Assessing the Eco-Efficiency of End-of-Pipe Technologies with the Environmental Cost Efficiency Indicator: A Case Study of Solid Waste Management

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Summary

The concept of *eco-efficiency* is being increasingly applied to judge the combined environmental and economical performance of product systems, processes and/or companies. Often, eco-efficiency is defined by the ratio of economic value added and environmental impact added. However, this definition is not appropriate for end-of-pipe treatment technologies because these technologies aim at improving the environmental performance of technical processes at the cost of financial expenses. Therefore, an indicator for the assessment of end-of-pipe technologies has been proposed. This indicator, called *Environmental Cost Efficiency (ECE)*, is defined as the ratio between net environmental benefits and the difference in costs. The ECE is applied to four end-of-pipe technologies for the treatment of municipal solid waste: sanitary landfill, mechanical-biological treatment, modern grate incineration and a staged thermal process (pyrolysis and gasification). An LCA was performed on these processes to quantify the net environmental benefit. Moreover, the approximate net costs (costs minus benefits) were quantified. The results show that, relative to grate incineration, sanitary landfills and mechanical-biological treatment are less costly but environmentally more harmful. We calculated the ECE for all combinations of technologies. The results indicate that the staged thermal process may be the most environmental cost efficient alternative to all other treatment technologies in the long run, followed by mechanical-biological treatment and grate incineration.

Introduction

The 1987 Brundtland Commission and the 1992 Rio Conference have established guidelines for *sustainable development* (World Commission on Environment and Development 1987). The three main objectives of sustainable development are ‘protection of man and environment’, ‘economic compatibility’ and ‘social compatibility’. Although these three dimensions all need to be considered in order to comply with the sustainability definition, many studies focus on only one of these objectives (usually the environment).

One approach for the integration of the environmental and economic dimension is the 'eco-efficiency' approach. Eco-efficiency was initially defined by Schaltegger&Sturm (1990) as the ratio between value added and environmental impact added. Currently, there are many definitions of 'eco-efficiency' floating around (see e.g. E/E conference (2004)). In the present study, *eco-efficiency* stands for a class of indicators which characterize the environmental and economic performance of systems. We define the term *efficiency* as the relation between a system's benefit and its disadvantages (Meier 1997). The benefits may be, for instance, financial benefits or reduced environmental impact. Disadvantages might be environmental impacts or financial costs. Many (but not all) existing eco-efficiency indicators consider the economical terms to be the numerator and the environmental terms the denominator (e.g. (Schaltegger 1996)). While this indicator may be very useful concerning product systems and companies, it is not appropriate in the context of End-Of-Pipe (EOP) technologies. EOP technologies are used to remove already formed pollutants from air, water, waste, or product. They are called 'end-of-pipe' because they usually represent the last stage of a process before the stream is disposed or released to the environment. There are two reasons why the traditional definition of eco-efficiency does not hold with regard to these technologies: First, there is usually no financial benefit to be expected, and second, EOP technologies are meant to reduce environmental impact. Therefore, putting the economic terms in the numerator would result in the ratio between financial costs divided by environmental benefit. This indicator would not comply with the above definition of efficiency (i.e., the goal is not to maximize this indicator). Therefore, an eco-efficiency indicator as described above cannot provide meaningful results with respect to end-of-pipe technologies. A modified indicator is thus needed to integrate the economical and environmental dimension of end-of-pipe technologies.

In this article we propose such an indicator: the *Environmental Cost Efficiency (ECE)*. First, we measure the cost-efficiency of end-of-pipe processes using ECE. We then apply the indicator to a case study in which we assess four treatment processes for municipal solid waste. Finally, we offer conclusions based on the evaluations.

Methods: Environmental Cost Efficiency of End-of-Pipe Technologies

In order to integrate the economical and environmental dimensions with regard to end-of-pipe treatment technologies and to evaluate the tradeoffs between the two dimensions, we have developed an indicator called the 'Environmental Cost Efficiency' (ECE). *The Environmental Cost Efficiency quantifies the environmental benefit of a Technology A over Technology B per additional cost* ($ECE_{A,B}$ in Equation 1). The ECE requires a prior separate financial and environmental assessment. Here we assume that in the financial assessment, discounted net costs (denominator in Equation 1) are quantified with standard economic methods such as Net Present Value (NPV, Equation 2) or the Annuity method (A, Equation 3). The annuity method equally distributes the net present value over the lifetime of the investment (Wöhe 1996). Since the annuity method is more appropriate than the Net Present Value approach regarding the comparison of technologies with different lifetimes, we recommend this method for the economic assessment. The measuring unit is therefore monetary (e.g. Euro per functional unit). The environmental assessment (numerator of Equation 1) can be performed with LCA.

Possible units of the impact potential may therefore be 'ecopoints' or 'CO_2-equivalents', depending on the method applied and the question to be studied.

$$ECE_{A,B} = \frac{NEB_{AB}}{AC_{AB}} = \frac{NEB_A - NEB_B}{NC_A - NC_B} = \frac{(-IP_A) - (-IP_B)}{NC_A - NC_B} \quad \left[\frac{\text{points}}{\text{Euro}}\right] \tag{1}$$

$$NPV_x = \sum_{t=0}^{T} ((B_{x,t} - C_{x,t}) * \frac{1}{(1+r)^t}) \quad [\text{Euros}] \tag{2}$$

$$A_x = \frac{NPV_x * (1+r)^T * r}{(1+r)^T - 1} \quad [\text{Euros}] \tag{3}$$

In equations 1 to 3, NEB_{AB} is the net environmental benefit of Technology A over B, AC_{AB} are the additional financial costs of implementing Technology A instead of B, IP_x is the environmental impact potential of Technology X, NC_x are the net costs (determined with Equation 3 in this work), $B_{x,t}$ and $C_{x,t}$ represent the benefits and costs of Technology X at time t, respectively, r is the discount rate, t is a time index and T is the lifetime of Technology X. NEB_x represents the environmental benefit of EOP Technology X measured against a 'null-option' (e.g. dumping the waste somewhere without a control system). Therefore NEB_A is the difference in impact potential between this ‘null-option’ and A ($NEB_A=IP_{NO}-IP_A$). Since the 'null-option' is the same for Technologies A and B, it cancels out when the difference between NEB_A and NEB_B is formed.

