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ENVIRONMENTAL ASSESSMENT OF INCINERATOR RESIDUE UTILISATION

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Abstract

Incineration ashes may be treated either as a waste to be dumped in landfill, or as a resource that is suitable for re-use. In order to choose the best management scenario, knowledge is needed on the potential environmental impact that may be expected, including not only local, but also regional and global impact. In this study, A life cycle assessment (LCA) based approach was outlined for environmental assessment of incinerator residue utilisation, in which leaching of trace elements as well as other emissions to air and water and the use of resources were regarded as constituting the potential environmental impact from the system studied. Case studies were performed for two selected ash types, bottom ash from municipal solid waste incineration (MSWI) and wood fly ash. The MSWI bottom ash was assumed to be suitable for road construction or as drainage material in landfill, whereas the wood fly ash was assumed to be suitable for road construction or as a nutrient resource to be recycled on forest land after biofuel harvesting. Different types of potential environmental impact predominated in the activities of the system and the use of natural resources and the trace element leaching were identified as being relatively important for the scenarios compared. The scenarios differed in use of resources and energy, whereas there is a potential for trace element leaching regardless of how the material is managed. Utilising MSWI bottom ash in road construction and recycling of wood ash on forest land saved more natural resources and energy than when these materials were managed according to the other scenarios investigated, including dumping in landfill.

Key words

LCA; MSWI bottom ash; wood ash; environmental assessment

1. Introduction

Incineration for energy production of biofuel, peat and different types of waste in Sweden generates approximately 1 million tonnes of ashes yearly (Ribbing, 2007). These ashes are of varying chemical and technical properties, depending on the type of fuel, the incineration process and the type of furnace (Rendek et al., 2007). Some of the ashes may be considered as usable for ground constructions or as a source of nutrients while others need to be put under controlled leaching conditions due to their contents of contaminants. For some ashes, such as bottom ash from municipal solid waste incineration (MSWI) or fly ash from wood incineration, there are different relevant management options, including different utilisation possibilities as well as disposal of the material in landfill.

In order to choose the best management scenario, knowledge is needed on the potential environmental impacts that can be expected from the possible management options. When assessing the potential environmental impacts, the system boundaries chosen are critical for the result. Roth and Eklund (2003) discussed different approaches to the environmental evaluation of by-products for road and ground constructions and concluded that widening the system boundaries can improve the basis for decision making. For MSWI bottom ash utilisation, research on environmental impact associated with utilisation has mostly been focused on the chemical properties of the material and the possible leaching of contaminants in different applications (Olsson, 2005). Knowledge of the chemical properties of a material is necessary when assessing the risk for local toxic effects. However, it is not sufficient if a wider range of aspects are to be covered, such as climate change, acidification, eutrophication and depletion of natural resources. A broader approach is needed to receive qualitative or quantitative information on the potential for environmental impact on a regional or global scale, and impact that is not directly associated with the chemical properties of the material.

In Olsson et al. (2006), a life cycle assessment (LCA) approach was outlined and used to study the potential environmental impact from substituting crushed rock with MSWI bottom ash in a road construction. It was concluded that a life cycle perspective was necessary if other types of environmental impact than only leaching from the material was to be captured. A few similar approaches for environmental assessment of secondary material in earth constructions can be found (Mroueh et al., 2001; Birgisdottir et al., 2007; Carpenter et al., 2007). In these studies, potential leaching from the reused materials is related to other emissions to air or water and to the natural resources that are needed by the system. These previous studies, however, have focused mainly on the choice of material for a certain construction and little attention has been given to the fact that the same material may be suitable for different purposes, with different environmental impact as the result. Although a secondary material seems to be favourable over a conventional material in a road structure, there might be even better ways of utilising the material from an environmental point of view. Wood fly ash is a suitable material for road construction but it is at the same time a nutrient resource that may be returned to forest land as ash recycling in order to sustain the nutrient status of the soil and decrease acidification problems. MSWI bottom ash is a useful substitute for crushed rock or natural gravel, not only in road constructions but also in other types of constructions, such as the drainage layer in the final covering of a landfill. For decisions on how to manage potential useful incineration residues, information is needed on the differences in environmental impact between possible management scenarios. Such information might be used as decision-support in specific cases, or serve as base for more strategic decisions on policies and programmes concerning the management of waste materials on a regional or national level.

The aim of this study was to outline an LCA based approach for environmental assessment of ash utilisation that compares different management strategies. The approach was

demonstrated through two case studies, in which the potential environmental impact from different management scenarios for two selected ash types, MSWI bottom ash and wood fly ash, were assessed.

