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Swedish Waste Prevention and Greenhouse Gas Emissions

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Abstract
Life-cycle assessments that calculate the environmental burdens per kg or tonne of waste generated are inadequate for the assessment of waste prevention strategies. This limitation can be amended by changing the functional unit to the annual quantity of waste generated in a geographical area. We estimate the reductions in greenhouse gas (GHG) emissions that would result from waste prevention in Sweden. Waste prevention is compared to a reference scenario dominated by energy recovery and to a scenario with increased recycling efforts. This comparison requires a careful modeling of the flows of recycled material into and out from Swedish product systems. Our model applies own price elasticity of the supply of and demand for material collected for recycling, in order to account for an equilibrium between supply and demand of these materials. As a consequence, Swedish collection offsets collection in other countries where uncollected material is deposited at landfills. Our results indicate that waste prevention contributes to a significant reduction in GHG emissions, but that collection for recycling of paper products is less beneficial than energy recovery. However, the uncertainties in the model must be reduced before conclusions regarding Swedish waste paper collection can be drawn.

1 Background
In Sweden, waste management during the last decade has been focused on improving the quality of the treatment and on reducing the amount of waste going to landfill. The shift from landfilling is positive from an environmental perspective, which has been shown in several system analyses of waste management in Sweden (Tillman et al., 1991, Finnveden and Ekvall, 1998, Finnveden et al., 2000, Ljunggren Söderman, 2000, Sundqvist et al., 2002a and Sundqvist et al., 2002b). They conclude, with few exemptions, that landfilling is the least preferred method for treating municipal solid waste (MSW) in Sweden.

However, although the treatment of the waste has improved, the amounts of MSW have grown. In fact, in 2000 Sweden exceeded the EU goal in stabilizing the amounts on the 1985 level (300 kg/capita,yr) by over 40 % (EEA, 2003, RVF, 2001). Swedish waste policy refers to the waste hierarchy, where waste prevention is

considered to be the best environmental option. However, the hierarchy does not show how much better waste prevention is compared to other options such as material recycling and waste incineration. Neither has waste prevention been an issue in earlier systems analyses of waste management in Sweden (Björklund et al., 1999, Finnveden et al., 2000, Ljunggren Söderman, 2003a, Sundqvist et al., 2002a, Sundqvist et al., 2002b). Life cycle assessments (LCAs) of waste management often calculate the environmental burdens per kg or tonne of waste generated. This implies that the quantity of waste is unaffected by the management measures investigated. Having identical amounts of waste treated in different scenarios makes it possible to simplify comparative analyses by neglecting the production and use of the materials (Finnveden, 1999). This simplification is sometimes called the "zero burden assumption", suggesting that the waste enters the system boundary without burdens.

LCA models that calculate the environmental burdens per kg or tonne of waste generated allow for environmental comparisons of different options for dealing with this waste, but not for analyses of changes in the quantities of waste generated. They are inadequate for the identification and assessment of waste prevention strategies. They also fail to account for the serious challenges posed by a continuation of the short-term and long-term trends of increasing waste flows, and consequently do not give information on how large capacity for waste treatment is required.

Regarding material recycling, earlier studies in Sweden (see above) as well as throughout Europe (see e.g. overviews by Profu, 2004 and Villanueva et al., 2004), normally assume that all waste that is collected for material recycling (minus material losses) will replace virgin production. However, scrap that is collected in a country is normally traded on different international markets. When collection of scrap is changed in one country, this might affect both the demand of scrap and the supply from collection elsewhere. A decrease in collection in other countries means that more material must be treated by alternative waste treatment methods such as incineration or landfilling. The net effect of increased collection of scrap in Sweden is then replacement of some virgin production (through the increase in scrap demand) and increased incineration or landfilling elsewhere (through the reduction in scrap collection in these countries).