Technology A is defined as the environmentally superior technology. This means that IP_B is bigger than IP_A and therefore the numerator of Equation 1 is always positive. If the net costs of Technology B are higher than those of A ($NC_A < NC_B$), Technology A is better from an economic and environmental point of view (win-win situation). In this case, no ECE needs to be calculated since the separate results of the economic and environmental assessment already point in the same direction. If the financial costs of A are higher than those of B ($NC_A > NC_B$), there is a trade-off between financial and environmental goals. In this case, a high ECE indicates a high cost-efficiency.

In the following Section, we will perform a financial and environmental assessment as indicated above, using the case study of four treatment technologies for municipal solid waste. Subsequently, we will calculate the ECE for each pair of technologies to resolve trade-offs between environmental and economic goals.

Case Study: Comparison of Treatment Technologies for Municipal Solid Waste

Goal and Scope of the economic and environmental assessment

The goal of this case study is to compare the waste treatment options listed in Table 1 and shown in Figure 1, using environmental and economical criteria. The analysis is performed with respect to mixed waste of an average composition. The results can be used to aid in the decision of which waste treatment is most suitable for the treatment of municipal solid waste in a given region.

The analysis is performed first for an infinite time frame and second, for a limited time period of approximately 100 years (*surveyable time period* (Finnveden et al. 2000)).

<insert Figure 1 here>

<insert Table 1 here>

The principal function of all technologies is the treatment of waste. Therefore, the functional unit includes the treatment of waste material. To make a fair comparison of the different technological options, the services delivered by the assessed systems must be equal. Since several co-products, such as electricity, heat, and metals, are produced in different quantities by the considered technologies, the systems need to be expanded (Figure 2).

<insert Figure 2 here>

The functional unit is a superset of all services provided by the four treatment technologies considered (Table 2). Table 2 shows that in the LCA, all systems need to be complemented by regular industrial processes producing primary products (system expansion). One should bear in mind that the reference systems used (Table 2) might be inadequate for some countries. This constitutes a source of uncertainty if the data is not adapted to the site-specific conditions (Ekvall and Finnveden 2001). Concerning financial costs, it was assumed that the market price of secondary metals produced by the PECK process is close to zero (metal recyclers will only pay a small amount of money for these metals, if at all, mainly because of the small quantities produced). The costs of sewage sludge disposal (Table 2) were neglected because of the small amounts involved. In the economic analysis, only the functions written in italics in Table 2 were considered.

<insert Table 2 here>

The environmental life-cycle impact assessment (LCIA) was performed with three common European methods: CML'01 (Guinée et al. 2001), Eco-indicator 99 (Goedkoop et al. 1999), and Swiss Method of Ecological Scarcity (SAEFL 1998). In the combined environmental/economic assessment, we only show the results of fully aggregating LCIA methods though, i.e. Eco-indicator 99 and Swiss Method of Ecological Scarcity.

Financial Costs

Figure 3 displays the net costs of the four technologies (total costs minus revenue for energy sales). Sanitary landfill is the cheapest treatment option, followed by mechanical-biological pretreatment (MBP) and thermal technologies. For PECK, cost data are based on estimates (Biollaz and Bunge 2003), and are therefore approximate.

<insert Figure 3 here>

The costs in Figure 3 do not include costs for aftercare of landfills. Aftercare of landfills can make sanitary landfills and, to a smaller extent, other types of landfills much more expensive than indicated in Figure 3. For instance, the decontamination of the sanitary/chemical landfill in Kölliken (Switzerland) (Wenger and Jordi 2001) has an estimated cost of between 200 to 235 Mio Euro (BUWAL 2001), which corresponds to between 571 and 671 Euro per tonne of waste.

Environmental assessment with LCA

Modeling the Technologies

For details concerning the modeling of the four treatment options, see Hellweg et al. (2003b). Here, we only present a rough overview of the major assumptions made.

It was assumed that the landfills for municipal solid waste, the output of the mechanical-biological treatment, and incineration residues are not covered by an impermeable layer.

The reason is that such coverings, if they are applied at all, only have a life expectancy of a couple of decades, and it is highly improbable that they would be continuously renewed in the future. The infiltration rate was therefore approximated at quite a high level: 400 mm/y, which is a reasonable estimate for humid sites.

The model for *sanitary landfills* is described in Finnveden et al. (2000) and based on Björklund (1998). Leachate purification and landfill fire data from Fliedner (1999) have been added. Landfills were assumed to have a collection system for landfill gas operating during the surveyable time period (100 years), with an efficiency of 50%. The gas collected was assumed to be used for electricity and heat production. Gas that is not collected passes through the soil, where 15% of the methane was assumed to be oxidized to CO_2. The leachate from the landfill was assumed to be collected and treated before being released to recipients. It was assumed that 80% of the leachate could be collected and transported to a municipal wastewater treatment plant during the surveyable time period. The remaining 20% is directly emitted. Emissions of chlorobenzene, chlorinated dioxins, PAH, PCB and Hg from landfill fires during the surveyable time period were included. It was assumed that 25% of the produced pollutants are emitted from the landfill.

Sound data for the *mechanical-biological treatment (MBP)*, were only available for the short-term emissions of one German plant (Wallmann 1999). We extrapolated from this data that approximately 2.7% of the total wet waste mass (Swiss composition) is recovered as iron scrap with a Fe-content of 96%, 25.5% are separated as a high calorific light fraction for energy recovery, while the rest (71.8%) is biologically treated. In order to estimate emissions from the biological digestion, we estimated the composition of the input waste of this plant from literature (Barin et al. 1996; Wallmann 1999) and adapted the emissions to Swiss waste, assuming constant transfer coefficients. The digestion output is deposited in landfills. The organic short-term emissions were taken from Wallmann (1999). As recommended in this study, we assumed that heavy metal emissions in the leachate are identical to those of slag landfills (Zimmermann et al. 1996), while other emissions to water, such as sulfates, ammonia, nitrates, phosphor, fluorides, and chlorides, were set equal to those of sanitary landfills (Zimmermann et al. 1996; Björklund 1998). Since oxygen enters the landfill, we assumed that no CH_4 emissions are formed and released after the first 100 years (Wallmann 1999).

