**
Combustible residue	1 930	3 246	908	6 085	7 370	**13 455**
Diapers	831	1 398	391	2 621		**2 621**
Rubber, textiles, etc.	401	674	189	1 264		**1 264**
Dry paper	2 762	4 645	1 300	8 706	3 678	**12 384**
Cardboard	787	1 324	370	2 481	1 096	**3 577**
Plastic sheets and bags	327	549	154	1 030	488	**1 518**
Plastic containers	223	375	105	702	340	**1 042**
Laminate	163	275	77	515		**515**
Glass	950	1 598	447	2 996	340	**3 335**
Metals	282	474	133	889	1 592	**2 481**
Sum	**14 848**	**24 972**	**6 988**	**46 809**	**21 957**	**68 765**

* Exclusive construction and demolition wastes

The scenarios are given in Table 4. They were chosen to illustrate the alternatives that are discussed in several Swedish municipalities today. The landfilling scenario was chosen to illustrate the need for decreased landfilling – the earlier studies had already shown that conventional landfilling was a bad option.

Table.4. Description of scenarios

Incineration: Incineration of all waste.
Landfilling: Landfilling of all waste.
Anaerobic digestion – bus: Anaerobic digestion of biodegradable waste. The biogas is used as fuel for busses. The rest of the waste is incinerated.
Anaerobic digestion - heat/el: Anaerobic digestion of biodegradable waste. The biogas is used for production of district heat and electricity. The rest of the waste is incinerated.
Composting: Composting of biodegradable waste in open windrows. The rest of the waste is incinerated.
Plastic recycling: Sorting out 70 % of HDPE from households and 80 % of HDPE and LDPE from business for material recycling. The rest of the waste is incinerated.
Cardboard recycling: Sorting out 70 % of cardboard from households and 80 % of cardboard from business for material recycling. The rest of the waste is being incinerated.

Some of the specific data used in the study are:

- The thermal efficiency (defined as produced amount of district heating, divided by the lower heating value in the waste) of the waste incinerator is 91 %, exclusive the flue gas condensation. The contribution from the flue gas condensations depends on moisture content in the waste, 80 % of the condensation heat is recovered. The NO_X-emission from the incinerator is 75 mg/MJ.
- The fuel used in compensatory district heating is biofuel with a total thermal efficiency of 109 % (based on the lower heating value), inclusive heat recovered from flue gas condensation.
- The fuel used in compensatory electricity production is natural gas in combined heat and power plants (CHP).
- Distances to all treatment plants are 7 km for waste from flats and apartments and, 10 km for waste from one-family houses, and 15 km for waste from rural areas.
- The average distance from anaerobic digestion plant or composting plant to arable land is 8 km.

All these assumptions were varied in a sensitivity analysis.

6.4 Sensitivity analyses

Several important choices were made in the goal definition and scoping stage, e.g. when choosing system boundaries and when using process data, see Section 5.3 above. The potential importance of different "municipality specific" and "site specific" parameters were studied in a sensitivity analysis. The results were thoroughly analysed to identify parameters that potentially could have an influence on the results. The following parameters were found to be of interest in the sensitivity analysis:

- Different methods of electricity production in the compensatory system: natural gas combined heat and power, coal condense or "average" Swedish electricity. The Swedish average electricity production is based on mainly hydropower and nuclear power, which gives very small environmental impact for the studied impact categories.
- Different fuels for district heating in the compensatory system: biofuel or oil.
- A variation of performance characteristics on waste incineration and alternative district heating production. Especially thermal efficiency and NO_X-emissions are of interest.
- The technical function of the incineration facility: Combined heat and power production from waste or heat station only.
- Different distances to waste treatment plants and recycling plants (from the centres of population).
- Different distances to arable land for compost and anaerobic digestion residue.
- Different economic weighting for the environmental costs

7 Results

Results for global warming, acidification, eutrophication, energy consumption, financial costs and total costs are displayed in diagrams below.

7.1 Environmental impacts

In the diagrams the waste system is displayed as one data category. This category comprises all processes in the waste management system as collection, transports, and the type of treatment used in the specific scenario including downstream processes as landfilling of residues and spreading of organic fertiliser.

7.1.1 Global warming

Figure 3 presents the results for global warming (emissions of greenhouse gases). Greenhouse gases are especially CO_2 from combustion of fossil fuels and plastic, and methane gas from landfilling of organic waste. Landfilling gives the worst impact due to methane emissions from the landfill. It should be observed that the landfill has a landfill gas recovery system and produces electricity from the landfill gas – even if the efficiency of the gas recovering system is poor (only 50 % of the generated methane gas is recovered), see Björklund (1998), and Sundqvist (1999). Recycling of plastic and anaerobic digestion show lower impact than incineration, because fossil fuels are saved when plastic is recycled, as well as fossil fuels are replaced when utilising the biogas.

