Including indirect environmental impacts in waste management planning

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Abstract

Activities within waste management systems, such as energy and material recovery, can lead to indirect environmental impacts that occur outside of waste management systems. In this paper, the effect of including indirect greenhouse-gas emissions on the choice of waste management solutions on a national level is explored. The global warming potentials (GWPs) of future waste management solutions for Sweden are compared. These include direct and indirect GWPs resulting from recovering power, heat, biogas, materials and nutrients. Furthermore, two of the assumptions that are presumed to be crucial for determining the indirect GWPs are examined in sensitivity analyses. It was found that indirect GWPs of waste management could be large when comparing a range of waste management solutions. Including indirect GWPs may even change the ranking of the solutions. However, the estimates of the indirect GWPs are sensitive to the assumptions made. Including them involves large uncertainties. Despite this, some general conclusions regarding the preferability of the respective solutions can be drawn. Including indirect environmental impacts is important when providing information to support strategic planning that involves choosing among waste management solutions. Ultimately, it is a question of improving the ability of waste management planners to design environmentally sustainable and robust waste management systems. Increased knowledge of the indirect environmental impacts of waste management can contribute to providing such an improvement.

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1. Introduction

Waste management is gradually shifting focus from waste elimination to integrated management of potentially valuable resources and residues. This is manifested in, for example, the efforts to increase materials and energy recovery that occur widely today. As a result, waste management systems interact more with systems that are not traditionally regarded as waste management and are beyond the usual managerial area of waste management planners. Examples are markets for material and energy, in which recovered materials and energy compete with other materials and energy production options. This shift in focus adds to the already prevailing complexity of waste management planning: technical, economic, environmental, political, legislative, institutional and social aspects are all part of waste management planning (Wilson, 1998).

Waste management planners can find assistance in systems engineering models to handle the complexity of their work. Typically, these models deal with the quantifiable aspects of waste management, such as technology and economy (Hasit and Warner, 1981; Kaila, 1987; Rushbrook and Pugh, 1987; Baetz, 1990; Ossenbruggen and Ossenbruggen, 1992; Anex et al., 1996; Everett and Modak, 1996; Faaij et al., 1998). Some models also deal with environmental impacts (Caruso et al., 1994; Sundberg et al., 1994; Hokkanen et al., 1995; White et al., 1995; Chang et al., 1996; Dalemo et al., 1997; Faaij et al., 1998; Thorneloe et al., 1998; Wang et al., 1998; Ljunggren, 2000; Tanskanen, 2000). Some models deal only with environmental impacts (Mizra, 1998). The models serve to support decision-makers by helping to structure complex information in the planning process. Performing a study with such a model can be valuable in helping to structure complex information in the planning process. Such studies can also help to strengthen communication within planning organisations (Ljunggren Söderman, 2000a).

However, the environmental analyses in systems engineering studies have often been limited to analysing direct environmental impacts of waste management, such as emissions from incineration, transport and landfill (Caruso et al., 1994; Hokkanen et al., 1995; Chang et al., 1996; Wang et al., 1998; Tanskanen, 2000). Little attention has been paid to the indirect environmental impacts of waste management. These are environmental impacts that occur outside the waste management system as a result of waste management activities. One example of such waste management activities is material recovery. If recovering a material results in the replacement of another material, the production of the replaced material can be avoided. The indirect

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1 Some of the authors do not use the term ‘systems engineering studies’, but instead the term ‘life cycle inventories’. However, today the difference in terms applied reflects the different disciplines from which the studies stem historically, more than actual differences in the approaches applied.
Environmental impact of material recovery is thus the avoided environmental impact of producing the replaced material.\(^2\)

There are some examples where indirect environmental impacts have been covered in systems engineering studies of waste management (Sundberg, 1993; White et al., 1995; Sonesson et al., 1997; Sundberg and Ljunggren, 1997; Thorneloe et al., 1998; Faaij et al., 1998; Mizra, 1998; Ljunggren, 2000; Ljunggren Söderman, 2000b; Sonesson et al., 2000). These studies have covered the indirect environmental impacts of supplying power and vehicle fuels and recovering power, heat, biogas, materials and nutrients. However, none of the studies have simultaneously covered all activities. The indirect environmental impact of waste management have also been discussed in life cycle assessments (LCA) of products (Tillman et al., 1994; Finnveden and Ekvall, 1998). Both types of studies have shown that indirect environmental impacts of waste management can be substantial in comparison to direct ones. This fact and the current trend of increasing interaction between the waste management sector and other sectors, as noted above, point to the potential importance of including indirect environmental impacts in systems engineering studies. Ultimately, it is a question of improving the ability of waste management planners to design environmentally sustainable and robust waste management systems. Increased understanding of the indirect environmental impacts of waste management can contribute to providing such an improvement.

The purpose of this paper is to study the significance of indirect greenhouse-gas emissions of waste management on a national level. First, indirect GWPs of a number of waste management solutions for Sweden are quantified and compared with direct ones. Then, the effect of including indirect GWPs on the choice of waste management solutions is examined. The indirect GWPs include indirect greenhouse-gas emissions of recovering (i) power, (ii) heat, (iii) biogas, (iv) materials and (v) nutrients. Furthermore, the sensitivity of indirect GWPs in relation to some of the assumptions made is analysed.

The waste management solutions analysed are based on an earlier study of solutions for Sweden around year 2010 in the light of expected policy shifts (Ljunggren Söderman, 2000b). In Ljunggren Söderman (2000b), cost-effectiveness and GWPs of the waste management solutions were analysed. The GWPs included direct and indirect greenhouse-gas emissions of recovering power, heat and biogas. It was found that including indirect impacts—especially that of power recovery—had a large influence on the total GWPs of the solutions. In the present study, the indirect GWPs of recovering materials and nutrients, as well as a sensitivity analysis, have been added to the analysis.