The *grate technology* is the most commonly used waste incineration technology in the world. Therefore, abundant data was available for the modeling (e.g., (Zimmermann et al. 1996; Morf et al. 1997 and 1998; Belevi 1998)). The variations in emissions from one incineration plant to another are large. We assumed that the incinerator is up to modern standards and that it is equipped with modern gas purification (wet flue gas treatment, wastewater treatment, NO_x removal), because it would be unfair and inaccurate to compare average or obsolete plants to new technologies, such as PECK. The net energy efficiency was assumed to be 15% for electricity and 35% for heat recovery. Further aspects of the modeling can be consulted elsewhere (Zimmermann et al. 1996; Hellweg et al. 2001 and 2003b).

The three main components of *PECK* (staged incineration, thermal ash treatment and mechanical slag treatment) were modeled based on information of solid outputs from experimental studies and trial runs. PECK combines conventional grate incineration with a rotary kiln. Waste is gasified with primary air on a grate at reducing conditions (950 ^{0}C) to evaporate volatile heavy metals. Subsequently, the products from the grate are burned in a rotary kiln with excess air at temperatures of up to 1,300 ^{0}C. The exhaust air is mixed with secondary air in a post combustion chamber, and the flue gas is treated in a conventional gas purification unit. The bottom ash is free of carbon. It is treated mechanically to recover Cu. The fly ash is treated thermally to recover volatile heavy metals and reduce the content of dioxins and furans. Wastewater treatment sludge from the gas cleaning was assumed to be landfilled. The metal products from PECK are expected to be recyclable in secondary Cu and Zn smelters and Fe blast furnaces. Lead is isolated as a side product in the zinc smelting. The energy efficiency was assumed to be 15% for electricity and 33% for heat recovery. More details on the modeling of the PECK technology are contained in Doka (2002) and Biollaz and Bunge (2003).

Selected Results

The results of the inventory analysis are contained in Hellweg et al. (2003b). Since the purpose of the study here is to show the integration of the environmental and economic analysis, we focus on the impact assessment results and do not discuss the inventory analysis further.

Concerning the impact assessment results according to CML'01, the incineration of mixed waste is more preferable than direct landfills and the mechanical-biological treatment concerning all impact categories. This is primarily due to the poor energy recovery of sanitary landfills, MBP, and to emissions such as CH_4, NMVOC, and NO_x to the air. MBP scores better than or roughly equal to sanitary landfills in all categories. PECK performs better than grate incineration regarding toxicity. This is the result of PECK's aim to recover heavy metals from the slag and filter ash and thus prevent metal emissions. In most other categories, PECK performs about equal to the grate technology. Only with respect to the resource-oriented categories *abiotic depletion* (CML'01) and r*esource surplus energy* (Eco-indicator 99) is PECK inferior to grate incineration. At first sight this is surprising, because it is the explicit aim of PECK to recover metals and minerals and, thus, to preserve resources. The poor results in the resource-related categories are due to the higher energy demand of PECK technology and the strong weight that many LCIA methods assign to fossil resources in comparison to metal resources.

The application of fully aggregating methods reinforces these results. Figure 4 displays the LCIA results with Eco-indicator 99 and Method of Ecological Scarcity.

<insert Figure 4 here>

Figure 4 confirms that sanitary landfill is, environmentally, the worst treatment option for mixed waste with respect to all damage categories and overall results. This is primarily due to the poor recovery of sanitary landfills, MBP, and to emissions of CH_4 and NMVOC to the air, as well as emissions of ammonia to water. Performing a ranking between the four technologies, we have obtained results that are opposite to the ranking according to financial costs (Section *Financial Costs*).

If only the emissions of the first 100 years were considered, the impact potential would drop considerably concerning all technologies (Figure 4). Sanitary landfills would still perform worse than the other technologies with respect to the aggregated results (however, they would score better in the category of global warming, because long-term emissions of CO_2 would not be considered). MBP would be slightly inferior to the thermal technologies, mainly because of its low energy efficiency. PECK would no longer score better than grate incineration, because no credit would be given for the avoided long-term emissions of metals. These results show that conclusions are contingent upon the choice of time frame.

Environmental-Economical Analysis

In this paragraph we will couple the above results from the impact assessment with financial costs. In an initial step, we compare the structure of financial costs and environmental impacts (Figure 5). In contrast to the previous environmental assessment (Figure 4), energy is displayed as credit (negative impact) in Figure 5 to enable the comparison with financial costs. Figure 5 shows that the structure of financial costs differs widely from that of environmental impact. Financial costs are mainly driven by costs for capital, maintenance, staff (fix costs) and costs for logistics. By contrast the environmental impact is mainly determined by emissions from the operation, i.e. landfill emissions and releases from the incineration plant. Hence, there is no correlation between financial costs and environmental impact.

<insert Figure 5 here>

Figure 6 shows the position of the four treatment technologies in a diagram displaying the environmental impact potential in comparison to economical costs (excluding logistics costs, which are constant for all technologies considered). Relative to grate incineration, sanitary landfills and mechanical-biological treatment are less costly but environmentally more harmful. PECK is about as costly as grate incineration, but its environmental impact potential is lower. Concerning the short-term assessment with a time frame of 100 years, these two rankings are similar; with the exception that PECK technology performs similarly to grate incineration concerning the impact potential and financial costs. However, if we take the cost of aftercare into account (which could justify a temporal cut-off after 100 years), sanitary landfills could also end up being the worst option concerning costs. In Figure 6, a clear ranking between the four technologies is not observable. Such a ranking would demand an alignment along the shaded arrow in Figure 6. However, the graph locates the technologies on a line that is almost perpendicular to the arrow. Therefore, there are trade-offs between environmental and financial goals that need to be resolved.

<insert Figure 6 here>

In order to better combine the economical and environmental results and resolve the trade-offs described above, we have employed the indicator of *Environmental Cost Efficiency (ECE)* (Equation 1). In order to quantify net environmental benefit, we need to form the difference between the impact potentials of two technologies. For instance, sanitary landfills have an impact potential of 0.172 Eco-indicator points and grate incineration 0.118 Eco-indicator points per tonne of waste (hierarchist perspective). The difference in net environmental benefit is therefore 0.054 Eco-indicator 99 points/t waste. The difference in net costs between sanitary landfill and grate incineration is 57,5 Euro/t waste (average costs). The resulting Environmental Cost efficiency of constructing a grate incinerator instead of a sanitary landfill is therefore ECE = 0.0009.