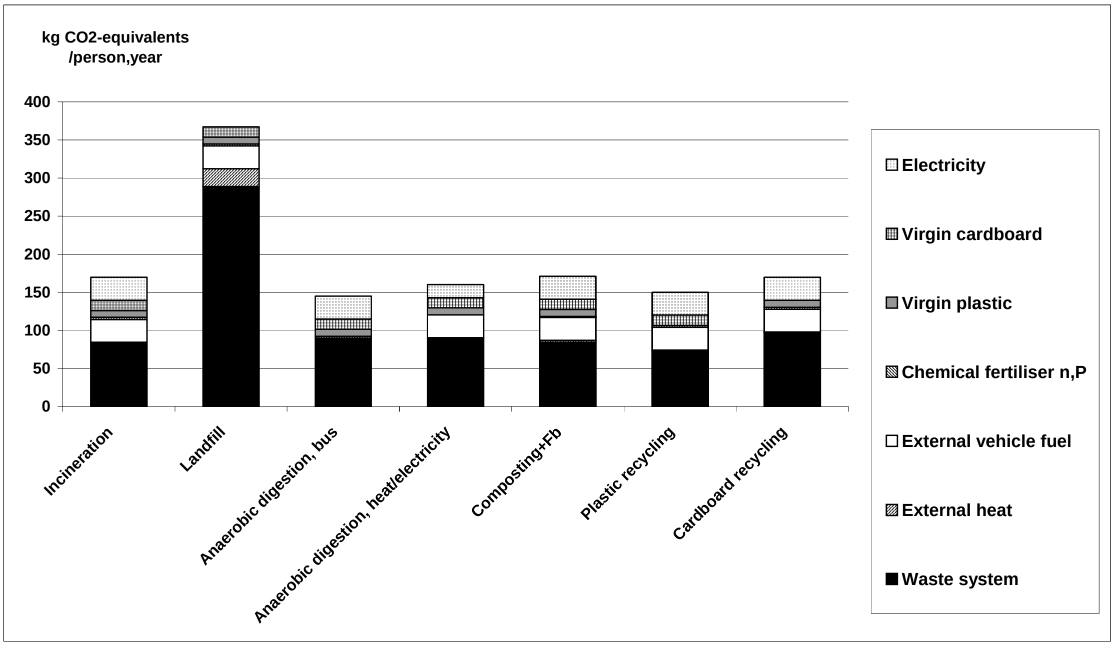


Figure 3. Emissions of greenhouse gases

7.1.2 Acidification

Emissions of acidifying substances are presented in Figures 4. Acidifying substances are mainly gases such as SO_2 (from e.g. fossil fuels), HCl (from waste incineration), NO_X (from all combustion processes: incineration, district heating production, engines, etc.), and ammonia from composting and from spreading of compost and anaerobic digestion residue. Landfilling gives the highest emissions of acidifying gases, due to emissions from the landfill gas combustion, and from district heat production in the compensatory system. Composting gives a high emission due to ammonia releases from the compost process. Anaerobic digestion with production of heat and electricity gives high NO_x-emissions from the combustion engine.

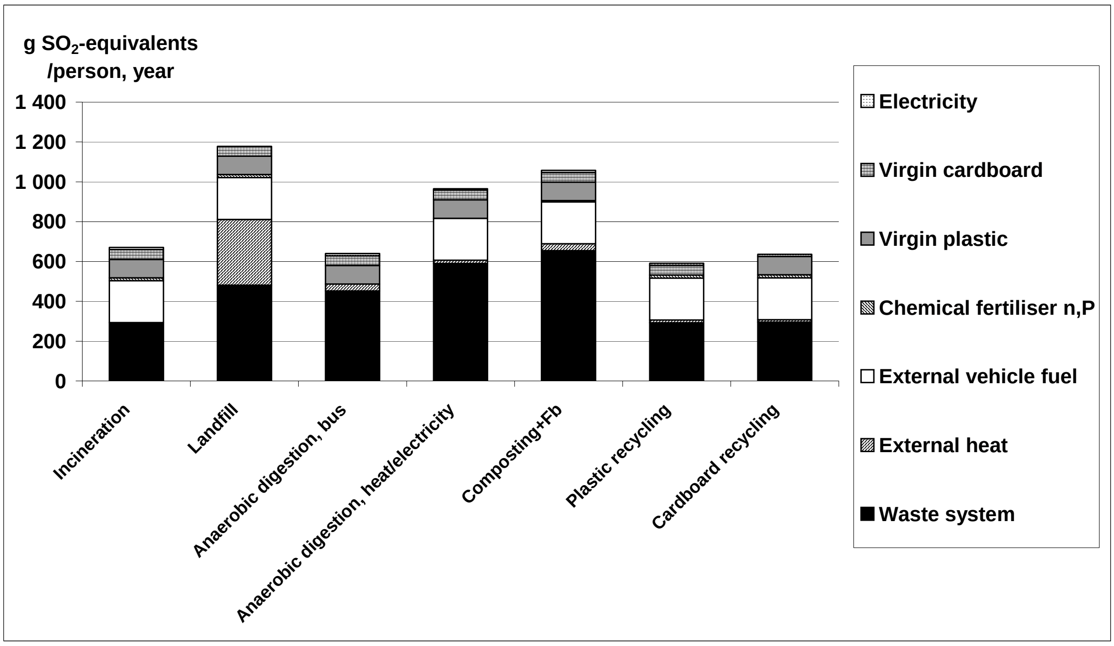
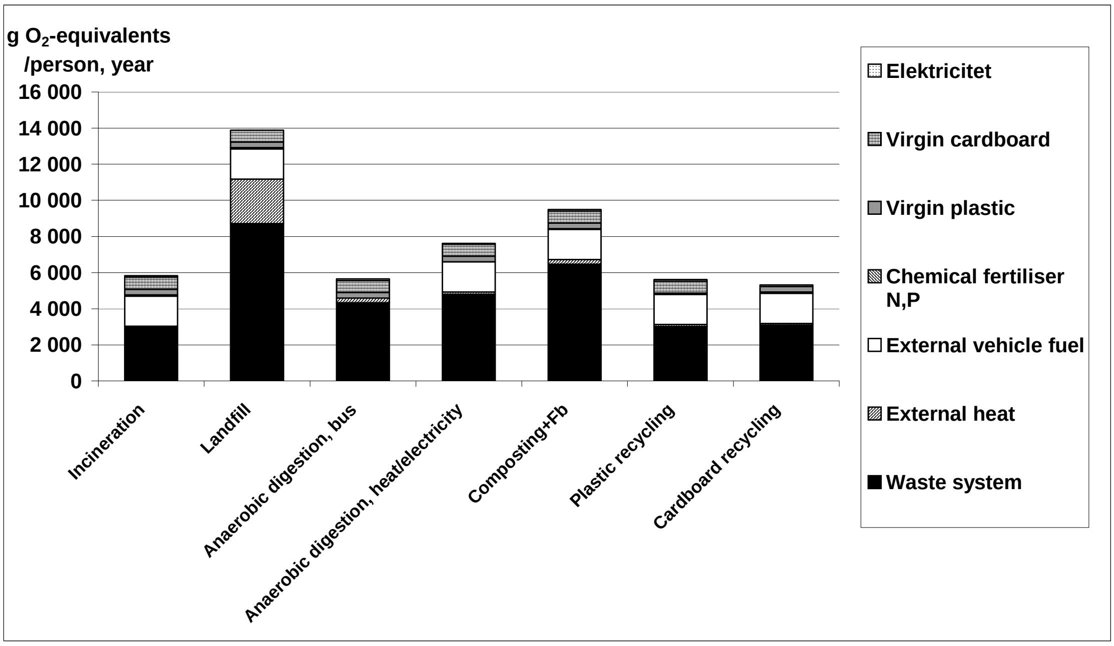


Figure 4. Emissions acidifying substances

7.1.3 Eutrophication

The emissions of eutrophicating substances are given in Figures 5. Eutrophicating substances are Nitrogen and Phosphorus compounds (N and P compounds) and COD (Chemical Oxygen Demand) in water, NO_X in combustion gases and ammonia (NH_3) releases from spreading of anaerobic digestion residue and compost. Landfilling gives the highest eutrophication impact depending on N- and P-compounds in the leachate water. Anaerobic digestion and composting causes emissions from spreading of the digestion residue respectively compost. The spreading model is based on new spreading technique where the material (digestion residue or compost) is cultivated into the soil and immediately covered with soil to decrease the release of ammonia[1]. Recycling of materials gives just slightly lower impact than incineration.