2 Aim, scope and method

The aim of the paper is to estimate the reductions in greenhouse gas emissions (GHG) resulting from waste prevention. We also compare waste prevention to increased recycling. This is made through three scenarios for the year 2016, where waste prevention is compared to other waste management strategies regarding the effects on GHG emissions (see Table 1):

A. Base-line scenario: Illustrating the current development, where an expansion of waste incineration and biological treatment are foreseen. Based on the prognosis of the PCE development during 2005-2015 by Ministry of Finance (2004),

Tab. 1: Waste prevention and waste sent to recycling and treatment in the three scenarios during the year 2016 (Million tonnes)

	Scenario A	**Scenario B**	**Scenario C**
Waste prevention	0	0.28	0
Material recycling	1.83	1.62	2.12
Biological treatment	0.70	0.70	0.70
Incineration with energy recovery	2.78	2.71	2.51
Landfilling	0.06	0.06	0.05
Sum	**5.37**	**5.37**	**5.37**

we have assumed that the MSW amounts will grow by 2 % per year.

B. Waste prevention: The waste prevention is increased, leading to less treatment by incineration and landfilling compared to the base-line scenario. We assume that Sweden, in percentage, will reach the same waste prevention for a selection of waste fractions during 2006-2016 as in the USA during 1990-2000 (USEPA, 2002a).

C. Increased recycling: The same amount that is prevented in scenario B is instead recycled. This means increased recycling and decreased incineration and landfilling compared to the base-line scenario.

Increased waste prevention and increased recycling might in reality be combined. Here, however, we have evaluated them separately to see how they individually affect the GHG emissions. To facilitate the assessment of waste prevention, we use the annual quantity of waste in Sweden as the functional unit, instead of 1 kg or tonne of waste generated.

The study deals with material that, after use in Sweden, ends up in the Swedish MSW management. Since different scenarios include different waste quantities, the zero burdens assumption is no longer valid. This means that we have to account for the environmental burdens associated with the production of all the materials that eventually become waste. The material often is produced elsewhere in the world. Fuel and electricity can also be produced in a different country compared to where it is used. Scrap material collected in Sweden may be exported and used in recycling processes in other countries. This means that the system investigated includes many processes outside Sweden.

The effects of Swedish collection for recycling (X) on demand (D) and supply from collection elsewhere (S) are estimated by using price elasticities for the demand (η_S) and supply (η_D) of collected scrap materials (derived from Ekvall, 2000):

(1) $$\eta = \frac{\Delta Q * P}{Q * \Delta P}$$

(2) $$\frac{\Delta S}{\Delta D} = \frac{\eta_S}{\eta_D}$$

(3) $\Delta X = \Delta D - \Delta S$,

where η is the own price elasticity, which is a measure of how the quantity (Q) demanded or supplied of a product changes due to a change in its price (ΔP). Effects of changes in the use of scrap-based material in Sweden are estimated using a similar calculation method.

3 Modeling and major assumptions

A model of Swedish MSW treatment was built up using spreadsheet modelling in Microsoft Excel. Five waste fractions (see Table 2) were affected by the choice of scenarios.

All treatment throughout the nation is aggregated into one system. For example, this means that all incineration plants in Sweden are modelled as a single system component, which has the average characteristics of all Swedish plants. Energy recovery is modelled according to the data in RVF (2006). This means that the energy mainly is recovered as district heat (92 %) and only to a small extent as electricity (8 %)[1].

Tab. 2: Generation and treatment as modelled for 2005 of the five waste fractions affected by the choice of scenarios. The data are estimates based on RVF (2006), Olofsson and Sundberg (2002), Andersen et al. (1999) and our own assumptions.

	Generated (ktonne)	Material recycling (ktonne)	Incineration (ktonne)	Landfilling (ktonne)
Newsprint	582	483	90	9
Office paper	211	135	69	7
Corrugated board	544	380	150	14
Metal packaging[2]	51	34	16	2
Glass	215	155	55	5

Any change in energy recovery from waste incineration is assumed to affect the

1 Due to a tax on incineration (introduced July 1, 2006), which favours combined heat and power production over heat production only, the distribution of energy recovery might gradually shift towards more electricity production. We have, however, not accounted for this possible effect.