<insert Table 3 here>

In Table 3 we calculate the ECE for all combinations of technologies. Average costs and aggregating LCIA methods were used in the assessment (Eco-indicator 99 and Method of Ecological Scarcity). Concerning Eco-indicator 99, only the hierarchist perspective is shown. Applying the egalitarian and individualist perspectives leads to comparable results. Table 3 shows that PECK is the most cost-efficient, environmentally superior alternative to all other treatment technologies. However, it needs to be considered that the data on PECK is uncertain, because this technology has not been implemented as a complete assembly and limited measurements of the solid outputs from trial runs or experimental devices were available. The second most efficient alternative to sanitary landfill is MBP, followed closely by grate incineration.

Discussion and Conclusion

The case-study illustrates that our Environmental Cost Efficiency indicator (ECE) is capable of resolving trade-offs between environmental and financial (dis)advantages of different end-of-pipe technologies. The ECE is one indicator among many that are used to quantify 'eco-efficiency'. The present study shows that it is important to have a suitable 'eco-efficiency' indicator for different problem situations. For instance, the application of eco-efficiency indicators that put economic values in the numerator and environmental impact in the denominator are not adequate for end-of-pipe technologies. The reason is that an increased value of the indicator would not correspond to increased efficiency in the case of EOP technologies. By contrast, the ECE quantifies the net environmental benefit of one technology over another per additional costs involved. The higher the environmental benefits and the smaller the additional costs of an end-of-pipe technology, the higher its efficiency classification by the ECE. The ECE thus represents a cost-efficiency indicator that can be adequately used for the assessment of end-of-pipe technologies. Therefore, we believe that in future work it is important to provide a toolbox of specific eco-efficiency indicators for different applications.

In this case study we calculated all results for two different time frames: 100 years and infinite. In the environmental assessment, there were considerable differences in environmental impact, which can be attributed to long-term emissions of heavy metals from landfills. Concerning the economical analysis, financial costs could be influenced by potential costs of aftercare for landfills. Since these costs may be substantial, they may reverse the financial-cost ranking of the technologies in the case study. However, if these costs occur in the far future, discounting would reduce them exponentially as a function of time. The consideration of potential (discounted) costs of aftercare might be used as an argument for neglecting long-term emission, because the remediation of landfills would prevent pollutants from being emitted. This would be equivalent to using a discount rate on long-term impacts (Hellweg et al. 2003a). In general, such assumptions about future remediation are not made in LCA, because they would prevent LCA from stimulating the development and application of (abatement) technologies where needed (Hellweg et al.

2003a). In our opinion, the long-term analysis presented in this paper thus seems to be more appropriate and consistent with the life-cycle approach than the 100-year assessment, even if potential costs of aftercare are considered.

In spite of the merits of an integrated assessment, indicators such as the ECE can never substitute the separate environmental and economic assessment. For instance, an expensive environmentally friendly technology may end up with the same rating as a very polluting, cheap process. However, these two technologies would not be equivalent. While the ECE quantifies the relation between environmental and economic benefits, it disregards the total volume of a financial investment, which might well be relevant to a given decision (for instance, if only limited financial resources are available). Moreover, in addition to eco-efficiency indicators, non-aggregated results of the environmental assessment are usually needed to understand the system, identify improvement potentials, and make the results transparent. For instance, in the above case study, the ECE may help to decide which of the four technologies should be implemented if the goal is to achieve the largest environmental benefit possible per unit of money invested. However, other results of the case study, such as the potential importance of future emissions of heavy metals leached from landfills, would not become apparent from the aggregated value of the ECE. Therefore, promising strategies for the reduction of these emissions, e.g. reducing the content of heavy metals in products, recovering heavy metals (material recycling or PECK technology), or vitrifying and thereby stabilizing the heavy metal containing residues (Hellweg et al. 2003b), would not have been identified. We thus draw the conclusion that, in addition to highly aggregated indicators such as the ECE, the results of a detailed separate environmental and economic analysis should be provided.

Another weakness of eco-efficiency indicators such as the ECE is that they do not incorporate rebound effects. For instance, if more waste were produced (e.g. because of the fewer environmental impacts per tonne of waste), the overall environmental impact may increase. Indicators such as the ECE do not reflect such rebound effects. Therefore, additional tools are needed to judge the overall impacts. Eco-efficiency indicators serve to highlight the relation between economic and environmental performance of systems, but they are not sufficient to judge the economic and environmental dimension of sustainability.

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Figure captions

Figure 1: Flowcharts of the processes considered (Hellweg et al. 2003b). The empty boxes indicate prior background processes that have also been considered.

Figure 2: System boundaries and functional unit (system output below the box). The flowcharts for the left part of the system (left to dashed lines) of the four technologies are given in Figure 1.

Figure 3: Net costs of waste treatment (total costs minus revenues for the sale of energy) (SAEFL 1999; Schmidt et al. 2001; Ludwig et al. 2003).

Figure 4: Impact assessment with Eco-indicator 99 (left, hierarchist perspective) and Method of Ecological Scarcity (right) for an infinite and short-term time horizon (Hellweg et al. 2003b). The functional unit is displayed in Table 2.

Figure 5: Structure of financial costs (in Euros) (Biollaz and Bunge 2003) and environmental impact (in Eco-indicator 99 points, hierarchist perspective) of the thermal technologies (infinite time frame).

Figure 6: Environmental impact potential (Eco-indicator 99, hierarchist perspective) and financial costs (without logistics) of the four treatment technologies.

Table captions

Table 1: Data sources and quality of the waste treatment technologies studied.

Table 2: Functional unit for the technology comparison concerning average municipal solid waste, services provided by the treatment technologies, and reference systems used for system expansion (SE) in the LCA.

Table 3: Environmental Cost Efficiency (ECE, Equation 1)) of choosing one treatment option instead of another. Each number quantifies the environmental advantage (in Eco-indicator 99 or Swiss Ecopoints) per monetary unit (in Euro) of the technology in the column (Technology A) over the technology in the line (Technology B).