\(^2\) Note that economic aspects of interactions between waste management and outside activities are usually captured in prices for items that are supplied to, or recovered from, the waste management system (e.g. capital goods, auxiliary materials and recovered materials and energy). However, these prices are usually limited to private sector costs (Hasit and Warner, 1981; Kaila, 1987; Rushbrook and Pugh, 1987; Baetz, 1990; Ossenbruggen and Ossenbruggen, 1992; Sundberg et al., 1994; White et al., 1995; Chang et al., 1996; Anex et al., 1996; Everett and Modak, 1996; Dalemo et al., 1997; Faaij et al., 1998; Thorneloe et al., 1998; Wang et al., 1998; Tanskanen, 2000).
This paper is structured as follows. The approach with which direct and indirect environmental impacts of waste management have been addressed in the study is explained in Section 2. The waste management solutions for Sweden that have been analysed are presented in Section 3. The indirect GWPs resulting from a number of waste management activities are presented in Section 4. The results of the analysis of direct and indirect GWPs and the sensitivity analysis are presented in Section 5. Finally, in Section 6 quantitative and qualitative aspects of the study are addressed.

2. Environmental impacts of waste management systems

Waste management systems can be described in terms of material and energy flows within, to and from them.

In Fig. 1, vertical flows represent material flows. Solid waste of a certain quantity and composition enters the system at the point where it is collected from the waste generators (e.g. households and industries). The waste is then treated in the waste management system, usually through a combination of treatment methods, as implied in Fig. 1. From the system exit: (i) recovered materials to be reprocessed and absorbed by the markets for materials; (ii) recovered nutrients in the form of compost or anaerobic digestion residues to be absorbed by the market, e.g. nutrients; and (iii) waste to be stored long-term in a landfill. Auxiliary materials, e.g. slaked lime for incineration and flue gas cleaning, are supplied for running the system. If investments in new equipment are made, capital goods are supplied to the system.

![Fig. 1. Material and energy flows within, to and from waste management systems.](image-url)
Horizontal flows represent energy flows. Auxiliary energy in the form of power and vehicle fuels is supplied for running the system. Heat, power and biogas can be recovered from the system and subsequently absorbed by markets for energy carriers.

These material and energy flows can give rise to both direct and indirect potential environmental impacts, as explained in Sections 2.1 and 2.2.

2.1. Direct environmental impacts of waste management

Direct environmental impacts result from waste treatment within the waste management system, i.e. material and energy flows within the system. These impacts occur as results of using treatment options, such as collection, transport, source separation, central separation, composting, anaerobic digestion, incineration and landfilling. The impacts depend on either waste-specific or process-specific properties, or both. An example is the GWP caused by greenhouse-gas emissions from incineration, transport, composting and landfilling.

2.2. Indirect environmental impacts of waste management

Indirect environmental impacts take place in systems outside the waste management system as results of activities within the latter. These impacts occur when material and energy flow to and from the waste management system.

One can distinguish between two types of indirect environmental impacts. One type is impacts caused by producing material and energy inputs supplied to the system, as described in Fig. 1. These include, for example, impacts from producing power and vehicle fuels, auxiliary materials and capital goods. If the supply of a given item to the waste management system decreases, the total demand for the item decreases since no other sector will increase its demand for the item. This leads to a decrease in the production of the item. This type of indirect environmental impact is sometimes referred to as an indirect burden (Clift et al., 2000) or the environmental impact of upstream activities (Björklund et al., 1998).

Another type of indirect environmental impact is caused when materials and energy are recovered from the waste management system, as described in Fig. 1. The recovered materials, energy and nutrients enter markets to compete with other items for meeting market demand. If competition is favourable (or if imposed by policies), items recovered from the waste management system replace other competing items. As a consequence, the demand for the replaced items decreases, which, in turn, leads to the avoidance of the production of the items and their associated environmental impacts. This type of indirect environmental impact is sometimes referred to as an avoided burden (Clift et al., 2000) or the environmental impact of downstream activities (Björklund et al., 1998).

The analysis of indirect environmental impacts is based on one assumption that simplifies the analysis: market demand for any given item is constant in all sectors beyond waste management and is not affected by waste management activities. Without this assumption, the analysis of both types of indirect environmental
impacts would be different. First, if material and energy inputs to the waste management system were limited resources and if inputs to that system were increased, other sectors beyond waste management would have to reduce or replace their use of these resources. This would lead to other indirect environmental impacts than those analysed in this study. Second, if market demand was not constant, items recovered from the waste management system would not replace any competing items, but would increase the market quantities offered. In the case of recovered materials, for example, this would lead to the production, use and final disposal of an additional product with associated environmental impacts. Although not expressed with the same terminology, the meaning of this assumption is equal to how indirect environmental impacts are usually addressed in life cycle inventory (LCI) models for waste management (White et al., 1995; Thorneloe et al., 1998; Mizra, 1998) and often in life cycle assessments of products (Tillman et al., 1994).

3. Waste management solutions for Sweden

The waste management solutions for Sweden analysed in this study are presented in this section. The solutions are based on an earlier study of waste management solutions for Sweden around 2010 in light of expected shifts in waste management policy (Ljunggren Söderman, 2000b). Among policy shifts expected in Sweden, the bans on landfilling of combustible and organic waste to be introduced in 2002 and 2005, respectively (Ministry of the Environment, 1998a) are of major importance. Since landfilling is the most common waste treatment method for the waste types analysed (household waste, construction and demolition waste, and non-industry-specific industrial waste\(^3\)), options to reduce landfilling are vital. Therefore, the solutions analysed in Ljunggren Söderman (2000b) included, for example, material recovery, incineration with heat recovery or combined heat and power (CHP) recovery and biological treatment methods, such as composting and anaerobic digestion. The analysis was carried out using the NatWaste (National Waste) model (Ljunggren, 1997, 2000; Ljunggren Söderman, 2000b,c), a systems engineering model developed for strategic planning of national solid waste management systems. For a thorough description of the earlier study, the reader is referred to Ljunggren Söderman (2000b).

For the present study, eight of the waste management solutions from Ljunggren Söderman (2000b) were chosen.\(^5\)

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\(^3\) About half of all household waste and two-thirds of industrial waste (non-industry specific) and construction and demolition waste were landfilled in 1994 (Statistics Sweden, 1995).

\(^4\) NatWaste was formerly referred to as MWS (MIMES/Waste for Sweden) (Ljunggren, 2000).

\(^5\) Solutions 1 through 8 correspond to the following solutions in Ljunggren Söderman (2000a): 1 = DH, 2 = CHP and 3 = C&DH in the Base scenario; and 4 = AD&DH in the Bio scenario; 5 = DH, 6 = CHP, and 7 = C&DH in the Recov scenario. Solution 8 corresponds to AD&DH in the Recov scenario with the exception that biogas is recovered as vehicle fuel in solution 8 and as combined heat and power in AD&DH in the Recov scenario.
In solutions 1 and 2, all household waste remaining after source separation is incinerated. Industrial and construction and demolition wastes are first centrally separated, followed by recovery of materials, incineration of combustible fractions and landfilling of residual fractions. In both solutions, energy is recovered from incineration as heat in currently existing plants. In solution 1, new incineration plants are used to recover heat, whereas in solution 2, new plants are used to recover CHP.