2 Modelled as steel for data reasons. According to RVF (1999), around 80 % of the metal packaging collected for material recycling is made of steel.

Swedish marginal district heat production and the Nordic marginal electricity production. The marginal district heat production is estimated by Sahlin et al., (2004) to be based on biofuels (70 %), oil (13 %), natural gas (10 %), peat (4 %) and electricity[3] (3 %). The analysis was simplified due to the fact that no analysis was made of the fate of biomass that was replaced by district heat from waste incineration. Potentially, this could be used for material or energy production and thus replace other materials/fuels. The same goes for biomass that is saved at material recycling of paper products. We did no analysis of the fate of that biomass either.

The Nordic marginal electricity source is estimated by Mattsson et al. (2003) to be a mix of natural gas, coal, wind power etc., which depends on the boundary conditions of the Nordic electricity system. We assume that the marginal electricity is produced from natural gas because gas is a recurring, important part in the results of Mattsson et al., and because natural gas is in between the extremes coal and wind power in terms of GHG emissions. Other technical data for waste treatment facilities were modelled using data from earlier waste management studies in Sweden (Olofsson, 2001; Ljunggren Söderman, 2003a-b).

To describe the effects on the demand of scrap and the supply from collection elsewhere, we use the own price elasticities in Table 3 for the waste scrap in Table 2. For example, Table 3 tells us that if the collection of old newsprint would increase by 1 tonne in Sweden, this would lead to an increased demand for 0.12/(0.2-(-0.12))=0.38 tonne old newsprint and to a decreased collection of 0.2/(0.2-(-0.12))=0.62 tonne old newsprint elsewhere (for further explanations in these relationships, see Ekvall, 2000).

Tab. 3: Assumed own price elasticities (presented by Ekvall, 2000 based on Palmer et al., 1997) and corresponding distribution of scrap replacing virgin production and leading to increased alternative waste treatment respectively.

Waste fraction	h_D	h_S	**Collected material replacing virgin production (%)**	**Collected material leading to increased alternative treatment (%)**
Office paper	-0.16	0.2	44	56
Newsprint	-0.12	0.2	37.5	62.5
Corrugated board	-0.16	0.2	44	56
Metal packaging	-0.63	1.4	31	69
Glass	-0.5	0.5	50	50

We have assumed that all the scrap collected in Sweden will have a marginal impact on the international market for each scrap type. For paper products and metals, there is a worldwide market for collected scrap. For glass we assume that the market does not extend beyond Northern Europe. The alternative treatment is then assumed to be landfilling, since this is the dominating treatment option in

3 Used in electric boilers and heat pumps.

a worldwide perspective (USEPA 2002a, EEA 2004).[4]

When waste is prevented, production of the material that eventually turns into waste is reduced. This material might be based on natural resources or recycled scrap material. Our estimate of the mix of virgin and recycled material in the prevented production is presented in Table 4.

Another effect of waste prevention is, of course, that the treatment of waste fraction is reduced. We used data on Swedish average treatment (see Table 2) to model the reduction in waste treatment.

The decreased demand for scrap due to reduced production and the decreased supply due to decreased collection will both affect the market for scrap. The net effect will be either a net reduced demand or a net reduced supply of scrap. The net effect can be illustrated taking newsprint as an example. When 1 tonne of newsprint is prevented, Table 4 tells us that the production from recycled newsprint decreases by 0.37 tonne. This means that the demand for old newsprint on the market decreases by 0.37/0.94 = 0.39 tonne. The second effect is decreased collection of old newsprint, which according to Table 2 is 483/582 = 83 %, corresponding to 0.83 tonne. The net effect of this is a decreased collection of 0.83-0.39 = 0.44 tonne. In Table 4, we have done the same calculations for all waste fractions. For all fractions but office paper the net effect is reduced supply of scrap. For office paper, the large material losses[5] at production from old material make the demand decrease more than the collection, which thus results in a net reduction in the demand for scrap.