2. Method

2.1. Environmental assessment approach

LCA is a tool for describing environmental aspects and potential impacts throughout a product's life, from raw material acquisition through production, use and disposal (ISO, 1997). Central issues are the use of a life cycle perspective, the definition of a system and the quantification of flows in to and out of the system (resources and emissions) as a base for an impact assessment. Although LCA was traditionally developed for environmental assessment of products there are examples where LCA has been used for other more complex functions, such as for evaluating strategies for treatment of solid waste (Finnveden et al., 2005) or various waste water systems (Tillman et al., 1998; Weiss et al., 2008). The LCA framework includes several possible methodological choices, for example the definition of system boundaries, which influences the outcome of the assessment. Each such choice should be based on the aim of the LCA (Tillman, 2000).

In this study, the methodology and concepts developed for LCA were used to compare different strategies for ash management. The approach outlined differs from previous studies (Mroueh et al., 2001; Olsson et al., 2006; Birgisdottir et al., 2007; Carpenter et al., 2007) by using a wider scope with more services included in the functional unit of the system. The approach was used in a case study of wood fly ash utilisation and a case study of MSWI bottom ash utilisation. In general, the work followed the established methods and practices for an LCA (ISO, 1997), including the principles for defining system boundaries and for conducting the inventory, the impact assessment and the interpretation.

Fig. 1. System boundaries for ash management. In scenario 1, the ash is used in service A, in scenario 2 it is used in service B and in scenario 3 it is dumped in landfill. Dashed boxes indicate that this activity is not present in all scenarios. Some of the activities include transports.

2.2. Definition of system boundaries and functional unit

For each case study, three possible management scenarios were compared. These included utilization possibilities A and B and disposal of the ash in landfill (Fig. 1). For the scenarios in which the ash was utilized, the ash was assumed to substitute other resources. To avoid allocation problems for the different services provided by the system, the system boundaries were expanded in order to include all relevant products or services associated with the identified management scenarios. Thus, the functional unit of the system includes the two different services (A and B) that the ash may contribute to in the chosen management scenarios as well as the function of managing the ash material. This implies that if the ash is

used to produce service A, other resources have to be used for service B in order to fulfill the function of the system. The reverse is true if the ash is used to produce service B. If the ash is dumped in a landfill without utilization, other resources are needed to produce both service A and B. This approach enables a broad evaluation of the system's environmental performance at each scenario alternative, including both the use of natural resources and aspects regarding landfilling.

Focus was put on the differences between different possible scenarios rather than on the total environmental impact caused by each scenario. Unit processes that were similar for all studied scenarios were excluded and the results should therefore be referred to as the *relative* potential environmental impact of the system. For example the production of ash was not considered, since the inflow of ash to the system is the same regardless of the management scenario. The scenarios for utilisation of ash were defined, e.g. by adjusting the dimensions of the construction, so that the substitution of natural material could be done without any decrease in the quality of the product. Hence, the use and maintenance, as well as the possible destruction, of the constructions in the different scenarios were assumed to be the same and the unit processes for these activities were not included.

2.3. Inventory, impact assessment and interpretation

During the inventory analysis, the use of resources (including energy) by the system and the emissions from the system were quantified for all unit processes. Those flows of resources and emissions will be further referred to as elementary flows (EFs). The EFs should include all material or energy that enters the system from the environment without previous human transformation, and material or energy that is discarded from the system into the environment without subsequent human transformation (ISO, 1997).

EFs associated with the life cycle of products used in the unit processes, such as fuel, electricity and chemical products, were included in the inventory. Thus, raw materials, energy and emissions from producing, utilising or disposing of these products were included. For example, the emissions from the combustion of diesel by the transporting lorry were inventoried as EFs, as was the raw material and the emissions from the production of the diesel. The EFs included were those that have the potential, based on current knowledge, to contribute to any type of environmental impact described by SETAC-Europe (1999) or defined in the Swedish environmental quality objectives (Swedish Environmental Objectives Council, 2007). Other criteria were data availability and the significance for the result of the study.

Generally, information used for calculating the EFs were obtained from literature (Davis and Haglund, 1999; Stripple, 2001; Svingby and Båtelsson, 1999) or estimated by researchers, project owners or entrepreneurs. Road transports were assumed to be done with a lorry, carrying 35 tonnes and returning empty and with the average fuel consumption of 0.45 l/km. The transport distance was assumed to be 30 km for all materials except the geotextile and the components for alternative nutrient compensation, for which longer transports with boat or train were calculated according to Baumann and Tillman (2004). The landfill was assumed to be 15 m thick and covered with a precovering layer of sand (0.2 m), a barrier layer of geosynthetic clay liner (bentonite and geofabric, 0.006 m), a drainage layer of sand (0.2 m), a surface layer of excavated soil (0.5 m) and a vegetation layer with soil on the top (1.35 m). Based on a sensitivity analysis of preliminary results, the production of geosynthetic clay liner was neglected.