In solution 3, all household waste remaining after source separation is first centrally separated, followed by composting of organic fractions, incineration of combustible fractions and landfilling of residual fractions. Industrial and construction and demolition wastes are centrally separated, followed by recovery of materials, incineration of combustible fractions and landfilling of residual fractions. Energy is recovered from incineration as heat.

In solution 4, all household waste remaining after source separation is centrally separated, followed by anaerobic digestion of organic fractions, incineration of combustible fractions and landfilling of residual fractions. Industrial and construction and demolition wastes are centrally separated, followed by recovery of materials, incineration of combustible fractions and landfilling of residual fractions. Energy is recovered from incineration as heat. Recovered biogas is used as vehicle fuel.

In solutions 5 through 8, waste management is the same as in solutions 1 through 4, respectively, except that the level of material recovery is higher in these solutions (as a result, the quantities managed in the other treatment options are lower).

The material and energy flows to and from the waste management system in the eight solutions are illustrated in Fig. 2. Further details on the solutions are provided in Appendix A. The same quantity of waste is treated in all solutions. The quantities of material and energy recovery from the waste management system vary significantly between the solutions. Heat recovery is twice as large in some solutions. Material recovery is 1.5 times larger in solutions 5 through 8. Recovery of power, biogas and nutrients, respectively, occur in only some solutions. Only the variation in vehicle fuel supply is negligible. It is clear that the solutions differ significantly both in waste treatment and in interaction between the waste management system and other systems. Whether or not these differences result in significant differences in GWP is explored in Section 5.

4. Indirect global warming potentials of waste management

As explained in Section 2, the analysis of indirect environmental impacts is founded on the assumption that items recovered from waste management systems replace other competing items. However, determining what item is replaced and to what extent its production is affected is not straightforward. Several possible alternatives often exist, as is further discussed in this section.
Fig. 2. Material and energy flows to and from the waste management system in solutions 1 through 8. (Mt, 10^6 tonnes; A.d., anaerobic digestion.)
In this study it is assumed that the competing item replaced is the one with the highest marginal production costs. Consequently, analysing what items are replaced should be based on economic analyses of the market sectors concerned. Moreover, since the waste management solutions studied represent a future situation around year 2010, the economic analyses should also represent such a future situation. Such an approach is advantageous if the purpose is to analyse potential indirect impacts of a waste management strategy. However, if the purpose were to analyse the indirect impacts of a given replacement, i.e. to answer questions such as ‘What if the recovery of x replaces y?’ market information would be of less importance.

In this study, the indirect GWPs of power and heat recovery are based on economic analyses of power production and district heating. No such information was available for the indirect GWPs of recovering biogas, material and nutrients. Instead, these are based on specific assumptions for each case (see Sections 4.3, 4.4 and 4.5). To improve the analysis of indirect global impacts, more information on the economy of the markets concerned would be needed. This need is also pointed out in Clift et al. (2000).

4.1. Power recovery

Energy can be recovered from waste by thermal treatment, anaerobic digestion and landfill gas collection and converted to electricity. The power can be distributed to a larger grid where it becomes available to external users and can be used instead of power produced in other facilities. Thus, the GWPs of other power production would be avoided.

Indirect GWPs of power recovery were analysed in Ljunggren Söderman (2000b). The same assumptions have been used in this study. Recovered power replaces power at the margin. The indirect GWP of power recovery is thus the avoided impact of power production at the margin. Full fuel cycle greenhouse-gas emissions from power production are included, i.e. production, distribution and combustion of fuels.

The results from a systems engineering study of the Nordic energy system were used for analysing marginal power production in Sweden around the year 2010. In the study, energy economics, technology development and energy policy instruments were considered. The assumptions that the Kyoto Protocol will have been ratified and that Sweden’s CO2 target will have been reached through a joint Nordic commitment by the year 2010 were important for the analysis. As a result, natural-gas-fired combined-cycle gas turbines (CCGT) would be the source of power at the margin. If the Kyoto Protocol and its CO2 targets were not reached, coal-fired power plants would produce power at the margin (Unger et al., 2000).6

6 Power is traded extensively between Sweden, Norway, Denmark and Finland on a common market.
7 Today, Danish coal-fired power plants are commonly regarded as the primary source of power at the margin in Sweden.
In Ljunggren Söderman (2000b), the alternatives of both natural-gas-fired CCGT and coal-fired power plants as sources for power at the margin were studied. Since these assumptions had large effects on the resulting GWPs, both alternatives are analysed in this study as well. In the base case, natural-gas-fired CCGT is the source for power at the margin. The alternative with coal-fired power plants is studied in sensitivity analysis A in Section 5.4.

4.2. Heat recovery

Heat can be recovered from waste by thermal treatment, anaerobic digestion and landfill gas collection. Once recovered, the heat can be made available for space and water heating through a district-heating network and can be used instead of district heat produced in other facilities. Thus, the GWPs of other heat production facilities would be avoided.

Indirect GWPs of heat recovery were analysed in Ljunggren Söderman (2000b). The same assumptions have been used in this study. Recovered heat replaces average Swedish district heat production. The indirect GWP of heat recovery is thus the avoided impact of average district heat production. Full fuel cycle greenhouse-gas emissions of district heat production are included, i.e. emissions from producing, distributing and combusting fuels.

An economic analysis of future Swedish district heating was performed in Ljunggren Söderman (2000b). The analysis showed that it was difficult to estimate the marginal district heating production option replaced by heat recovered from waste at the national level (Ljunggren Söderman, 2000b). There are currently about 300 district heating networks in Sweden. If heat recovered from waste were to replace a specific production option, the option replaced would differ depending on the configuration of the local district heating system. However, the variety of production options that would be replaced locally is probably limited. The marginal production costs of these options do not differ significantly. This fact makes it possible to estimate a national level of marginal production costs for the options that heat recovered from waste would replace. However, greenhouse-gas emissions from these production options vary significantly, which makes it difficult to estimate the marginal effect on emissions at a national level. In sum, it is possible to estimate the marginal production costs of the options that recovered heat from waste would replace, but not the marginal effect on emissions of such a replacement. With this background, the indirect GWPs of recovering heat from waste were based on average district heating production. However, this should not be regarded as a shift in methodology, but as the best estimate possible, until studies examining marginal district heat production at the national level in more detail become available (Ljunggren Söderman, 2000b).