Table 1: Data sources and quality of the waste treatment technologies studied.

Waste treatment technology	Data source for extensive technology description	Data sources for financial costs[a]	Data sources for the LCI[b]	Data quality
Sanitary landfill	(Ludwig et al. 2003, Section 2.2)	(Schmidt et al. 2001)	(Björklund 1998; Finnveden et al. 2000)	In general high, with the exception of long-term emissions.
Mechanical-Biological (Pre-) treatment (MBP) prior to landfill	(Ludwig et al. 2003, Section 4.1)	(Ludwig et al. 2003, Section 4.1)	(Wallmann 1999), assumptions	In general high with the exception of long-term emissions from the landfilled digestion output.
Grate incineration	(Ludwig et al. 2003, Section 3.3)	(SAEFL 1999)	(Zimmermann et al. 1996; Hellweg et al. 2001)	High quality with the exception of long-term emissions from slag/filter ash landfills
Staged thermal process: PECK [c] technology	(Ludwig et al. 2003, Sections 5.2.1-5.2.4)	(Ludwig et al. 2003, Section 5.2.4)	(Hellweg et al. 2001; Doka 2002)	Very uncertain (no full-scale plant implemented)

[a] Cost of transport from Schmidt et al. (2001).

[b] LCI data for background processes such as production of ancillary products, recycling of valuables, transport, and infrastructure were taken from CORINAIR (1990 and 1996), Frischknecht et al. (1996), Zimmermann et al. (1996), Fugleberg (1999), Norgate and Rankin (2000), and IPCC (2000).

[c] The PECK process consists of a staged process (pyrolysis and gasification step), combined with a thermal filter ash treatment and mechanical slag treatment.

Table 2: Functional unit for the technology comparison concerning average municipal solid waste, services provided by the treatment technologies, and reference systems used for system expansion (SE) in the LCA.

Services/ functions	Functional unit	Amount provided by sanitary landfill	Amount provided by MBP	Amount provided by grate incineration	Amount provided by PECK-Process	Reference system for system expansion
Disposal of waste (average composition)	*1 t*	*1 t*	*1 t*	*1 t*	*1 t*	-
Co-disposal of sewage sludge[a]	13 kg	13 kg (SE)	13 kg (SE)	13 kg (SE)	13 kg	Co-disposal in the respective treatment plant
Generation of electricity	*1.8 GJ*	*0.6 GJ (SE)*	*0.8 GJ (SE)*	*1.8 GJ*	*1.7 GJ (SE)*	European grid electricity (UCPTE)[b]
Generation of heat	*4.2 GJ*	*1.2 GJ (SE)*	*1.8 GJ (SE)*	*4.2 GJ*	*3.8 GJ (SE)*	Industrial natural gas furnace[b]
Production of pig Fe	26 kg	- (SE)	26 kg	20 kg (SE)	19 kg (SE)	Production of primary pig Fe[b]
Production of Cu	460 g	- (SE)	- (SE)	- (SE)	460 g	Production of Cu[b]
Production of Zn	910 g	- (SE)	- (SE)	- (SE)	910 g	Production of Zn[b]
Production of Pb.	440g	- (SE)	- (SE)	- (SE)	440g	Production of Pb[b]
Production of mineral material	161 kg	- (SE)	- (SE)	- (SE)	161 kg	Construction sand from natural sources[b]

[a] The PECK technology needs sewage sludge for the treatment of filter ash. Therefore, all other systems are required to treat the same amount of sewage sludge as well.

[b] Production from average industrial sources (Frischknecht et al. 1996).

Table 3: Environmental Cost efficiency (ECE, Equation 1)) of choosing one treatment option instead of another. Each number quantifies the environmental advantage (in Eco-indicator 99 or Swiss Ecopoints) per monetary unit (in Euro) of the technology in the column (Technology A) over the technology in the line (Technology B).

Method environmental assessment: Eco-indicator 99[a]; economic assessment: annuities (Equation 3)				
		TECHNOLOGY A		
		MBP	Grate incineration	PECK
TECHNOLOGY B	Sanitary landfill	0.001	0.0009	0.0026
	MBP		0.0008	0.0043
	Grate incineration			++[b]
Method environmental assessment: Swiss Method of Ecological Scarcity[a]; economic assessment: annuities (Equation 3)				
		TECHNOLOGY A		
		MBP	Grate incineration	PECK
TECHNOLOGY B	Sanitary landfill	78	49	127
	MBP		17	183
	Grate incineration			++[b]

[a] In the environmental life-cycle impact assessment, any method could have been used. Here, to give an example, we applied the methods Eco-indicator 99 (above) and Swiss Ecological Scarcity (below).

[b] '++' indicates that both the environmental and economic performance of Technology A were better than those of B.