Leaching estimates of contaminants from the crushed rock and the ashes were based on results from laboratory scale experiments together with infiltration estimates over a 100 years period, according to Avfall Sverige (2008). Information on average trace element leaching

from the materials were obtained for the MSWI bottom ash (RVF, 2002), for crushed rock (Ekvall and Weidema, 2006) and for wood ash leaching (Avfall Sverige, 2008). The leaching from the constructions (road and drainage layer) and the landfill was approximated by results from batch tests using a liquid to solid (L/S) ratio of 10 or 2, respectively, whereas the leaching from ash recycled on forest land was approximated by results from availability tests. Due to a limited amount of available data, only As, Cd and Pb were included in the case study of wood ash, whereas As, Cd, Cr, Cu, Ni, Pb and Zn were included in the case study of MSWI bottom ash. Leaching from uncrushed natural materials, such as sand, was not included.

In the impact assessment, the EFs quantified through the inventory were regarded as the potential environmental impact from the system. The relative importance of each EF was estimated by normalising the results against the resource use and the emissions on a national basis (Avfall Sverige, 2008). Thus, the use of energy was divided by total national energy use whereas for example emissions of greenhouse gases were divided with total national emissions of greenhouse gases. Due to lack of statistical data, however, the use of crude oil, rock phosphate and potassium and the emissions of phenol and oil to water were not included in the normalisation. Sensitivity analyses were continuously carried out.

2.4. Case study of wood ash

In Sweden, around 150 000 tonnes of ash is produced annually from incineration of biofuels that have not been mixed with contaminated fuels (Avfall Sverige, 2008). This ash, which is here referred to as wood ash, may be seen as a nutrient resource and the recommendation from the Swedish Forest Agency is to use it for ash recycling on forest land from which the biofuels have been harvested (Samuelsson, 2001). However, the ash is also a useful construction material, with technical properties suitable for small forest roads (Mácsik and Svedberg, 2006).

Table 1

Studied scenarios for wood ash management

Service provided by the system	Material used in scenario 1	Material used in scenario 2	Material used in scenario 3
Nutrient source	Wood ash	Alternative nutrient source ^a	Alternative nutrient source ^a
Road construction	Crushed rock	Wood ash	Crushed rock
Management of the material through landfilling	Landfilling is not needed	Landfilling is not needed	Wood ash and material for landfill final covering

^a The alternative nutrient source was assumed to be composed with dolomite as the main component and with the same amount as Ca, Mg, K, P and Zn as 1 tonne of wood ash.

In the case study, potential environmental impact from the management of wood ash produced in Borås in south western Sweden was studied. The possible management options included ash recycling on forest land, utilisation as a road construction material in a small forest road covered with gravel, or disposal of the ash in landfill (Table 1). Ash recycling practice was based on experiences from Borås, where wood ash is transformed into granules and spread on forest land by a specially designed tractor. For the scenarios in which the ash was utilised in a road construction or dumped on landfill, an alternative nutrient compensation, with dolomite as the main component, was assumed to be spread on forest land

in order to provide the same amount of Ca, Mg, K, P and Zn as the wood ash. The road construction used in the case study was based on experiences from the road Ehnsjövägen, situated northeast of Stockholm (Mácsik and Svedberg, 2006). The ash was assumed to be mixed with crushed rock (30 weight-% of ash) and used in a 0.2 m sub-base and base course layer. For the scenarios in which the ash was dumped in landfill or recycled on forest land, the road construction was assumed to be built with crushed rock only. The landfill scenario included the disposal and compaction of the ash, as well as the final covering of the landfill, but no cleaning of the landfill leachate. More detailed information on the different scenarios and the inventory in the case study on wood ash can be found in (Olsson et al., 2008).

Table 2

Studied scenarios for MSWI bottom ash management

Service provided by the system	Material used in scenario 1	Material used in scenario 2	Material used in scenario 3
Drainage material	MSWI bottom ash	Sand	Sand
Road construction	Crushed rock	MSWI bottom ash	Crushed rock
Management of the material through landfilling	Landfilling is not needed	Landfilling is not needed	MSWI bottom ash and material for landfill final covering

2.5. Case study on MSWI bottom ash

The residues from waste incineration are generally more contaminated than the wood ash, and its content of base-cations is lower. It is therefore not suitable as a nutrient resource. However, the technical properties of MSWI bottom ash make it suitable as a substitute for natural material such as gravel or crushed rock in constructions. The yearly production in Sweden of MSWI bottom ash is around 450 000 tonnes (Avfall Sverige, 2008).