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8 Nearly all energy that is recovered from waste is currently used for space and water heating in Sweden.
Two alternative levels of indirect GWPs of heat recovery are studied in sensitivity analyses A and B. The effect of the source of marginal power production on indirect GWPs is illustrated in analysis A (see Section 4.1). In analysis B, the impact is based on average district heating except for peak load production options. Typically, heat is recovered from waste evenly over the year. Thus, typical peak load and upper mid-load technologies can be excluded from the district heat production options that would be replaced locally by heat recovered from waste.

4.3. Biogas recovery

Biogas can be recovered from organic waste through anaerobic digestion and landfill gas collection. Once recovered, biogas can be used as a vehicle fuel to replace fuels of fossil origin, such as diesel and natural gas. Thus, the GWPs of using vehicles with other fuels would be avoided. In this study, it is assumed that recovered biogas replaces diesel. The indirect GWP of biogas recovery is thus the impact of using biogas-fuelled vehicles minus the impact of using diesel-fuelled vehicles (IVL, 1999). The GWP of using diesel takes into account emissions from the full fuel cycle, i.e. production and distribution of diesel and the actual combustion in vehicles.

However, biogas can be used for other purposes than for fuelling vehicles. For example, it can be combusted in gas turbines to produce heat and power. In this case, recovered biogas would replace other district heat and power production (as described in Sections 4.1 and 4.2, respectively). The greenhouse-gas emissions avoided when replacing diesel are larger than those from replacing district heat and power production (Ljunggren Söderman, 2000b) and natural gas (IVL, 1999).

4.4. Material recovery

Once reprocessed, recovered materials can be used for producing new products and can replace the use of other materials. In this study, it is assumed that recovered materials replace virgin materials of the same type (e.g. recovered paper replaces virgin newsprint). The impacts of producing virgin materials are then avoided. Thus, the indirect impact of material recovery is the impact of regional transport and reprocessing of the recovered material minus the impact of producing the virgin material. Impacts include virgin material production from cradle to gate, i.e. extraction of raw materials, transportation of raw materials and material production. The indirect GWPs of recovering six materials are included in the study: paper, cardboard, metal, glass, plastics and wood.

Assuming that recovered materials replace virgin materials of the same type is one of the most commonly used assumptions in life cycle analyses today (White et al., 1995; Thorneloe et al., 1998; Ekvall and Finnveden, 2000). However, there are other alternatives. One alternative is that the virgin material replaced is of a different type.

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9 Power-consuming technologies, such as electric boilers, heat pumps and combined heat and recovery technologies account for a considerable part of the energy required for Swedish district-heat production.
For example, recovered plastics could be used for producing construction materials that otherwise would have been produced from virgin wood. A second alternative is that another recovered material of the same type is replaced. In Ekvall (2000), several examples of recovered materials for which market demand may be limited at given prices are pointed out. Because of the limited market, there is a risk that recovering a material in one geographic area results in reduced collection in another geographic area. If this is the case, the uncollected material must instead be treated as waste, with associated environmental impacts. Similarly, a third alternative is that recovering one material can result in reduced collection of another type of material. In reality, it is probably a mix of these four alternatives and a fifth alternative that nothing is replaced (Ekvall, 2000).

The virgin materials replaced when each of the six materials studied is recovered are listed in Table 1. Life cycle inventories (LCIs) have been used to quantify the greenhouse-gas emissions avoided by displacing these materials. As far as possible, the LCIs used are taken from recently published studies and represent Swedish conditions (Boustead, 1992; Sunér, 1996; Widheden et al., 1998; Trätek, 1999; Ölund and Eriksson, 1999; CIT Ekologik, 1999). When such data were not available or were not sufficiently detailed and transparent, international data were used.

In reality, the recovered materials in Table 1 could replace several different materials, since they could be separated into several fractions when being reprocessed (e.g. metals could be separated into ferrous and non-ferrous metals). This level of detail was beyond the scope of this analysis.

Several life cycle analyses have shown that the power consumed in virgin material production could constitute a significant part of the GWPs (Finnveden and Ekvall, 1998). The assumptions on the source of power consumed follow the assumptions on power recovery (see Section 4.1). Thus, two alternative sources of the power consumed were examined: one in the base case and a second in sensitivity analysis A in Section 5.4. However, due to insufficient transparency of the LCI data available, it was not possible to perform such sensitivity analyses for assumptions for virgin production of plastics, metal and wood.

<table>
<thead>
<tr>
<th>Material recovered from waste</th>
<th>Virgin materials replaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>Newsprint</td>
</tr>
<tr>
<td>Cardboard</td>
<td>Cardboard</td>
</tr>
<tr>
<td>Metal</td>
<td>Steel</td>
</tr>
<tr>
<td>Glass</td>
<td>White glass</td>
</tr>
<tr>
<td>Plastics</td>
<td>High-density polyethylene pellets</td>
</tr>
<tr>
<td>Wood</td>
<td>Wood fibre board</td>
</tr>
</tbody>
</table>
4.5. Nutrient recovery

Compost or anaerobic digestion residues resulting from biological treatment of organic waste can be recovered for their nutrient content and used as fertiliser within the agricultural sector. In this study, it is assumed that recovered compost and anaerobic digestion residues replace artificial fertilisers. The impacts of artificial fertiliser production are then avoided. Thus, the indirect impacts of recovering compost or anaerobic digestion residues are the avoided impacts of producing artificial fertilisers. Impacts include artificial fertiliser production from cradle to gate, i.e. extraction and transportation of raw materials and fertiliser production. The indirect GWPs of recovering three nutrients are included in the study: nitrogen (N), phosphorus (P) and potassium (K).

Assuming that recovered compost or anaerobic digestion residues replace artificial fertilisers is one of the most commonly used alternatives in life cycle analyses today (Tillman et al., 1996; Faaij et al., 1998; Sonesson et al., 2000). However, compost and anaerobic digestion residues can also be used as filling material for landscaping purposes, as cover material for landfills and as humus supply to soil. In those cases, recovered compost and anaerobic digestion residues would replace other materials with similar properties.