Tab. 4: Prevented recycled production, material losses at recycling and share of reduced collection for material recycling when 1 tonne of each fraction is prevented. These data are used for calculating the net reduced collection to the market of scrap.

Waste fraction	**Prevented recycled production (%)**	**Tonne of material produced per tonne of recycled inputs in the recycling process[e]**	**Share of reduced collection for material recycling when 1 tonne of each waste fraction is prevented (%)[f]**	**Net effect on supply (ΔX) and demand (ΔY) to the market when 1 tonne of each waste fraction is prevented (tonne)**
Office paper	44[a]	0.66	64	**ΔY** = -0.03
Newsprint	37[b]	0.94	83	**ΔX** = -0.44
Corrugated board	44[a]	0.93	70	**ΔX** = -0.22
Metal packaging	20[c]	0.98	66	**ΔX** = -0.46
Glass	60[d]	0.98	72	**ΔX** = -0.11

a) Due to lack of specific data, it has been estimated to be the same as global utilisation of

4 The choice between incineration and landfilling for alternative treatment of glass is not important for this study, since both lead to very low GHG emissions when glass is treated.

5 Around 30 % of office papers constitutes of kaolin (Hedenberg et al., 1997), which cannot be recovered in the material recycling process.

recovered paper products (CEPI, 2003), b) Estimated based on FAO (2001) and FAO (2004), c) Estimation based on APEAL (2004), where it is stated that "Steel packaging contains up to 25% recycled material ", d) Estimation based on Ecoinvent (2004), e) USEPA (2002b), f) Calculated from Table 3.

The data in Tables 3 and 4 can together with equations (2) and (3) be used to estimate the effect for material with reduced supply (see Table 5). For newsprint, we have $\Delta X = -0.44$ from Table 4. Table 3 and equation (2) gives us $\Delta S = 0.2/(-0.12)^* \Delta D = -1.67^*\Delta D$. Equation (3) thus gives us $\Delta D = \Delta X/2.67 = -0.16$, and thus $\Delta S = 0.27$[6]. The same calculation is made for corrugated cardboard, metal packaging and glass. For office paper, we have $\Delta X = 0$, since the net effect is reduced demand. For this material, equation (3) is replaced by the following equation (derived from Ekvall, 2000):

(4) $\Delta Y + \Delta D = \Delta S,$

where ΔY describes the net change in scrap demand for production of products used in a geographical area, and ΔD is the resulting change in scrap demand for production of products used outside this area. For office paper, $\Delta Y = -0.03$ (according to Table 4). Table 3 and equation (2) gives us $\Delta S = 0.2/(-0.16)^* \Delta D = -1.25^*\Delta D$. Thus $\Delta D = -0.03/ (-2.25) = 0.014$, and $\Delta S = -0.017$.

Tab. 5: Effects on reduced recycling replacing virgin production and reduced alternative treatment when waste is prevented.

	Reduced collected material replacing virgin production when 1 tonne of each waste fraction is prevented (tonne)	**Reduced alternative treatment when 1 tonne of each waste fraction is prevented (tonne)**
Office paper	-0.014	-0.017
Newsprint	0.16	0.27
Corrugated cardboard	0.10	0.12
Metal packaging	0.14	0.31
Glass	0.05	0.05

4 Results and discussion

The results are presented in Table 6 (mass flows) and Table 7 (GHG emissions). The large waste prevention for Newsprint (in terms of tonnes/yr) is not surprising considering the comparatively large waste generation of Newsprint (c.f. Table 2). In all scenarios, incineration is the main treatment method remaining after waste prevention and collection for material recycling due to the landfill ban.

Scenario B leads to much lower emissions, mainly due to the prevention of pro-

6 It is a round-off effekt that makes it appear as ΔX is not equal to $\Delta D - \Delta S$.

Tab. 6: Waste prevented and treated in Sweden 2016 (ktonne/yr). A, B, and C stand for the three scenarios.