The potential environmental impact from management of MSWI bottom ash produced in the Uppsala region in Sweden was studied in the second case study. The possible management options included utilisation as a drainage layer material on a landfill, utilisation as a sub-base

material in an asphalt covered road, or disposal in landfill (Table 2). The drainage layer construction was based on experiences from the landfill Dragmossen in Älvkarleby (Mácsik et al., 2006). The MSWI bottom ash was assumed to substitute sand in a 0.2 m drainage layer and geotextile was then assumed to be added on the top and at the bottom of the MSWI bottom ash layer, in order to separate the materials. Inventory data for the road construction was based on experiences from the test road Törringevägen southern Sweden (Hartlén et al, 1999) and the previous inventory in Olsson et al. (2006). The bottom ash was assumed to substitute crushed rock in a 0.4 m sub-base layer, with a somewhat increased base course of crushed rock (0.15 m instead of 0.08 m) in order to maintain the technical properties. The chemical treatment of landfill leachate was included for the time period from disposal until the covering of the landfill (20 years). More detailed information on the different scenarios and the inventory in the case study on MSWI bottom ash is available in Avfall Sverige (2008).

3. Results and discussion

3.1. Wood fly ash management

The use of natural resources and energy and the emissions to air and water included in the case study on wood fly ash are reviewed as the system's EFs for the studied scenarios in Table 3. According to the normalisation results, the use of natural materials and the emissions of Cd can be considered the system's most important EFs.

Recycling of the ash on forest land was the scenario that saved most natural resources except for crushed rock. In scenario 2 or 3, natural materials were needed to produce the alternative nutrient compensation and in scenario 3, additional natural materials were needed for landfill covering. To save crushed rock, on the other hand, it was most beneficial to use the ash for road construction. The amount of crushed rock and sand to be saved if all wood ash would be managed according to scenario 1 or 2 was, however, only <1% of the annual use

of these materials. The use of natural resources for production of alternative nutrient compensation in scenario 2 and 3 was more significant. The use of dolomite would, for example, correspond to almost half of the annual extraction of dolomite in Sweden, if alternative nutrient compensation were to substitute the total national wood ash production.

Table 3

The system's elementary flows (EFs) for the scenarios compared for managing 1 tonne of wood ash. The results for each scenario should be interpreted as relative to the other scenarios, since only those unit processes in which there are differences between the scenarios are included and not the total system. In scenario 1, the wood ash is recycled on forest land, in scenario 2 it is used for road construction and in scenario 3 it is dumped in landfill.

Elementary flow	Unit	Scenario 1	Scenario 2	Scenario 3
Resource use				
Energy ^a	GJ	0.52	2.72	2.89
Sand	tonnes	0	0	0.04
Other natural aggregates ²	tonnes	3.92	2.33	4.10
Zn	kg	0	0.50	0.50
P	kg	0	15	15
Dolomite	kg	0	780	780
K	Kg	0	70	70
Emissions to air				
CO	g	29	106	114
CO ₂	g	24536	95846	102946
CH ₄	g CO ₂ -ekv	0.6	2.9	3.1
F ₂	g	0	11	11
HC	g	13	58	62
NO _x	g	198	826	884
N ₂ O	g CO ₂ -ekv	163	660	708
Particles	g	5.3	29.5	31.2
SO ₂	g	12	549	552
SO ₃	g	0	63	63
VOC	g	0.09	0.60	0.64
Emissions to water				
COD	g	0.37	1.43	1.54
N-tot	g	0.06	0.23	0.24
Oil	g	0.12	0.48	0.51
Phenol	g	0.18	0.68	0.73
As	g	0.34	0.017	0.013
Cd	g	4.3	0.006	0.006
Pb	g	2.2	0.20	0.087

^a Energy includes the different types of fuel used within the system, and precombustion for fuel production.

^b Natural aggregates include excavated materials such as crushed rock and soil, of which the crushed rock constitutes the dominant fraction (>95%).

The estimated leaching of As, Cd and Pb from crushed rock and wood ash were larger in scenario 1 than in scenario 2 or 3 (Table 3), due to the relatively large amount of water that was assumed to reach the wood ash in this scenario. Assuming that the total annual production of wood ash is recycled on forest land, the release of As and Pb would be relatively small (<1%) compared to the yearly national release from goods and product used in the society whereas the release of Cd from the wood ash would be much more significant. The amount of available Cd in the ash contributed to about the same amount as the total yearly release from goods and products in Sweden. Ash recycling, however, implies a return of substances that were once removed from the forest area through biomass harvesting and if biomass harvesting had been included within the system boundaries, the amount of As, Cd and Pb in the recycled ash would not have constituted an emission. The road construction as well as the landfill alternatives would then result in a net-removal of the As, Cd and Pb from the forests in a 100-year perspective, provided that the alternative nutrient compensation in scenario 2 and 3 is not contaminated.

Fig. 2. Use of energy by the different activities in the system, assuming nutrient compensation to be needed in all scenarios (left) or only in scenario 1 (right). In scenario 1 (white bars), the wood ash is recycled on forest land, in scenario 2 (grey bars) it is used for road construction and in scenario 3 (black bars) it is dumped in landfill. Transports of material for landfill covering are included in the landfilling.