It is assumed that the N, P and K in compost or anaerobic digestion residues replace an equal amount of artificial fertilisers. In reality, using compost, anaerobic digestion residues or artificial fertilisers can differ in several respects (Dalemo et al., 1998), such as plant uptake, emissions from soil, handling (storing, spreading on arable land, etc.) and local circumstances. Published LCIs have been used to quantify the avoided greenhouse-gas emissions from artificial fertiliser production of N, P and K (Tillman et al., 1996).

4.6. Indirect global warming potentials quantified

The GWPs of the solutions analysed in this study are quantified using estimates of the potential climate effects of three greenhouse gases on a 100-year time-scale—fossil carbon dioxide (CO₂), methane (CH₄) and nitrous oxides (N₂O)—expressed in CO₂-equivalents.¹⁰ In Table 2, the indirect GWPs that result from power, heat, biogas, material and nutrient recovery are summarised on a per-unit basis. The base case and sensitivity analyses A and B are shown.

5. Results

Comparisons of the direct and indirect GWPs of the eight waste management solutions for Sweden are presented in this section. The results of two sensitivity analyses on the effects of assumptions regarding (A) power production and (B) heat

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¹⁰ The CO₂-equivalent factors applied were: CH₄: 21 and N₂O: 310 (Houghton et al., 1996).
Table 2
The indirect global warming potentials of material, nutrients and energy recovery on a per-unit basis

<table>
<thead>
<tr>
<th></th>
<th>Power</th>
<th>Heat</th>
<th>Biogas</th>
<th>Paper</th>
<th>Cardboard</th>
<th>Metal</th>
<th>Glass</th>
<th>Plastics</th>
<th>Wood</th>
<th>Compost</th>
<th>A.d. residue</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(tonnes CO\textsubscript{2}-eq./tonne)</strong></td>
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</tr>
<tr>
<td>Base case</td>
<td>-0.38</td>
<td>-0.16</td>
<td>-0.20</td>
<td>-0.74</td>
<td>-0.21</td>
<td>-1.07</td>
<td>-0.28</td>
<td>-0.71</td>
<td>0.01</td>
<td>-0.09</td>
<td>-0.02</td>
</tr>
<tr>
<td>Sensitivity A</td>
<td>-1.07</td>
<td>-0.24</td>
<td>-0.20</td>
<td>-2.34</td>
<td>-0.70</td>
<td>-1.07</td>
<td>-0.51</td>
<td>-0.71</td>
<td>0.01</td>
<td>-0.09</td>
<td>-0.02</td>
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<tr>
<td>Sensitivity B</td>
<td>-0.38</td>
<td>-0.11</td>
<td>-0.20</td>
<td>-0.74</td>
<td>-0.21</td>
<td>-1.07</td>
<td>-0.28</td>
<td>-0.71</td>
<td>0.01</td>
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<td>(tonnes CO\textsubscript{2}-eq./MWh)</td>
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<td>-0.11</td>
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</tr>
</tbody>
</table>
recovery are also presented. The GWP of each of the eight solutions has been analysed. All results are compared to solution 1, which is currently one of the most commonly discussed solutions for Swedish waste management in light of the coming bans on landfilling (Swedish Association of Waste Management, 2000).

5.1. Direct global warming potentials

Despite the fact that waste treatment differs considerably in solutions 1 through 4, the analysis shows that there is little difference in their direct GWPs (Fig. 3). Solutions 1 and 2 are based, to a large extent, on waste incineration, whereas solutions 3 and 4 are based on a combination of biological treatment and waste incineration. Solution 3 has somewhat higher GWP than solution 1 because of emissions of nitrous oxides from composting. However, the GWPs of solutions 5 through 8 are significantly less than that of solution 1 (and 2 through 4). This is because the quantity of incinerated plastics is reduced when material recovery is higher. Methane emissions from landfilling contribute to the GWPs, but differ little between the solutions.\footnote{Despite the bans on landfilling of combustible and organic waste, landfilling of CH$_4$-generating residues from central waste separation is part of all solutions. It is assumed that 40% of the CH$_4$ generated is emitted to air after landfill gas collection and landfill top layer oxidation.}

Thus, the direct GWPs indicate that increased material recovery is a good solution if GWP reductions are desired. The solutions employing waste incineration or a combination of waste incineration and biological treatment are roughly equal in
terms of GWP. This also holds for the solutions employing heat recovery or CHP recovery and those employing composting or anaerobic digestion.¹²

5.2. Indirect global warming potentials

The GWPs of the indirect waste management activities resulting from power, heat, biogas, material and nutrient recovery are shown for solutions 2 through 8, compared to solution 1, in Fig. 4. There are indirect GWPs in all solutions. They vary significantly, but some of the individual contributions are of the same magnitude as the differences in direct GWPs.

5.2.1. Power recovery

The largest quantity of power is recovered in solution 2. In solution 6, less power is recovered because waste is diverted to material recovery. No power is recovered in the other solutions. This results in a negative indirect GWP of power recovery in solutions 2 and 6 because natural-gas-based power production is avoided. This reduction in the indirect GWP of power recovery is relatively large, despite the fact that natural-gas-based power production is low in GWP intensity compared to other fossil fuels.

¹² As explained in Section 3, solutions 2 and 8 include waste incineration with both heat recovery and CHP recovery. For ease of readability, these solutions will henceforth be referred to as including waste incineration with CHP recovery.
5.2.2. Heat recovery

Heat is recovered from waste incineration in all solutions, but in different quantities. Because a largest quantity is recovered in solution 1, district heat production is increased in solutions 2 through 8 in order to satisfy the constant market demand. This results in a positive indirect GWP of heat recovery in all other solutions than solution 1. The indirect GWPs are large in solutions 5 and 6 compared to solution 1 because less heat is recovered when waste is diverted from incineration to material recovery. In solutions 7 and 8, they are even larger because even less heat is recovered when waste is diverted from incineration to both material recovery and biological treatment.

Note that the increase in indirect impacts of heat recovery is smaller than the reduction in direct impacts in solutions 5 through 8. Thus, the increase in indirect GWP when district heat production increases outside of the waste management system is smaller than the reduction in direct GWP when incineration decreases in the waste management system. This is explained by the fact that reduced incineration of plastics accounts for nearly three-fourths of the reduction in heat recovery from waste, while fossil fuels account for about half of the increase in district heat production.