Waste fraction	Waste prevention			Material recycling			Incineration			Landfilling		
	A	B	C	A	B	C	A	B	C	A	B	C
Office paper	0	42	0	168	141	210	93	78	51	2	2	1
Newsprint	0	116	0	601	504	716	121	101	7	2	2	0
Corrugated cardboard	0	69	0	472	424	541	200	180	133	4	4	3
Metal packaging	0	18	0	42	30	60	21	15	4	0	0	0
Glass	0	40	0	193	164	233	73	62	34	1	1	1
Sum	**0**	**284**	**0**	**1476**	**1264**	**1760**	**508**	**436**	**229**	**10**	**9**	**5**

Tab. 7: Change of material flows and GHG emissions in scenarios B and C compared to scenario A in 2016

	Scenario B		Scenario C	
	Change in waste flow (tonnes)	**Change of GHG emissions compared to scenario A (ktonnes)**	**Change in waste flow (tonnes)**	**Change of GHG emissions compared to scenario A (ktonnes)**
Prevented virgin production	165002	-213	0	0
Prevented recycled production	119467	-95	0	0
Recycled production replacing virgin production	-29875	13	118247	-31
Incineration in Sweden	-71371	20	-278779	83
Landfilling in Sweden	-1457	-1	-5689	-2
Alternative treatment outside Sweden	-47140	-18	166221	59
Net change		**-293**		**109**

duction of (recycled and virgin) materials. Nearly half of the reduction in GHG emissions is explained by prevented newsprint production. Scenario C leads to higher emissions than scenario A mainly due to reduced wastepaper incineration in Sweden and increased alternative treatment of paper products outside Sweden. The reduced incineration of paper and cardboard in Sweden in scenarios B and C leads to increased emissions from this part of the system, since the alternative production of district heat and electricity has higher GHG emissions than paper and cardboard incineration. The alternative treatment of paper and

cardboard outside Sweden is assumed to be landfilling, which generates large methane emissions.

Although the model used is less detailed than earlier models of Swedish waste management, we find it clear that increased waste prevention could lead to large reductions of GHG emissions. It may be a significant limitation in previous systems analyses of Swedish waste management that waste prevention was not included as an alternative. By reducing the MSW amounts in 2016 by 5.3 % in scenario B, the total GHG emissions are lowered compared to the other scenarios by 240-300 ktonnes/yr (taking all our sensitivity analyses into account)[7].

Looking at the results regarding material recycling, the model indicates a delicate result from a policy point of view. In order to decrease GHG emissions, we should stop collecting paper products for material recycling in Sweden and instead focus on increasing the demand for paper products produced from recycled paper fibres. Both actions would, according to our model, lead to reduction of alternative treatment of paper products worldwide, which is more valuable than to reduce the incineration of paper products in Sweden. However, one has to make this interpretation carefully. It has not yet been demonstrated that the collection of scrap material in one part of the world affects the price on scrap material and, hence, the collection and alternative treatment of this material elsewhere. Furthermore, increased incineration of Swedish MSW could lead to reduced import of waste for incineration in Sweden and, hence, to increased alternative treatment of this waste elsewhere. The alternative treatment of paper products elsewhere might also have a better environmental performance than the landfill in our model.

Although our model is not as detailed as the earlier ones, we find it clear that waste prevention has the potential of being far more effective than material recycling in order to reduce the GHG emissions. Likely this is the case for other emissions as well. Systems analyses that exclude waste prevention will not estimate the benefits of this option. There is also a risk that waste prevention will receive less attention from policy-makers, compared to options that are assessed and compared in many waste systems analyses. The waste prevention option should therefore always be considered in the planning of a waste systems analysis as an alternative to expanded treatment capacity. The analysis should include time periods where the waste amounts change based on the development of identified factors (population, personal consumer expenditure, GDP etc.) that drive the waste generation.

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7 For comparison, the total annual GHG-emissions in Sweden are around 70 Million tonnes.

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