Recycling of ash on forest land was found to be the most energy efficient way to manage the ash. The differences in energy consumption between the scenarios were mainly due to the production of alternative nutrient compensation in scenario 2 and 3 which was found to be a highly energy consuming activity (Fig. 2, left). Still, the amount of energy to be saved by using the total amount of wood ash produced instead of alternative nutrient compensation would only correspond to about 0.01% of the total annual energy use in Sweden. The emissions to air, and the emissions to water of COD, nitrogen, oil and phenol, were strongly dependent on the use of energy. Hence, recycling of ash on forest land (scenario 1) was also the scenario with the smallest amount of air emissions. According to a sensitivity analysis for transport distances, the ash recycling on forest land was the most energy efficient scenario even if the transport distance for the wood ash would exceed 200 km.

However, it can be discussed whether it is realistic to assume an alternative nutrient compensation to be used in scenario 2 or 3. If no nutrient compensation is used in these scenarios, the production of crushed rock and the transports would cause the system's major use of energy (Fig. 2, right).

It can also be discussed if it is realistic to assume similar technical properties of the wood ash road as of a conventional road with crushed rock. Previous experiences indicate that the long term technical sustainability can be improved when using fly ash in the sub-base and base course layers of a road construction, even if the layer thickness is decreased (Lahtinen, 2001; Macsik and Svedberg, 2006; Avfall Sverige, 2008). A sensitivity analysis was therefore conducted in which the maintenance was included. The ash road was assumed to need half the amount of maintenance activities as the conventional road for the same period of time and the thickness of the sub-base and base course layer was decreased to 0.2 m. However, due to the large amount of energy needed for producing alternative nutrient compensation, these new assumptions did not lead to any new results. Although the system would use somewhat more

natural materials and energy, the differences between the studied scenarios remained. If, on the other hand, these assumptions were combined with the assumption that the alternative nutrient compensation in scenario 2 or 3 is not needed, the results would change. The maintenance would then constitute the most important activity for the use of energy and scenario 2 would be the most energy efficient scenario.

3.2. MSWI bottom ash management

The use of natural resources and energy and the emissions to air and water included in the case study on MSWI bottom ash are reviewed as the system's EFs for the studied scenarios in Table 4. According to the normalisation results, the use of natural materials and the emissions of trace elements can be considered the system's most important EFs.

The scenarios compared used different types of natural materials. Crushed rock was used for road construction in scenario 1 and 3, and sand was used for the drainage layer in scenario 2 and 3, whereas other excavated natural materials were used for landfill covering in scenario 3. If the total production of MSWI bottom ash in Sweden is utilised in drainage layers according to scenario 1, the amount of sand that would be saved corresponds to almost one third of the total amounts used annually. For the other excavated materials, the annual production is larger and the amounts to be saved by using all MSWI bottom ash in road constructions only constitute a minor fraction (<1%).

Trace element leaching, particularly of Cu, was identified as one of the most important EFs from the system. If utilising the annual Swedish production of MSWI bottom ash in drainage layers or road constructions according to scenario 1 or 2, the estimated leaching of Cu during 100 years would correspond to about 0.7 % of the annual release of Cu from other sources. The estimated leaching of trace elements from crushed rock and MSWI bottom ash was largest in scenario 1 (Table 4), where the ash was used in the drainage layer and crushed rock was used in the road.

Table 4

The system's elementary flows (EFs) for the scenarios compared for managing 1 tonne of MSWI bottom ash. The results for each scenario should be interpreted as relative to the other scenarios, since only those activities in which there are differences between the scenarios are included and not the total system. In scenario 1, the bottom ash is used as drainage material, in scenario 2 it is used for road construction and in scenario 3 it is dumped in landfill.

Elementary flow	Unit	Scenario 1	Scenario 2	Scenario 3
Resource use				
Energy ^a	MJ	168	89	172
Sand	tonnes	0.0	0.9	1.0
Other natural aggregates ^b	tonnes	1.2	0.4	1.4
Crude oil ^c	Kg	0.94	0	0
Emissions to air				
CO	g	7.3	6.3	10.2
CO ₂	g	6144	5059	8332
CH ₄	g CO ₂ -ekv	0.17	0.09	0.19
HC	g	3.3	2.5	4.3
NO _x	g	49	40	67
N ₂ O	g CO ₂ -ekv	42	33	55
Particles	g	1.3	0.9	1.6
SO ₂	g	3.1	2.3	3.9
VOC	g	0.03	0.01	0.03
Emissions to water				
COD	g	0.096	0.061	0.108
N-tot	g	0.015	0.010	0.017
Oil	g	0.032	0.020	0.036
Phenol	g	0.046	0.029	0.051
As	g	0.023	0.009	0.020
Cd	g	0.008	0.003	0.007
Cr	g	0.13	0.03	0.11
Cu	g	3.0	2.9	2.0
Ni	g	0.12	0.05	0.09
Pb	g	0.04	0.02	0.02
Zn	g	0.19	0.12	0.12

^a Energy includes the different types of fuel used within the system, and precombustion for fuel production.