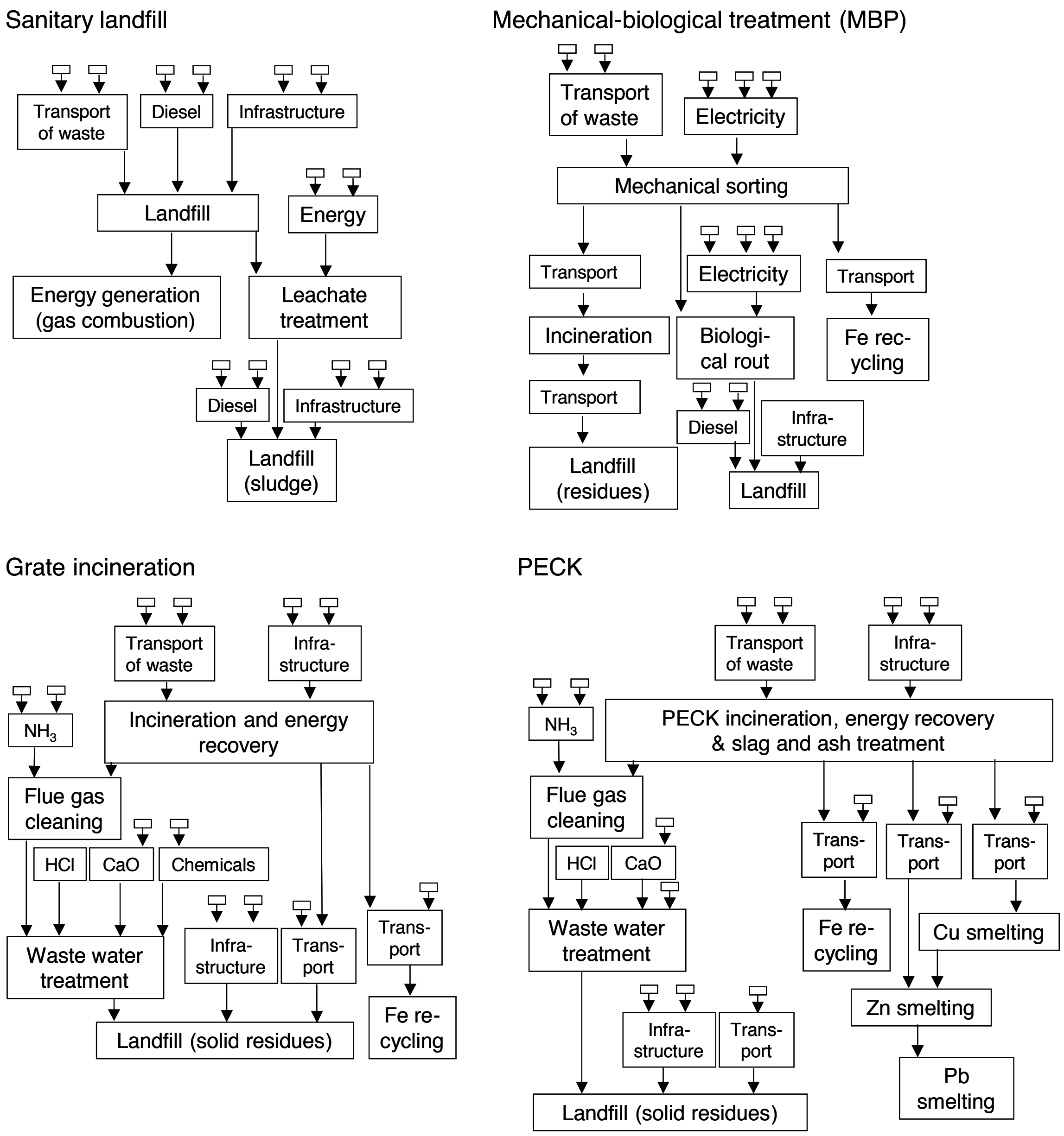

Sanitary landfill
Transport of waste
Diesel
Infrastructure
Landfill
Energy
Energy generation (gas combustion)
Leachate treatment
Diesel
Infrastructure
Landfill (sludge)
Mechanical-biological treatment (MBP)
Transport of waste
Electricity
Mechanical sorting
Transport
Electricity
Transport
Incineration
Biologi-cal rout
Fe rec-ycling
Transport
Diesel
Infra-structure
Landfill (residues)
Landfill
Grate incineration
Transport of waste
Infra-structure
NH3
Incineration and energy recovery
Flue gas cleaning
HCl
CaO
Chemicals
Infra-structure
Trans-port
Trans-port
Waste water treatment
Landfill (solid residues)
Fe re-cycling
PECK
Transport of waste
Infra-structure
NH3
PECK incineration, energy recovery & slag and ash treatment
Flue gas cleaning
HCl
CaO
Trans-port
Trans-port
Trans-port
Waste water treatment
Fe re-cycling
Cu smelting
Zn smelting
Infra-structure
Trans-port
Pb smelting
Landfill (solid residues)

FIGURE 1

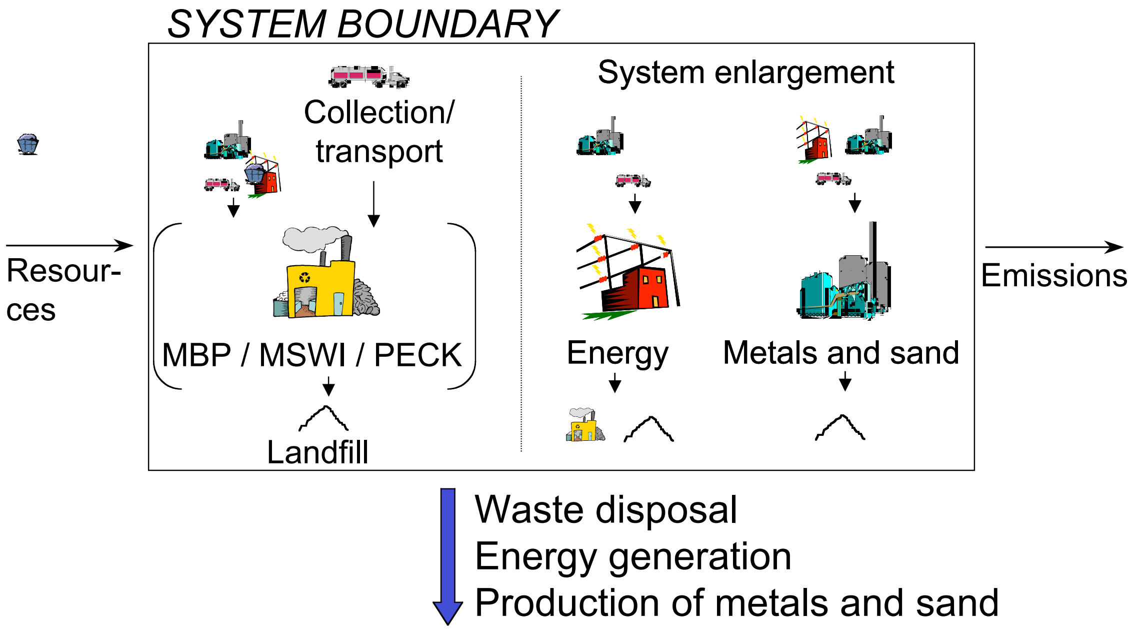

SYSTEM BOUNDARY
Resour-
ces
Collection/
transport
MBP / MSWI / PECK
Landfill
System enlargement
Energy
Metals and sand
Emissions
Waste disposal
Energy generation
Production of metals and sand