Figur 5. Emissions of eutrophicating substances

7.1.4 Photooxidant formation

Photooxidant formers have been divided into VOC (volatile organic compounds) and NO_X. The VOC emissions are shown in Figure 6, and the NO_X emissions in Figure 7.

Methane is included in VOC but has another weighting than other VOC:s. Landfilling gives the highest emissions due to the methane emissions. Anaerobic digestion gives higher emissions than incineration, depending on emissions from the biogas use.

Landfilling gives the highest NO_X-emissions, depending on emissions both from the landfill gas combustion, and from the district heat production in the compensatory system. The two anaerobic

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[1] In the former study (Sundqvist *et al*, 1999) the digestion residue and compost were just spreaded on the soil, which causes a lot more releases of ammonia.

digestion alternatives give different results. Using the biogas as bus fuel gives lower emissions of NO_X than using the biogas for electricity and heat production in a gas engine.

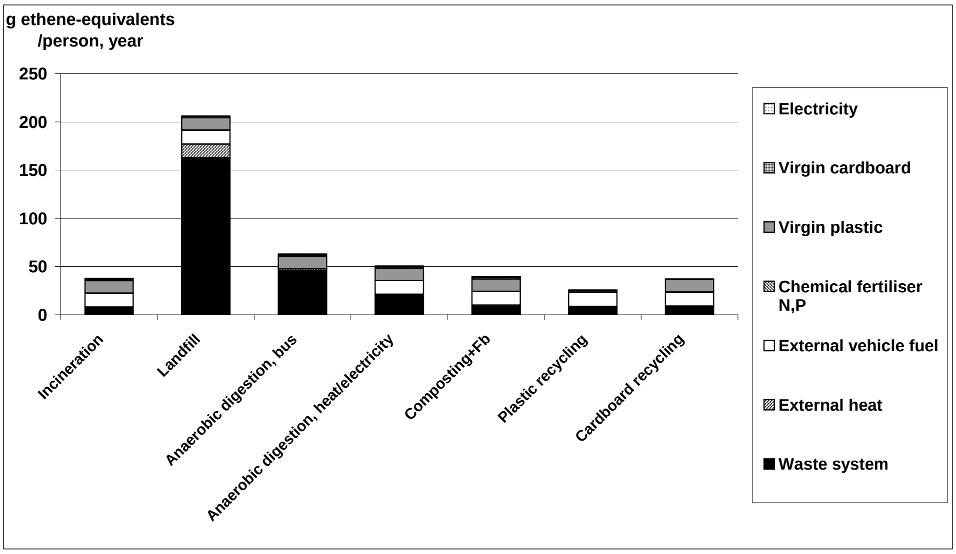


Figure 6. Emissions of photooxidants - VOC

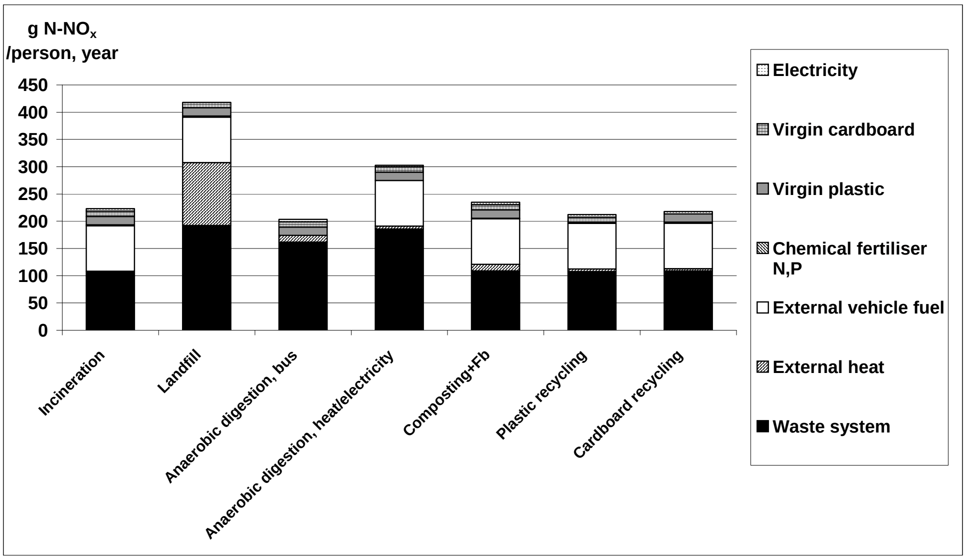


Figure 7. Emissions of photooxidants - NO_X

7.2 Energy - consumption of primary energy carriers

In Figures 8 and 9, the energy consumption for the different scenarios is given. There is a net consumption of energy for the whole system (including the compensatory system). In general the differences in energy consumption between the scenarios are small, except for the landfill scenario which consumption of energy resources is much higher. This is because of the production of district heating, fuels, fertilisers, plastic and cardboard in the compensatory system. The lowest total consumption can be seen for recycling of plastic package waste. Another result from the study, not shown in the diagrams, is that the energy consumption for collection and transports of waste is small compared to the energy consumption of the other processes in the studied system.

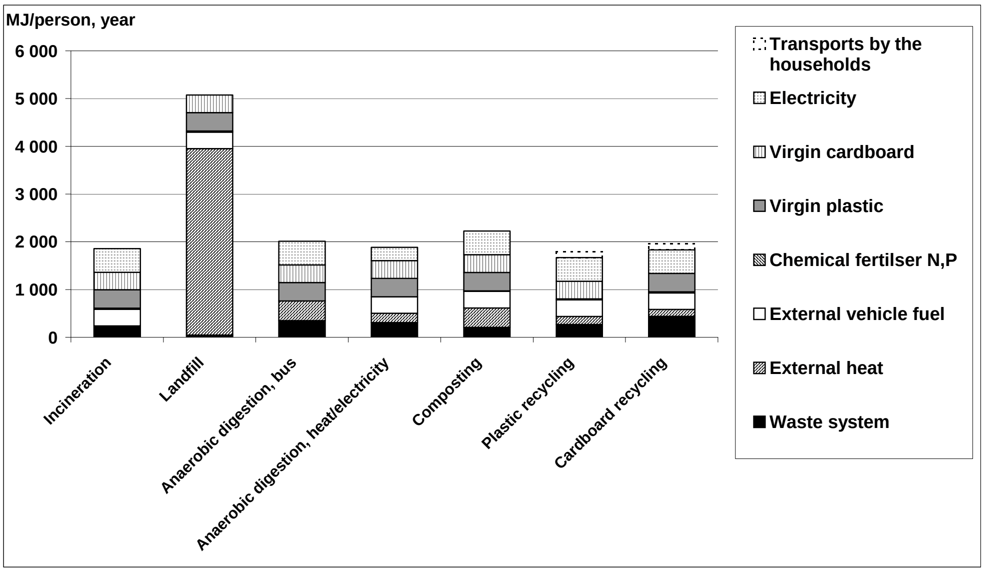


Figure 8. Consumption of primary energy carriers – total consumption for different processes