^b Other natural aggregates includes excavated materials such as crushed rock and soil, of which the crushed rock constitutes the dominant fraction (>80%).

^c Crude oil used as a raw material for geotextile production

The reason for the low leaching in scenario 2, where the bottom ash was used in the road construction, is that in this scenario there was no use of crushed rock and, thus, no leaching from this material was included. In the landfill scenario, leaching from crushed rock in the road construction was included. At the same time, the leaching from the bottom ash was smaller in scenario 3 than in the other scenarios due to a lower expected amount of infiltrating

water. It should be noted, however, that although the average values indicated some difference between the scenarios, the variance in data was large and the dataset was too small to allow for any general conclusions regarding differences in trace element leaching. The results from the laboratory experiments showed similar average leaching from the MSWI bottom ash as from the crushed rock (within one order of magnitude) at L/S 10 for all trace elements except Cu. Due to the large contribution from the crushed rock to the total leaching from the scenarios, different assumptions regarding the infiltration rate were of minor importance for the outcome, except for the Cu leaching.

As in the wood ash case study, the emissions to air and the emissions to water of COD, nitrogen, oil and phenol were strongly linked to the use of energy and if energy was saved, a decreased amount of these emissions were released. The most energy efficient way to manage the MSWI bottom ash in this case study was to use it in the road construction (scenario 2). The production of crushed rock was found to be an energy consuming process, which constituted a large part of the total energy use in scenario 1 and 3 (Fig. 3). However, transporting the material was also relatively important for the system's use of energy. According to a sensitivity analysis for transport distances, scenario 2 may include a transport distance for the MSWI bottom ash that is up to 80 km longer than in scenario 1 or 3, and still be the more energy saving scenario.

A sensitivity analysis was also performed for differences in maintenance of the road built with crushed rock and the road built with MSWI bottom ash. Based on Strippel (2001), the maintenance of the road was included and a 20% difference in maintenance activity was assumed. The total use of energy increased significantly as a result of the included maintenance, but the relation between the scenarios remained, regardless of which material that was assumed to imply less road maintenance.

3.3. Applying a life cycle perspective on ash management

Most commonly in LCAs, the EFs for a system are aggregated by classification and characterization, and sometimes the different impact categories are weighted against each other. In this study, the EFs were used directly for the impact assessment, together with normalisation results. Since the normalisation was used for prioritising the most important EFs, it can here be considered as a weighting method. There were three reasons for the methodological choice to not use classification and characterisation. Firstly, after talking to different stakeholders and entrepreneurs it was found that aggregating the information by classification and characterisation was of limited interest to the decision-makers associated with ash management in Sweden. Secondly, the methods for consistently and accurately calculating the contribution of each inventory data to different types of potential environmental impact can be questioned. Finally, data gaps can limit the inclusion or coverage of a number of impact categories, thus limiting the possibilities to draw conclusions from the results (Finnveden, 1998). For example, human and eco-toxicological impact categories would suffer from severe data gaps due to insufficient knowledge about many ash substances.

Fig. 3. Use of energy by the different activities in the system. In scenario 1 (white bars), the bottom ash is used as drainage material, in scenario 2 (grey bars) it is used for road construction and in scenario 3 (black bars) it is dumped in landfill. Transports of material for landfill covering are included in landfilling.

For environmental impact that prevails over a long period of time, such as leaching of contaminants, the choice of time perspective may be crucial for the outcome of an LCA. Finnveden et al. (1995) suggested three different time perspective to be used in LCAs of landfills, a surveyable time period of 100 years, a critical time period and a hypothetical infinite time period. In this study, a time perspective of 100 years was used for the environmental assessment. This temporal cut-off presumes that there will be no impact from future emissions, which is most likely not the case. Regarding the focus of the study, which was on the differences between different management possibilities rather than on the total impact from the system, however, this temporal cut-off was considered as relevant. Leaching from the ashes will occur to some degree regardless if the material is re-used or if it is dumped in landfill. In a very long time perspective, the differences in leaching from the constructions with ash and from the ash in landfill will decrease. In addition, the relative importance of leaching from the crushed rock will decrease, due to a lower amount of available trace elements.

The leaching estimates during this time period was calculated by combining results from laboratory scale leaching tests with an assumption of the future infiltration rate. It should be noted that there might be significant differences between specific ashes and specific types of rock material, and that the average values used here may therefore not be valid in other cases. Further, the leaching estimates are based on several assumptions. It may, for example, be argued that laboratory scale experiments do not sufficiently represent the future field conditions since the amount of water in contact with the material and the physical impact on the particles may be significantly different. The equilibrium conditions may also be questioned. Therefore, the estimates presented here should be interpreted as an indication of what might be expected, rather than a detailed prediction.