FIGURE 2

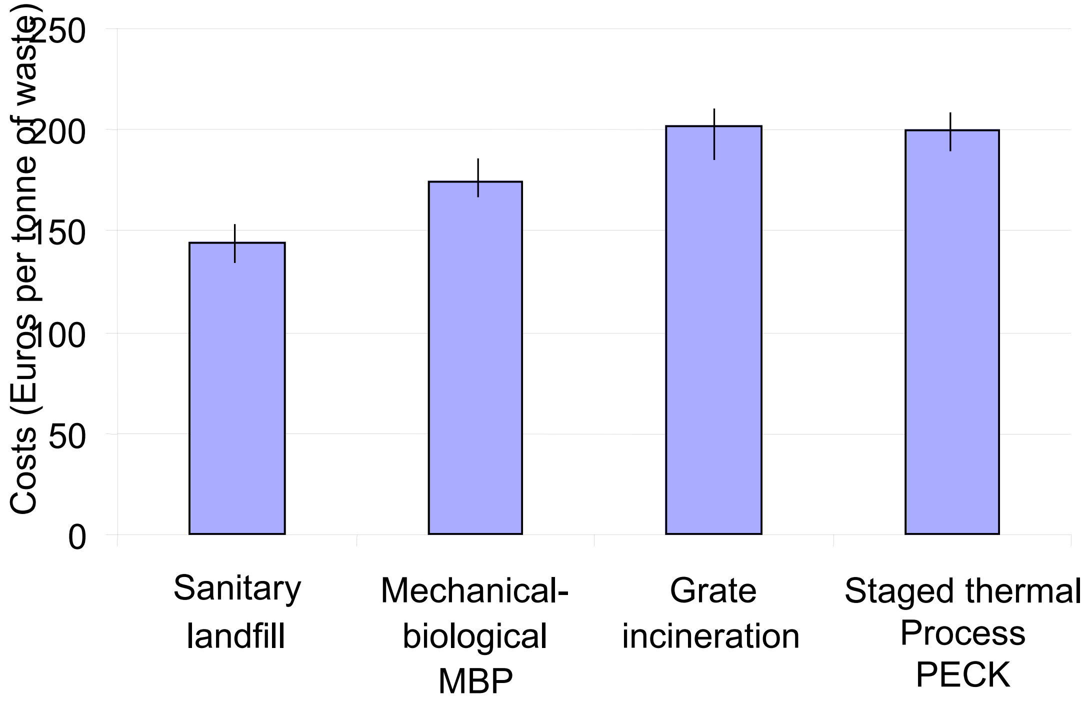
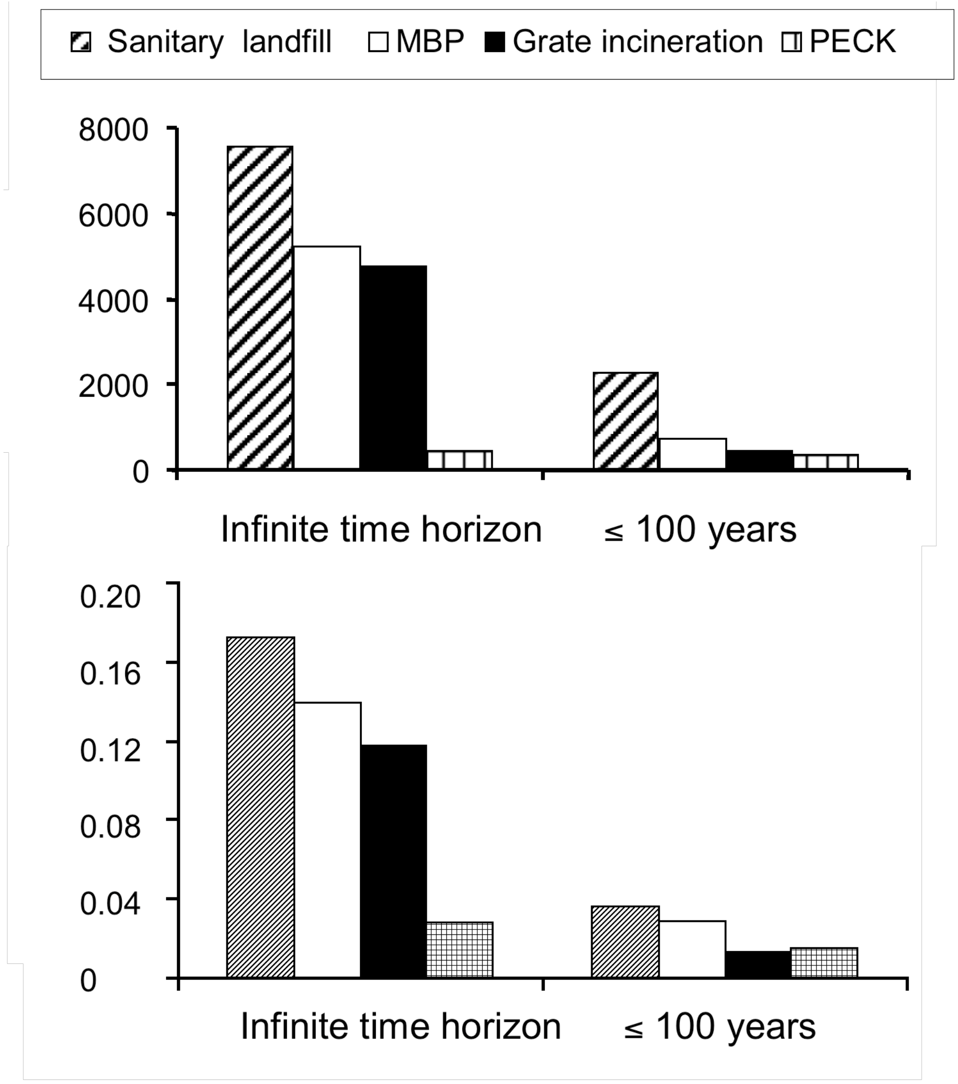

Costs (Euros per tonne of waste)
0
50
100
150
200
250
Sanitary landfill
Mechanical-biological MBP
Grate incineration
Staged thermal Process PECK

FIGURE 3



▨ Sanitary landfill
☐ MBP
■ Grate incineration
▥ PECK
8000
6000
4000
2000
0
Infinite time horizon
≤ 100 years
0.20
0.16
0.12
0.08
0.04
0
Infinite time horizon
≤ 100 years