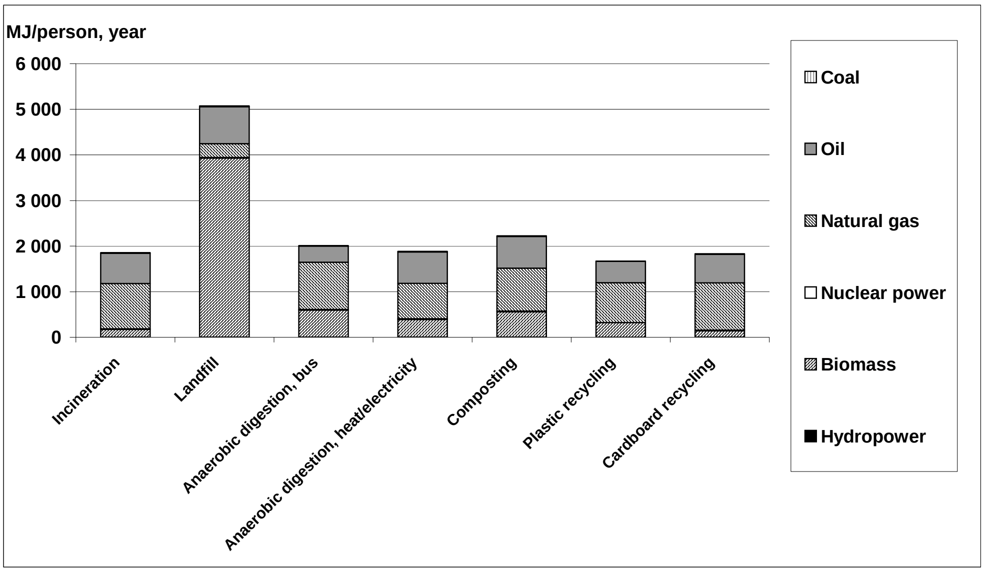


Figure 9. Consumption of primary energy carriers – consumption of different primary energy carriers

7.3 Economy

7.3.1 Financial life cycle costs

The financial life cycle costs are shown in Figure 10. The financial life cycle costs are only slightly higher for the recycling scenarios than for incineration. Biological treatment (anaerobic digestion and composting) is more expensive than incineration. Landfilling is the most expensive waste treatment due to the landfill tax, and because of the costs for producing new district heating and vehicle fuel in the compensatory system.

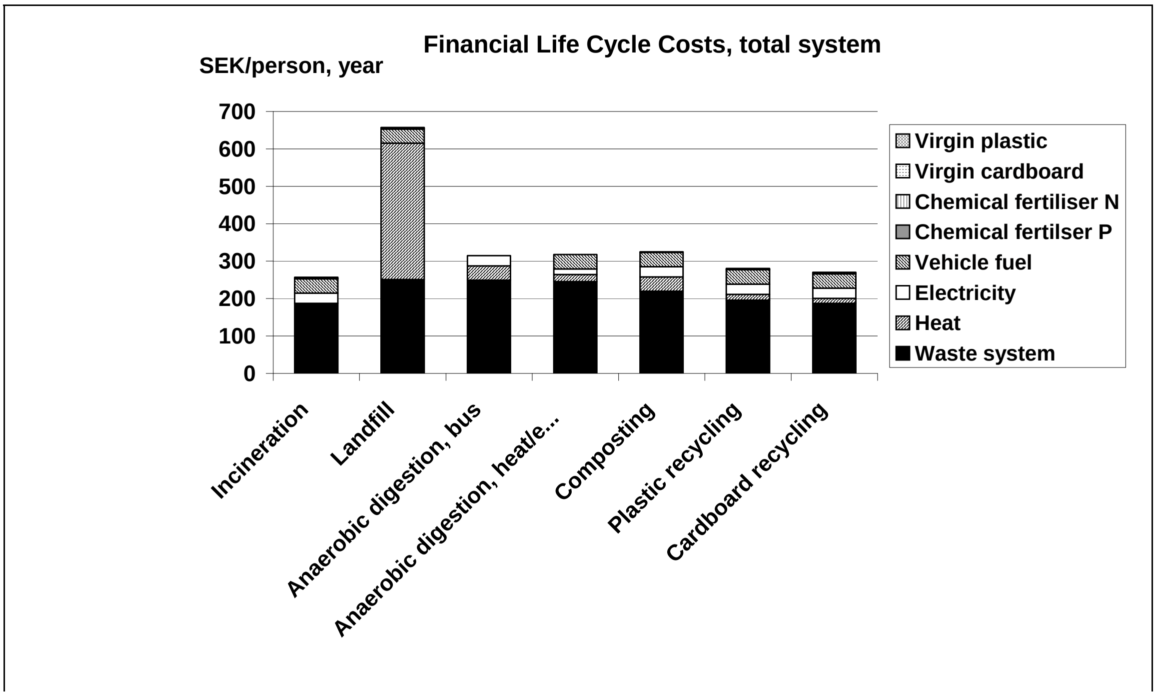
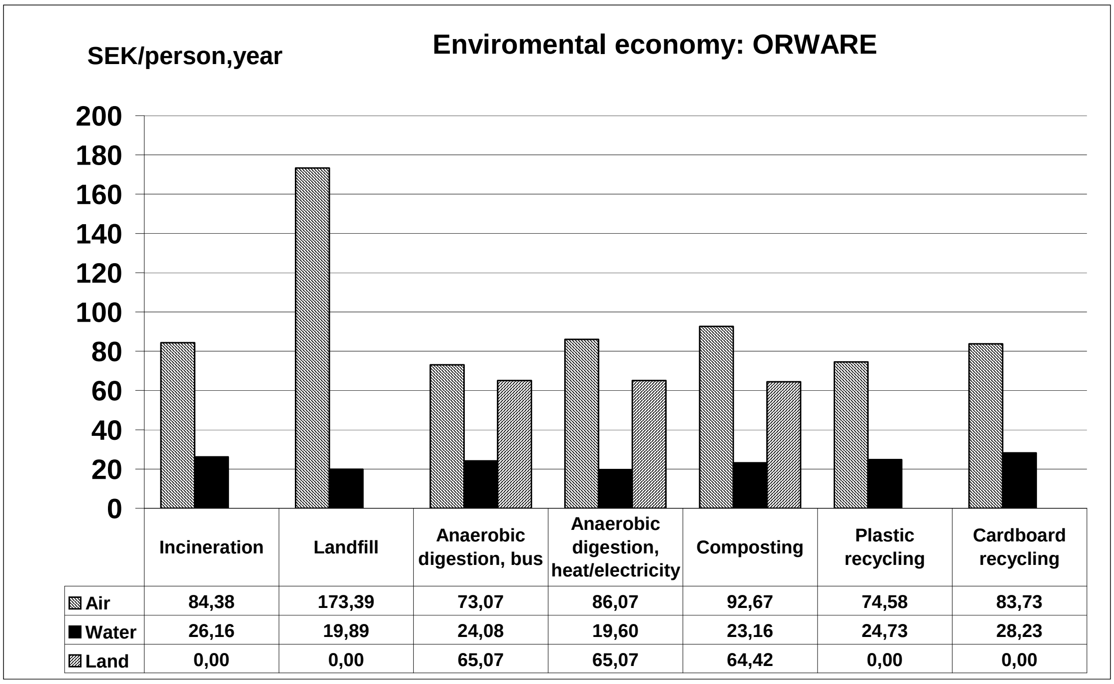