Furthermore, to predict toxic effects, information on the distribution and the peaks in concentrations at certain occasions may be more relevant than information on the accumulated leaching in a 100 years perspective. Since trace element leaching was found to be relatively important in the environmental assessment of ash utilisation, case specific risk assessments such as provided by Carpenter et al. (2007) are recommended as a complement in order to cover this issue more in detail.

3.4. General findings and their implementation

In both case studies, the investigated EFs can be divided into three different categories, i) the use of natural resources, ii) the use of energy and the associated emissions to air and water, and iii) the direct emissions from the material. General findings were that the utilisation of both wood fly ash and MSWI bottom ash ashes saves natural resources and energy, whereas the consequences on the trace element leaching are more uncertain and may depend on the specific materials. Thus, there is a potential for toxic effects, regardless how the ashes are disposed of, but the dumping of the ashes in landfill is likely to cause additional types of environmental impact such as climatic change, acidification, and depletion of resources. Whereas toxic effects may be considered as a local impact, the other types of environmental impact occur on a regional or global scale. It should be noted, however, that there are also types of potential environmental impact that were not investigated in the case studies, such as noise, dust emissions during production, occupation of land area and emissions from the ashes and the crushed rock of other potentially toxic substances than the ones included here.

Further, in both case studies it was found that different types of potential environmental impact were dominating in the different stages of the system's life cycle. Whereas the differences in the use of natural resources and energy were largest during the extraction and

refinement of raw materials, the leaching of trace elements occurred when using the services of the system. Hence, the case studies confirm the importance of using a life cycle perspective in order to cover a wide range of potential environmental impact.

The outlined approach had a relatively broad scope. In order to include different alternatives for ash utilisation, the system boundaries were expanded compared to previous LCAs of ash utilisation (Birgisdottir et al., 2007; Olsson et al., 2006; Carpenter et al., 2007) in which the choice of material for a certain construction was the focus for the analysis. Such a focus is relevant if the aim is to improve the environmental performance of the construction. However, if the aim is to create a decision support for how to manage a certain material, the increased scope presented here is necessary. In strategic planning of regional material supply, for example, several possibilities need to be considered for how to manage both virgin and reused materials efficiently to meet the demand for construction materials in a certain region. In the case studies presented here, only two utilisation possibilities were included, but the outlined approach may be expanded further.

Due to the broad range of environmental aspects covered, it may be argued that the life cycle perspective improves the possibilities for sustainable development. Still, because ash management is associated with conflicting types of environmental impact, prioritising between environmental objectives may be unavoidable in a decision situation. Generally acceptable methodologies for this are needed, such as multicriteria analysis approaches (e.g. Hung et al., 2006). Further, the outlined approach might need to be combined with other tools in order to receive a multi-dimensional and relevant base for decisions on ash management.

References

- Avfall Sverige, 2008. Miljökonsekvensanalys av Naturvårdsverkets förslag till kriterier för återvinning av avfall i anläggningsarbeten. Report No F2008:04. Avfall Sverige Utveckling, Malmö, Sweden (in Swedish).
- Baumann, H., Tillman, A., 2004. The Hitch hiker's guide to LCA. An orientation in the life cycle assessment methodology and application. ISBN 91-44-02364-2. Studentlitteratur, Lund, Sweden.
- Birgisdottir, H., Bhandar, G., Hauschild, M. Z., Christensen, T. H., 2007. Life cycle assessment of disposal of residues from municipal solid waste incineration: Recycling of bottom ash in road construction or landfilling in Denmark evaluated in the ROAD-RES model. Waste Management 27, S75-S84.
- Carlsson, A., Wadeskog, A., Palm, V., Kanlén, F., 2006. Material Flow Accounts and Policy. Data for Sweden 2004. Environmental Accounts. Statistics Sweden.
- Carpenter, A. C., Gardner, K. H., Fopiano, J., Benson, C. H., Edil, T. B., 2007. Life cycle based risk assessment of recycled materials in roadway construction. Waste Management 27, 1458-1464.
- Davis J., Haglund C., 1999. Life cycle inventory (LCI) of fertiliser production. Fertiliser products used in Sweden and Western Europe. SIK-report No 654. Kemisk miljövetenskap, Chalmers, Göteborg, Sweden.
- Ekvall, T., Weidema, B. P., 2004. System boundaries and input data in consequential life cycle inventory analysis. Int. J. LCA 9, 161-171.
- Finnveden, G., 1998. On the possibilities of life-cycle assessment - development of methodology and review of case studies. Doctoral thesis at the department of Systems Ecology, Stockholm University, Stockholm, Sweden.