FIGURE 4

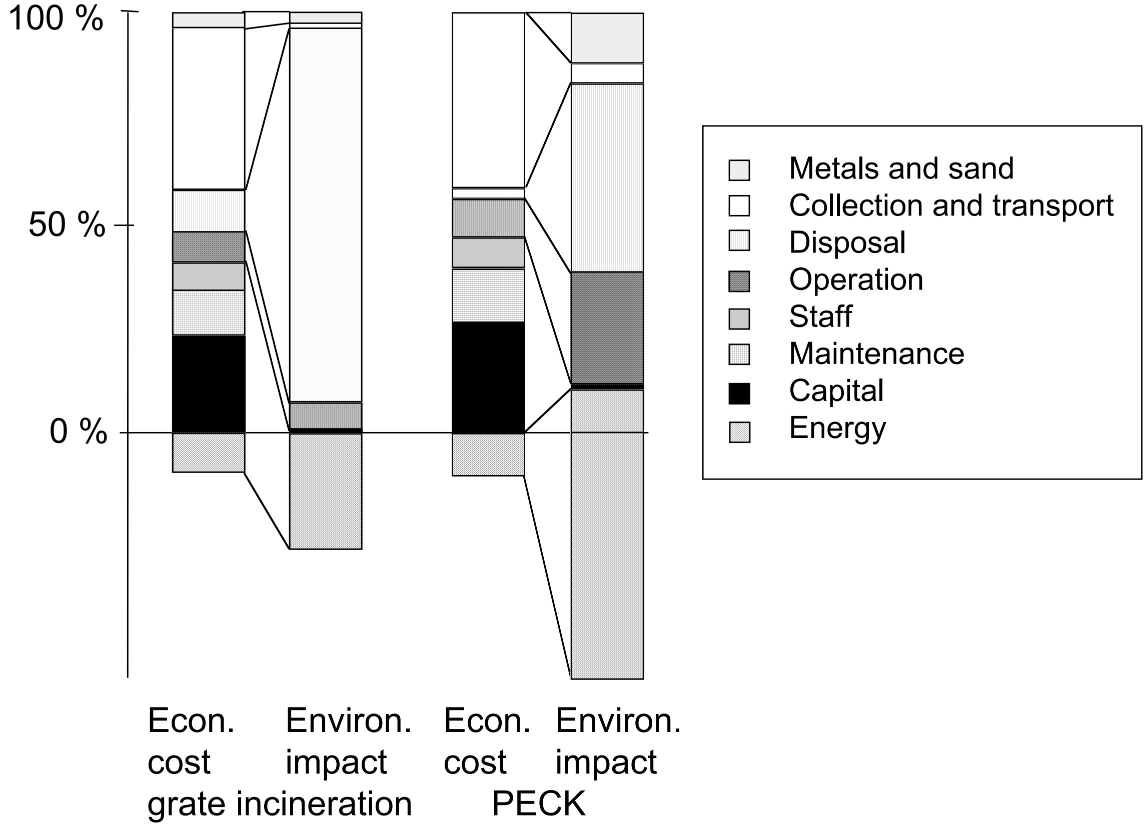

100 %
50 %
0 %
Metals and sand
Collection and transport
Disposal
Operation
Staff
Maintenance
Capital
Energy
Econ. cost
Environ. impact
Econ. cost
Environ. impact
grate incineration
PECK

FIGURE 5

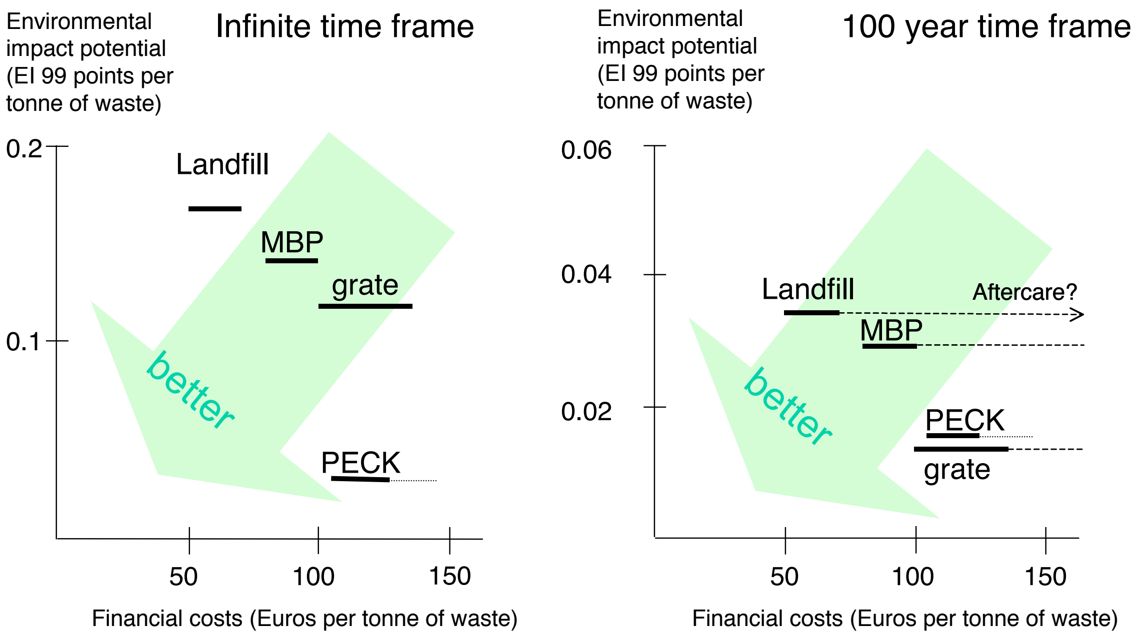

Environmental impact potential (EI 99 points per tonne of waste)
Infinite time frame
0.2
0.1
Landfill
MBP
grate
PECK
better
50
100
150
Financial costs (Euros per tonne of waste)
Environmental impact potential (EI 99 points per tonne of waste)
100 year time frame
0.06
0.04
0.02
Landfill
Aftercare?
MBP
PECK
grate
better
50
100
150
Financial costs (Euros per tonne of waste)

FIGURE 6