5.2.3. Biogas recovery

The same quantity of biogas is recovered in solutions 3 and 8. In these solutions, all organic household waste in Sweden is treated through anaerobic digestion. This results in a negative indirect GWP of biogas recovery compared to solution 1 because the use of diesel is avoided.

5.2.4. Material recovery

As explained in Section 3, two different levels of material recovery have been studied: material recovery is lower in solutions 1 through 4 than in 5 through 8. Consequently, solutions 5 through 8, in which virgin material production is avoided, exhibit negative indirect GWPs of material recovery compared to solution 1.

Each material’s contribution to the indirect GWP of material recovery in solutions 5 through 8 is shown in Fig. 5. Recovering plastics and paper produces the largest contributions. In the case of plastics recovery, the contribution is large because the indirect GWP per unit waste treated is large (see Table 1) and the total recovered quantity is four times larger in solutions 5 through 8 than in 1 through 4. Paper recovery does not increase as much in total quantity, but contributes significantly because of the large indirect GWP per unit waste treated. Metal recovery, which has a large indirect GWP per unit waste treated, does not contribute much because the

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13 The heat value of plastics is high compared to other waste fractions. Plastics account for only 20% by mass of the total reduction in incineration between solutions 1 through 4 and 5 through 8 (see Table A2 in Appendix A).

14 Note that this refers to the share of fossil fuels in district heat production including power consumed in district heating plants (it is assumed that the source of marginal power production is fossil in this study). The share of fossil fuels is about one-third, excluding power consumed in district heating plants.
total recovered quantity differs little from that in solution 1. Wood recovery is the only material for which the indirect GWP is not negative. However, the small indirect GWP per unit of wood recovered results in a negligible contribution.

5.2.5. Nutrient recovery

In solutions 3, 4, 7 and 8, nutrients are recovered in the form of compost or anaerobic digestion residues. There is a negative indirect GWP of nutrient recovery in these solutions because artificial fertiliser production is avoided. The indirect GWP of nutrient recovery is lower in solutions with anaerobic digestion (solutions 4 and 8). The quantity of N, P and K that is recovered is lower in these solutions because of higher nutrient losses in the anaerobic digestion process. Despite the fact that all organic household waste in Sweden (close to half of all household waste) is composted or anaerobically digested and recovered as nutrients in these solutions, the indirect GWP of nutrient recovery is the smallest of the indirect GWPs analysed. This is primarily explained by the low concentration of nutrients in organic household waste.

5.3. Total global warming potentials

The direct, indirect and total (i.e. the sum of direct and indirect) GWPs of the solutions compared to solution 1 are shown in Fig. 6. It is clear that the difference between including and excluding indirect GWPs is considerable, even though all solutions involve both positive and negative contributions from the indirect GWPs.

When indirect GWPs are included, the choice of how to recover energy from waste incineration becomes crucial. The CHP solutions result in lower GWPs than those with heat recovery only. This is clear if comparing solutions 1 to 2 and solutions 5 to 6. Thanks to the indirect GWPs of avoiding other power production, the solutions with power recovery are preferable in terms of GWP. This also holds for very small power-to-heat ratios (above 0.02).15

Furthermore, with indirect GWPs included, the choice of biological treatment is important. The solutions with anaerobic digestion (solutions 4 and 8) have significantly lower total GWPs than those with composting (solutions 3 and 7). Thus, it is more advantageous to recover biogas than to recover larger quantities of nutrients.

Nonetheless, some of the conclusions drawn based on the direct GWPs alone remain unchanged when indirect GWPs are included. Increased material recovery is a good solution if GWP is to be reduced. Solutions 5 through 8, in which material recovery is high and energy recovery is comparatively low, result in lower total GWPs than any of the other solutions studied. In these solutions, the negative contribution to indirect GWPs of reduced heat recovery is clearly outweighed by the positive contributions to direct and indirect GWPs. For example, reducing heat

15 Power-to-heat ratios in Swedish waste incineration facilities for CHP recovery are at least 0.1 today. In this study of future waste management solutions, the power-to-heat ratio was 0.35.
recovery from waste results in lower total GWP than reducing other district heating production. This is clear when comparing solutions that illustrate the impact of shifting between material and energy recovery (compare solutions 1 to 5; 2 to 6; 3 to 7; and 4 to 8, respectively).

The total GWPs of some of the solutions remain comparable despite differences in indirect GWPs, because positive and negative contributions compensate for each other.

**Total Global Warming Potentials**

Fig. 6. Direct, indirect and total global warming potentials of solutions 2 through 8 for Swedish waste management compared to solution 1 (10^3 tonnes CO_2-equivalents/year).
other. For example, the total GWPs of solutions with incineration and heat recovery remain close to the total GWPs of solutions combining anaerobic digestion with incineration and heat recovery (compare solutions 1 and 4, and 5 and 8, respectively). Thus, the choice between anaerobic digestion and incineration of organic household waste is of little importance in terms of GWP.

5.4. Sensitivity analyses

The effects of changes in the base case assumptions regarding power and heat production, on the indirect GWPs and consequently the total GWPs of the waste management solutions studied, are illustrated in sensitivity analyses A and B, respectively.

5.4.1. Sensitivity analysis A: power production

In the base case, marginal power is produced using natural gas. In sensitivity analysis A, it is assumed that marginal power production is based on coal (see Section 4.1). This change in marginal power production affects not only the indirect GWPs of power recovery, but also those of heat recovery and material recovery (as explained in Sections 4.2 and 4.4). The direct, indirect and total GWPs when marginal power production is based on coal are shown in Fig. 7. Coal-based power has a higher GWP on a per-unit basis than natural-gas-based power. Therefore, the indirect GWPs from recovering power, materials and heat on a per-unit basis increase in the sensitivity analysis compared to the base case (by 2.8, 1.8 and 1.5 times, respectively; see Table 2).

Because the power recovered in solutions 2 and 6 replaces coal-based power production outside the waste management system, the total GWPs of these solutions are significantly lower in sensitivity analysis A than in the base case. This holds in particular for solution 2.

In solutions 5, 7 and 8, the indirect GWP of material recovery nearly compensates for the indirect GWP of heat recovery, with the result that the total GWPs of these solutions compared to that of solution 1 are nearly unchanged in comparison to the base case.