- Finnveden, G., Albertsson, A.-C., Berendson, J., Eriksson, E., Höglund, L. O., Karlsson, S., Sundqvist, J.-O., 1995. Solid waste treatment within the framework of life-cycle assessment. *J. Cleaner Prod.* 3, 189-199.
- Finnveden, G., Johansson, J., Lind, P., Moberg, Å., 2005. Life cycle assessment of energy from solid waste - part 1: general methodology and results. *J. Cleaner Prod.* 13, 213-229.
- Hartlén, J., Grönholm, R., Nyström, T., Schultz, J., 1999. Återanvändning av sekundära material inom anläggningsområdet. AFR report 275. Naturvårdsverket, Stockholm, Sweden.
- Hung, M.-L., Ma, H.-W., Yang, W.-F., 2006. A novel sustainable decision making model for municipal solid waste management. *Waste Management* 27, 209-219.
- ISO, 1997. ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva, Switzerland.
- Lahtinen, P., 2001. Fly ash mixtures as flexible structural materials for low-volume roads. Doctoral thesis at the department of Civil and Environmental Engineering, Helsinki University of Technology, Helsinki, Finland.
- Mácsik, J., Maurice, C., Mossakowska, A., Eklund, C., 2006. Pilotförsök med flygaskastabiliserat avloppsslam (FSA) som tätskikt. VA-forsk report No 2006-01. Svenskt Vatten AB, Stockholm, Sweden.
- Mácsik, J., Svedberg, B., 2006. Skogsbilvägsrenovering av Ehnsjövägen, Hallstavik. Report No Q4-285. Värmeforsk, Stockholm, Sweden.
- Mroueh, U.-M., Eskola, P., Laine-Ylijoki, J., 2001. Life-cycle impacts of the use of industrial by-products in road and earth construction. *Waste Management* 21, 271-277.
- Olsson, S., 2005. Environmental assessment of municipal solid waste incinerator bottom ash in road constructions. Licentiate thesis at the department of Land and Water Resources Engineering, KTH, Stockholm, Sweden.

- Olsson, S., Kärrman, E., Gustafsson, J. P., 2006. Environmental systems analysis of the use of bottom ash from incineration of municipal waste for road construction. *Resour. Conserv. Recycl.* 48, 26-40.
- Olsson, S., Kärrman, E., Rönnblom, T., Erlandsson, Å. 2008. Skogsbränsleaska som näringsresurs eller konstruktionsmaterial – Miljöeffekter av olika handlingsalternativ. Final report from Värmeforsk project Q6-610, Värmeforsk, Stockholm, Sweden.
- Rendek, E., Ducom, G., Germain, P., 2007. Influence of waste input and combustion technology on MSWI bottom ash quality. *Waste Management* 27, 1403-1407.
- Ribbing, C., 2007. Environmentally friendly use of non-coal ashes in Sweden. *Waste Management* 27, 1428-1435.
- Roth, L., Eklund, M., 2003. Environmental evaluation of reuse of by-products as road construction materials in Sweden. *Waste Management* 23, 107-116.
- RVF (2002). Kvalitetssäkring av slaggrus från förbränning av avfall. 02:10, Svenska Renhållningsverksföreningen, Malmö, Sweden.
- Samuelsson, H. (2001). Rekommendationer vid uttag av skogsbränsle och kompensationsgödsling. Meddelande 2, Skogsstyrelsens förlag, Jönköping, Sweden.
- SETAC-Europe, 1999. Best Available Practice Regarding Impact Categories and Category Indicators in Life Cycle Impact Assessment. *Int. J. LCA* 4, 167-174.
- SGU, 2006. Grus, sand och krossberg, produktion och tillgångar 2005. Per. publ. 2006:3. SGU, Stockholm, Sweden.
- Svingby, M., Båtelsson, O., 1999. LCA av lättfyllnadsmaterial för vägbankar. Detaljerad rapport. Vägverket, Borlänge, Sweden.
- Stripple, H., 2001. Life Cycle Assessment of Road, A Pilot Study for Inventory Analysis. Second revised edition, B1210E. IVL Svenska Miljöinstitutet AB, Göteborg, Sweden.

- Swedish Environmental Objectives Council, 2007. Sweden's Environmental Objectives – in an interdependent world, de Facto 2007, ISBN 91-620-1260-6.
- Tillman, A.-M., 2000. Significance of decision-making for LCA methodology. *Environmental Impact Assessment Review* 20, 113-123.
- Tillman, A. M., Svingby, M., Lundström, H., 1998. Life Cycle Assessment of municipal waste water systems. *Int. J. LCA* 3, 145-157.
- Weiss, P., Eveborn, D., Kärrman, E., Gustafsson, J.P., 2008. Environmental Systems Analysis of four on-site wastewater treatment options. *Resour. Conserv. Recycl.* doi:10.1016/j.resconrec.2008.06.004.