Figure 10. Financial Life Cycle Costs

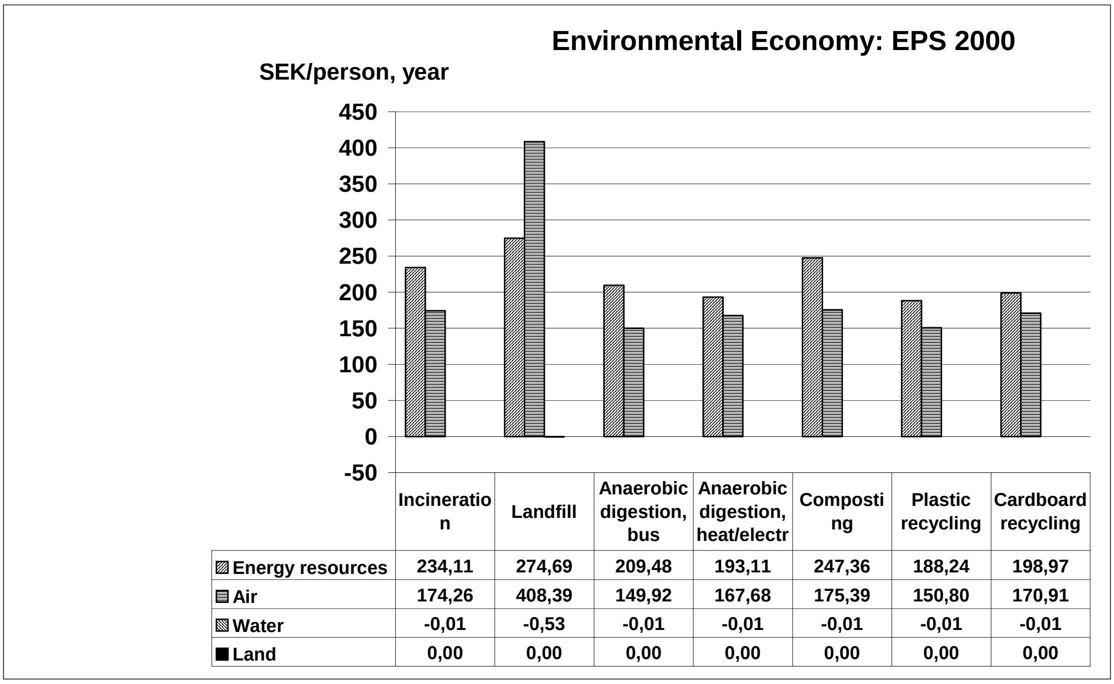
7.3.2 Environmental costs

The environmental costs have been calculated with three different methods. The results are shown in Figures 11, 12, and13. The three methods give different results. The tendency is the same for all methods, but the costs are lower in "ORWARE" than in EPS 2000, which in turn is lower than ECOTAX. The largest difference is found for the recycling scenarios. ORWARE has no valuation of the natural sources, but EPS 2000 and ECOTAX 99 have, which makes recycling more favourable in EPS 2000 and ECOTAX 99, than in ORWARE.



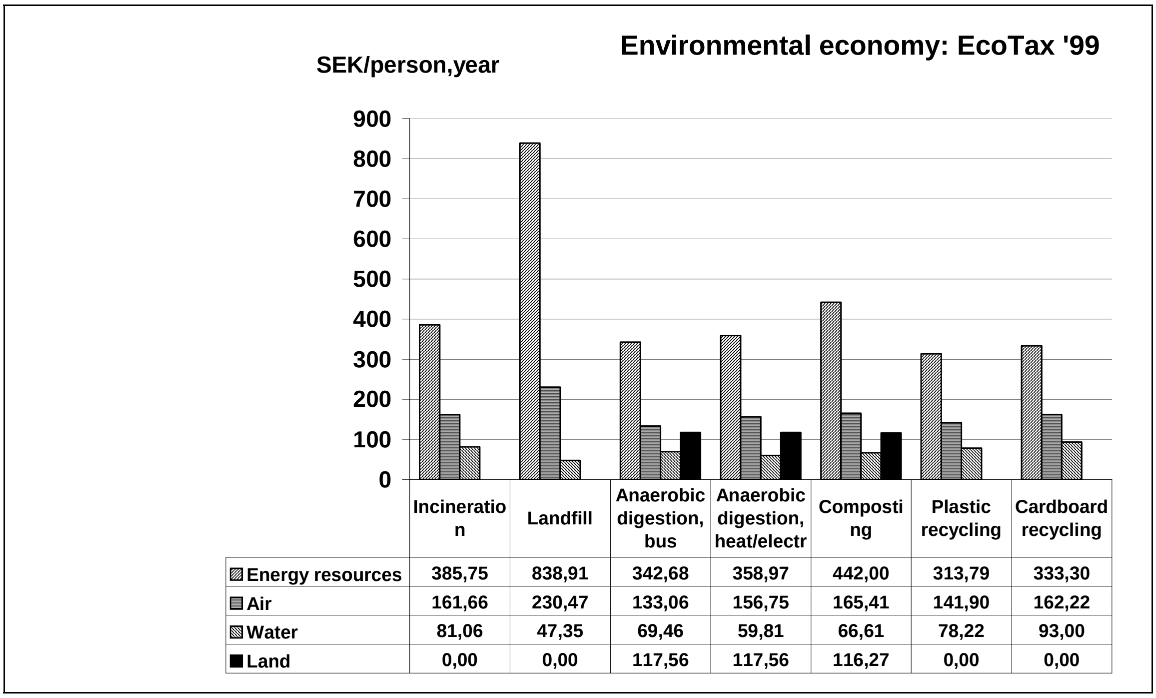
	Incineration	Landfill	Anaerobic digestion, bus	Anaerobic digestion, heat/electricity	Composting	Plastic recycling	Cardboard recycling
▧ Air	84,38	173,39	73,07	86,07	92,67	74,58	83,73
■ Water	26,16	19,89	24,08	19,60	23,16	24,73	28,23
▨ Land	0,00	0,00	65,07	65,07	64,42	0,00	0,00