As opposed to the base case, not all solutions with a high level of material recovery result in lower total GWPs than those with a low level of material recovery. Instead, the total GWPs of solution 2 (low level of material recovery combined with high CHP recovery) and solution 6 (high level of material recovery combined with lower CHP recovery) are nearly equal. This is because the advantages of power recovery increase more than those of material and heat recovery in these solutions. The other conclusions from the base case remain unchanged.

5.4.2. Sensitivity analysis B: heat recovery

In the base case, it is assumed that the indirect GWP of recovering heat is based on average district heat production. In sensitivity analysis B, peak load production options are excluded from the average (see Section 4.2). This reduces indirect GWP
of heat recovery on a per-unit basis, by 33% compared to the base case (see Table 2). The direct, indirect and total GWPs in sensitivity analysis B are shown in Fig. 8.

All of the conclusions from the base case remain unchanged in sensitivity analysis B. The total GWPs of solutions 2 through 8 compared to solution 1 are lower than in the base case because the indirect GWP of heat recovery is reduced. This amplifies the conclusion from the base case that all solutions with a high level of material recovery result in lower total GWPs than solutions with a low level of material recovery.

6. Conclusions and discussion

6.1. Methodology

One of the major difficulties in analysing indirect environmental impacts is to establish what, if anything, is replaced, when something is recovered from the waste management system. It was necessary to make case-specific assumptions in this regard for material, nutrient and biogas recovery because economic analyses of product substitution in these market sectors were not available. The results depend of course upon the assumptions made. For example, recovered paper is assumed to replace virgin newsprint. In Sweden, virgin newsprint production is based on mechanical pulp, which requires large inputs of external power. If recovered paper replaced paper based on chemical pulp (which is, to a large extent, self-supporting in energy) instead, the avoided GWPs of paper recovery would be smaller. This is of
particular interest in this study because avoided power production is based on fossil fuels. Furthermore, it is difficult to estimate whether or not the assumptions are reasonable for a situation around year 2010. There could, for example, be problems in achieving the high levels of material recovery assumed in some of the solutions with regard both to sufficient separation in the waste management system and to quality issues related to using recovered materials in new products. Other examples are that quality requirements and moral concerns could create barriers to using compost or anaerobic digestion residues for growing crops or fodder.

The amount of input data required for quantifying the indirect environmental impacts is an additional source of difficulty. All indirect activities that occur as a result of changes in waste management systems are related to large and complex systems and each set of input data used involves an abundance of data. Consequently, it is nearly an impossible task to ensure that all of the assumptions, about for example system boundaries, allocations and use of marginal or average data, are the same for all sets of data used. This is especially problematic when detailed and transparent published data are not available. Furthermore, published LCIs usually describe current state-of-the-art production. This means that future technological progress is usually not taken into account when using this methodology.

The number of indirect activities is virtually infinite. To begin with, the first order changes in activities are numerous. Each change in these indirect activities leads, in turn, to new indirect activities. Moreover, there are potential feedbacks between the indirect activities. Consequently, it is impossible to account for all indirect activities. In addition, while the focus of this study was on potential climate impacts, an
analysis of other environmental impacts—such as acidification and eutrophication—may be equally relevant. The approach used in this study could be extended to include further environmental impacts. However, the indirect waste management activities that are significant for the results probably vary depending on the environmental impacts studied. Hence, expanding the number of impacts studied could rapidly increase the number of indirect activities that would need to be addressed.

The goal of the study was to include as many as possible of the first-order indirect activity changes that lead to significant changes in greenhouse-gas emissions. In spite of this, some of the perhaps more evident ones are not included in the study, a fact which deserves comment. First, not all of the recovered materials are included in the indirect GWP of material recovery. The ones not included are labelled ‘Others’ (see Appendix A). These probably consist of inert materials, such as gypsum, concrete and excavated materials. More knowledge about their composition would be required to analyse the indirect GWP of their recovery. Second, the indirect GWP of supplying auxiliary materials and capital goods is not included. Generally, these impacts are small in comparison to direct or other indirect environmental impacts (White et al., 1995; Lindfors et al., 1995; Brännström-Norberg et al., 1996; Clift et al., 2000). Whether or not this holds for waste management solutions in general is, however, uncertain. Finally, the indirect GWP of supplying auxiliary power is not included. Including this could be important if the solutions studied differ substantially in waste treatment methods that consume power without producing energy internally, such as central separation and composting. Still, indirect waste management activities are not all relevant at all times. Which impacts should be studied depends on the question at hand, as was exemplified in the comparisons of the eight solutions in this study. The indirect GWP of supplying (producing and transporting) vehicle fuels was not included because the difference in the quantities supplied between the solutions studied is negligible.  

6.2. Comparison of waste management solutions

The GWPs of eight solutions for Swedish waste management around 2010 have been analysed in this study. The differences in the indirect GWPs of the waste management activities analysed are of the same magnitude as the differences in direct GWPs. Furthermore, the indirect GWPs are sensitive in relation to assumptions made. However, despite the fact that some results varied between the base case and sensitivity analyses, some general conclusions regarding the preferability of the respective solutions can be drawn:

- Because of the positive indirect GWP of power recovery, it is preferable to recover energy from incineration as CHP and not only as heat. Thus, to minimise GWP, all new waste incineration investments should be in CHP facilities. This holds as

Note that the actual combustion of vehicle fuels is included in the direct GWP of waste management.
long as marginal power production is based on fossil fuels and the share of fossil fuels in district heat production does not increase substantially.

- Because of the positive indirect GWP of biogas recovery, it is preferable to treat organic household waste by anaerobic digestion rather than by composting. This holds if the recovered biogas replaces fossil fuels for vehicles. In Ljunggren Söderman (2000b), it was also found to hold if the biogas is used for CHP recovery and replaces power and district heat (using the same assumptions as in the present study).

- The indirect GWP of nutrient recovery from organic waste is relatively small. This means that anaerobic digestion is preferable to composting even if only compost and not anaerobic digestion residue would be recovered and used as fertiliser.

- The choice between incineration and anaerobic digestion of organic household waste is not clear-cut in terms of GWP. Incineration with heat recovery and anaerobic digestion are more or less interchangeable options, as long as biogas replaces fossil fuels for vehicles.

- The indirect GWP of material recovery shows that there are savings to be made when recovered materials replace other materials. However, the results do not permit any conclusions regarding material versus energy recovery. Such conclusions would have required analysing the recovery of each material separately, not a mix of materials as in this study. The results indicate, though, that reducing incineration of plastics is preferable to recovering heat. This conclusion becomes even stronger when taking the indirect impacts of material recovery into account.

- The source of marginal power production has a large effect on the results. It influences not only the indirect GWP of power recovery, but also those of heat recovery and material recovery. Moreover, the effect is determined not only by whether it is based on a fossil fuel, but also by which fossil fuel, as shown in sensitivity analysis A.

Thus, including indirect GWPs of material recovery and nutrient recovery has expanded upon the knowledge gained in the analysis performed by Ljunggren Söderman (2000b). In Ljunggren Söderman (2000b), the preferable waste management solution (in terms of GWP) differed, depending on whether the source of marginal power production was assumed to be natural gas or coal. In the present study, including the indirect GWP of material recovery resulted in one solution having the lowest GWP, regardless of whether the source of marginal power production was assumed to be natural gas or coal. However, the inclusion of indirect GWPs of nutrient recovery does not change the conclusions from Ljunggren Söderman (2000b).

The focus of this study was on analysing waste management solutions for Sweden at the national level. Care must be taken when extending the conclusions to the local level, in particular with regard to the indirect GWP of heat recovery. Locally, the benefit of replacing district heat production with waste incineration would be larger than the results indicate in some district heating networks, while it would be smaller in others. The base case and sensitivity analysis B does not cover the full range of indirect GWP of heat recovery at the local level.
6.3. Concluding remarks

The difference between the largest and smallest GWPs of the waste management solutions studied is about 1.2 megatonnes of CO₂-equivalents per year. Is such a difference significant in comparison with Swedish long-term targets for greenhouse-gas emission reductions? According to proposed Swedish environmental quality objectives, annual greenhouse-gas emissions should be reduced by 40 megatonnes of CO₂-equivalents by the year 2050 (a reduction by 60% compared to 1995) (Ministry of the Environment, 1998b). In the perspective of this magnitude of reductions, the differences in GWP between the waste management solutions are small. However, even solutions that involve relatively small reductions may have to be considered in order to reach such an extensive target, especially if the solutions are advantageous from an economic point of view.¹⁷

Indirect GWPs of waste management can be large when comparing a range of waste management solutions. Including indirect GWPs can even change the ranking of the solutions. Hence, including indirect GWPs is important when providing information to support strategic planning that involves choosing among such solutions. However, this study also shows that an analysis of indirect GWPs involves large uncertainties. There is room for decreasing the uncertainties by generating more information, e.g. about the market sectors involved. Ultimately, it is a question of improving the ability of waste management planners to design environmentally sustainable and robust waste management systems. Increased understanding of the indirect environmental impacts of waste management can contribute to providing such an improvement.

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Dr Deborah W. Cornland provided invaluable support throughout this study. Professor Anne-Marie Tillman shared her expertise in life cycle assessment. Dr Tomas Ekvall gave helpful comments on the manuscript. The Swedish National Energy Administration financed the study.

Appendix A: Waste management solutions for Sweden

In Tables A1–A3, details on the waste management solutions analysed are provided. For further details on data in the study, the reader is referred to Ljunggren Söderman (2000d).

Table A1

| Waste treatment in waste management solutions for Sweden (10³ tonnes/year) |

¹⁷ A comparison of the costs of the waste management solutions analysed in this study is presented Ljunggren Söderman (2000a).
<table>
<thead>
<tr>
<th>No.</th>
<th>Incineration with heat recovery</th>
<th>Incineration with CHP recovery</th>
<th>Composting</th>
<th>Anaerobic digestion</th>
<th>Land-filling&lt;sup&gt;18&lt;/sup&gt;</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>(10&lt;sup&gt;3&lt;/sup&gt; tonnes/year)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>3098</td>
<td>–</td>
<td>0</td>
<td>–</td>
<td>2167</td>
</tr>
<tr>
<td>2</td>
<td>1883</td>
<td>1215</td>
<td>0</td>
<td>–</td>
<td>2167</td>
</tr>
<tr>
<td>3</td>
<td>1574</td>
<td>–</td>
<td>1275</td>
<td>–</td>
<td>1932</td>
</tr>
<tr>
<td>4</td>
<td>1574</td>
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<td>–</td>
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<td>1932</td>
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<td>1036</td>
<td>–</td>
<td>–</td>
<td>1275</td>
<td>1586</td>
</tr>
</tbody>
</table>

Table A2
Material recovery in waste management solutions for Sweden (kilotonnes/year)

<table>
<thead>
<tr>
<th>No.</th>
<th>Paper</th>
<th>Cardboard</th>
<th>Metal</th>
<th>Glass</th>
<th>Plastics</th>
<th>Wood</th>
<th>Other</th>
<th>Total</th>
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<tbody>
<tr>
<td></td>
<td>[10&lt;sup&gt;3&lt;/sup&gt; tonnes/year]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–4</td>
<td>529</td>
<td>212</td>
<td>196</td>
<td>95</td>
<td>69</td>
<td>85</td>
<td>526</td>
<td>1712</td>
</tr>
<tr>
<td>5–8</td>
<td>664</td>
<td>298</td>
<td>216</td>
<td>149</td>
<td>336</td>
<td>272</td>
<td>592</td>
<td>2527</td>
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</tbody>
</table>

Table A3
Energy supply and recovery in waste management solutions for Sweden (TWh/yr)

<table>
<thead>
<tr>
<th>No.</th>
<th>Vehicle fuel supply</th>
<th>Heat recovery</th>
<th>Power recovery</th>
<th>Biogas recovery</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>[TWh/year]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
<td>8.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>7.5</td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>7.1</td>
<td>–</td>
<td>–</td>
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<td>7.1</td>
<td>–</td>
<td>1.1</td>
</tr>
<tr>
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<td>0.4</td>
<td>5.6</td>
<td>–</td>
<td>–</td>
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<td>6</td>
<td>0.4</td>
<td>5.2</td>
<td>0.4</td>
<td>–</td>
</tr>
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<td>7</td>
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<td>4.2</td>
<td>–</td>
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<td>0.4</td>
<td>4.2</td>
<td>–</td>
<td>1.1</td>
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<sup>18</sup> Includes landfilled residues from waste incineration.
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