Figure 11. Environmental economy – ORWARE weighting factors



	Incineration	Landfill	Anaerobic digestion, bus	Anaerobic digestion, heat/electr	Composting	Plastic recycling	Cardboard recycling
▨ Energy resources	234,11	274,69	209,48	193,11	247,36	188,24	198,97
▤ Air	174,26	408,39	149,92	167,68	175,39	150,80	170,91
▧ Water	-0,01	-0,53	-0,01	-0,01	-0,01	-0,01	-0,01
■ Land	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Figure 12. Environmental economy – weighting factors according to EPS 2000



	Incineration	Landfill	Anaerobic digestion, bus	Anaerobic digestion, heat/electr	Composting	Plastic recycling	Cardboard recycling
▨ Energy resources	385,75	838,91	342,68	358,97	442,00	313,79	333,30
▤ Air	161,66	230,47	133,06	156,75	165,41	141,90	162,22
▧ Water	81,06	47,35	69,46	59,81	66,61	78,22	93,00
■ Land	0,00	0,00	117,56	117,56	116,27	0,00	0,00

Figure 13. Environmental economy – weighting factors according to ECOTAX 99

7.3.3 Welfare economy (financial costs plus environmental costs)

In Figures 14, 15, and16, the total welfare costs or “societal costs” are given. Total costs have been calculated as the financial life cycle costs, excluding environmental taxes and fees, plus the environmental costs (with three different methods, see above).

Environmental costs according to ORWARE shows that recycling (of plastics and cardboard) has slightly higher welfare costs than incineration, but EPS and ECOTAX give the opposite. However in all three methods the differences between incineration and recycling are small. All three environmental valuation methods show that biological treatment (anaerobic digestion and composting) is more expensive than incineration. Landfilling is the absolutely most expensive alternative in all three methods.

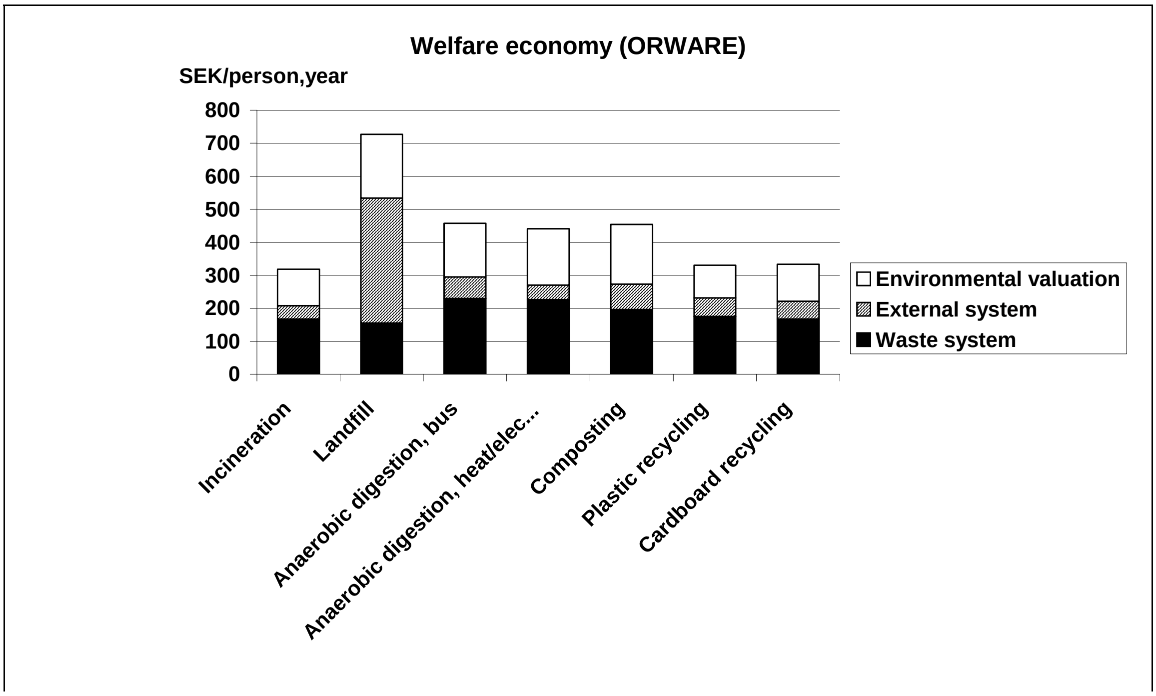


Figure 14. Welfare economy, with environmental economy according to ORWARE

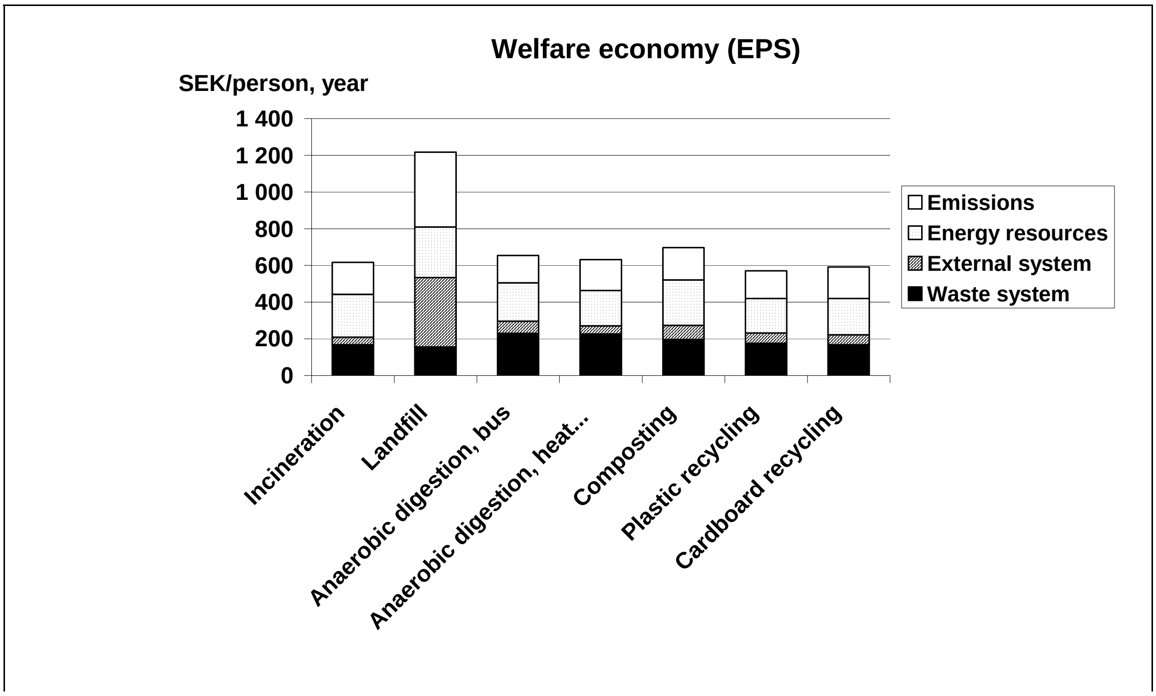


Figure 15. Welfare economy, with environmental economy according to EPS 2000

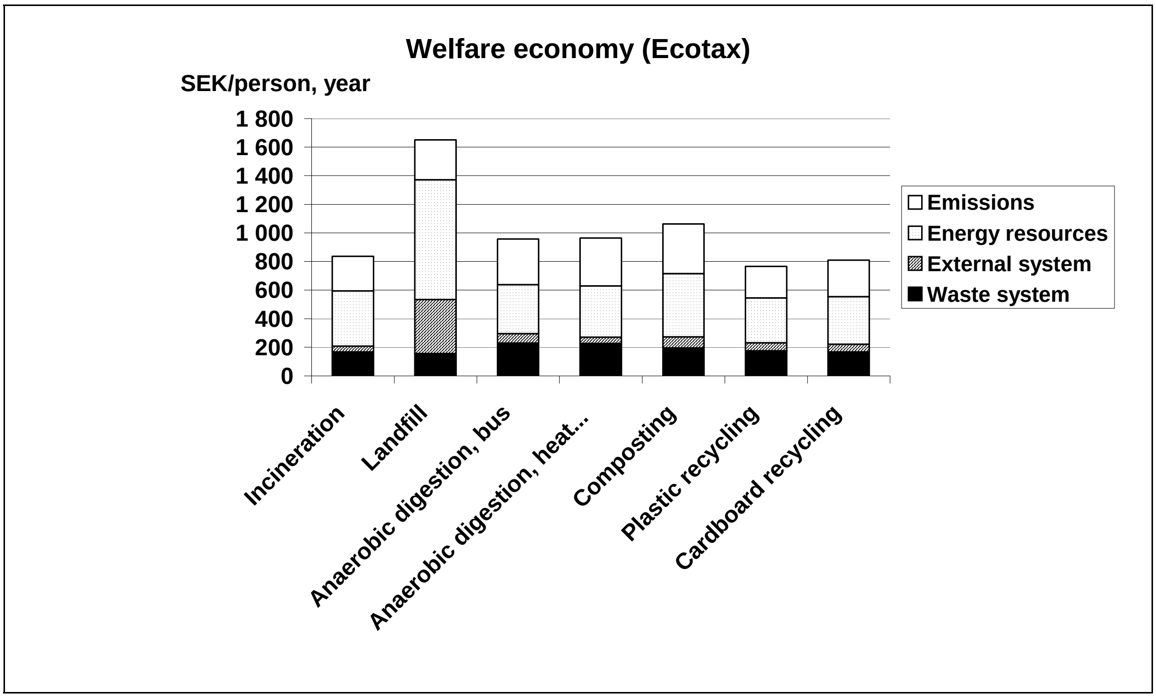


Figure 16. Welfare economy, with environmental economy according to ECOTAX

8 Sensitivity analysis

8.1 General sensitivity analysis

The results from the sensitivity are shown in Table 5 below.

Table 5. Summary of sensitivity analysis

Scenario	Changes compared to base scenario
Production of electricity	
Coal condense	Anaerobic digestion with production of electricity and heat gives slightly lower total energy consumption than incineration. Ranking is not changed.
Swedish average electricity[2]	No change in ranking
District heating production	
Oil	The two anaerobic digestion alternatives gives higher emissions of greenhouse gases than incineration
Thermal efficiency	No change in ranking
NO_X-emissions (high NO_X-emission for waste incineration, low NO_X-emission for biofuel or oil)	No change in ranking
NO_X-emissions (low NO_X-emission for waste incineration, high NO_X-emission for alternative biofuel or oil)	Incineration gives lower NO_X-emission, lower emissions of acidifying substances, lower emissions of eutrophicating substances than anaerobic digestion.

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[2] The Swedish average electricity production is based on mainly hydropower and nuclear power, which gives very small environmental impact for the impact categories that has been studied.

Scenario	Changes compared to base scenario
Power production	
Combined power and heat production	Emissions of greenhouse gases from incineration become lower than emissions from cardboard recycling. No other changes in ranking
Transport distance	
500 km distance to incineration	No change in ranking for environmental impacts categories and energy consumption. But one of the three environmental cost valuation methods anaerobic digestion lower welfare costs than incineration.
150 km distance to incineration	No change in ranking
1000 km distance to recycling	Cardboard recycling gives slightly higher emissions of greenhouse gases than incineration.
Work by the households	
Minimum time consumption, time valued to fall, 60 SEK/h	The welfare costs for plastic recycling and cardboard recycling increase and become higher than the costs for incineration.
Maximum time consumption, time valued to 60 SEK/h	The welfare costs for plastic recycling and cardboard recycling increases with more than 100 %. Energy consumption for cardboard recycling and plastic recycling increases, and is slightly higher than for incineration. The energy consumption for plastic recycling is still lower than for incineration.
Average time consumption, time valued to 60 SEK/h	The welfare costs for plastic recycling and cardboard recycling increases with almost 100 %. The welfare costs for cardboard recycling and plastic recycling is higher than the costs for incineration.
Spreading of anaerobic digestion residue and compost	
Distance to arable land 50 km	No change in ranking
The compost and the digestion residue can not be spread but have to be incinerated	The welfare costs for composting becomes lower than for anaerobic digestion, but still higher than incineration.
Valuation of resources	
Doubled price for energy and doubled environmental costs for greenhouse gases.	No change in ranking, but all financial life cycle costs, and welfare costs increases.
Energy price and valuation of greenhouse gases increases by a factor =5	No change in ranking, but life cycle costs and welfare costs for all scenarios increases.
The phosphorus price increases by a factor =10	No change in ranking. The phosphorus price has to increase by a factor 100 to make the welfare costs for anaerobic digestion and composting equal to the costs for incineration.
Landfill as a carbon sink	The difference between landfilling (of all waste) and incineration (of all waste) decreases, but landfilling is still the least favourable.

8.2 Sensitivity analysis – special options

8.2.1 Study of collection system

Different waste collection systems for recyclable material have been studied: collection at home, collection in the close neighbourhood (100 inhabitants per collection point), or collection in the far neighbourhood (1000 inhabitants per collection point). The collection system has very low influence on the total consumption of energy resources, the total environmental impact and the total welfare costs.

8.2.2 Study of peoples transports to recycling stations

Another aspect is when people take their cars to transport the waste to the recycling stations. A survey was made as a part of the study (See Sundqvist et al, 2002). It showed that a lot of households used their own cars to transport the waste. About 50 % of the people said they used the car very often to take the sorted waste to the recycling station. Mostly people take the pre-sorted waste at the same time as they are taking the car for other reasons, e.g. going to shop or going to work. In a calculation example we assumed that 20 % of the households took their car once a week to the recycling station, and the extra distance for the waste transport was 500 m. The calculations indicated that if the extra transport distance for the waste was small, the total energy consumption will be small. Plastic recycling is still favourable, but the energy saving for cardboard recycling can be eliminated. However, if more people are using the car, or the transport distance is longer, then the private transports can be of importance, and eliminate the advantages with material recycling.

8.2.3 Study of peoples time consumption for waste handling

Different waste management systems have different impacts on people, for example the time people have to spend with waste management. Through a survey to households we found that an average household spent about 30 minutes per week with waste management. The activity that consumes the most time is the transportation to the recycling station. This affects especially the scenarios where people have to go to a recycling station with pre-sorted waste fractions, e.g. plastic waste or cardboard waste in the recycling scenarios. If the time for people is valued to 60 SEK/h (about 6,5 €/h) in the financial life cycle cost analysis or in the welfare cost analysis, the costs for plastic recycling or cardboard recycling will be considerably higher than the costs for incineration, anaerobic digestion or composting, see figure 17.

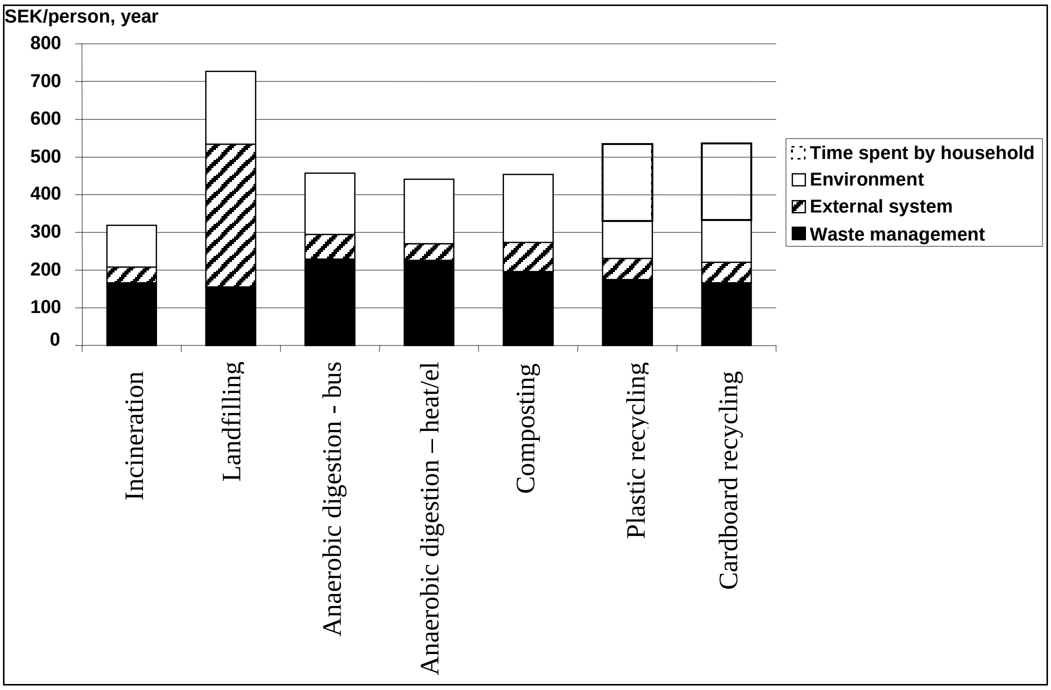

Figure 17. Consequences if people's time for waste management at home are valued 60 SEK/h (6,5 Euro/h)

8.2.4 Reactor composting

In this study, open windrow composting was modelled. The open windrow compost causes some emissions of nitrogen to air through releases of ammonia and nitrogen dioxide. In a separate study the emissions from ”closed” compost or reactor compost were estimated, where the exhaust gases are treated to separate out ammonia. The reactor compost showed lower impact than the open windrow compost but still higher than incineration.

9 Conclusions

The most obvious conclusion is that landfilling should be avoided. Wastes that can be treated by incineration, material recycling, anaerobic digestion or composting should not be disposed by landfilling. This is valid even if landfill gas is recovered, and the leachate is collected and treated. This is due to that the resources in the waste are inefficiently utilised when landfilled, making it necessary to produce materials, fuels and fertilisers from virgin resources.

It is impossible to draw unambiguous conclusions of which of the other treatment options that is “most preferable”. There are advantages and disadvantages with all treatment options. In a system perspective there are small differences between incineration and aerobic digestion of easy degradable organic waste, and between incineration and material recycling of e.g. plastics and cardboard. Material recycling, anaerobic digestion and incineration should not be seen as competing options, but as completing options. Since it is impossible to obtain 100 % material recycling or 100 % biological treatment there will always be some combustible waste that has to be incinerated. There should always be possibilities to incineration, even if the waste has to be transported to a regional incineration plant.

In a comparison of material recycling and incineration of recyclable materials (e.g. plastics and cardboard), and biological treatment and incineration of easy degradable organic waste, no unambiguous conclusions can be drawn:

- Anaerobic digestion of easy degradable organic waste has a higher welfare cost than incineration, and has both environmental advantages and disadvantages compared to incineration.

- Composting of degradable waste (open windrow composting) has hardly any advantages with respect to environment and energy turnover when being compared to incineration or anaerobic digestion. Composting gives a higher welfare cost than anaerobic digestion and incineration.

- Generally, material recycling seems to give lower consumption of energy resources and lower environmental impact than incineration, but higher financial costs and higher welfare costs. The result is however different for different materials. Recycling gives most advantages for non-renewable materials such as metals[3] and plastics. If the work at home with source separation is valued and considered in the welfare economic calculus, recycling gives higher welfare cost than incineration.

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[3] Recycling of metals has not been assessed in this study, but other studies show the advantages by recycling.

Transports of waste, when the waste once has been collected, is of very low importance considering consumption of energy resources, environmental impact and costs, if the transport is performed in an efficient manner. Private transports of source separated waste (from home to the collection site) can be of importance if the transport is made by car.

The type of collection system has very low influence on the total consumption of energy resources, the total environmental impact and the total welfare costs. However, the collection system can affect the time people have to spend on waste management (and the welfare cost if the separation and transportation time for people is considered in the welfare economic calculus).

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