

The significance of boundary conditions and assumptions in the environmental life cycle assessment of paper and cardboard waste management strategies. An analytical review of existing studies

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## Summary

A review of existing LCAs on paper and cardboard waste has been undertaken. The objectives of the review were threefold. Firstly, to see whether a consistent message comes out of published LCA literature on optimum disposal or recycling solutions for this waste type. Such message has implications for current policy formulation on material recycling and disposal in the EU. Secondly, to identify key methodological issues of paper waste management LCAs, and enlighten the influence of such issues on the conclusions of the LCA studies. Thirdly, in light of the analysis made, to discuss whether it is at all valid to use the LCA methodology in its current development state to guide policy decisions on paper waste.

A total of nine LCA studies containing altogether 73 scenarios were selected from a thorough, international literature search. The selected studies are LCAs including comparisons of different management options for waste paper.

Despite claims of inconsistency, the LCA review showed an overall environmental preference for recycling over incineration or landfill options, for paper and cardboard waste. A systematic exploration of the LCA studies showed, however, important methodological dependencies, pitfalls and sources of error, mainly concerning differences in the definition of the system boundaries. 15 key assumptions were identified that cover the three paper cycle system areas: raw materials and forestry, paper production, and disposal/recovery. It was found that the outcome of the individual LCA studies largely depended on the assumptions made on these areas, and any differences in results and conclusions can be unambiguously tracked back to differences in these assumptions.

# Introduction

With the purpose of identifying existing studies on the environmental aspects of the management of paper and cardboard waste streams, a search for available studies was conducted by Villanueva et al. (2004). Preference was given to studies following scientifically valid and if possible standardised assessment methodology, preferably Life Cycle Assessment (LCA) methods meeting the standards of the International Organisation for Standardisation, ISO.

A three string search approach was followed: 1) targeted search by personal contacts to a large number of LCA institutions and –experts and paper and cardboard institutions and –organisations worldwide, 2) literature search of international journals and databases, and 3) internet search using search engines such as Google.

The search resulted in an initial identification of many hundreds of potentially relevant references. These were then evaluated based on their titles and abstracts (whenever available) leading to the establishment of a gross list of 108 studies. These studies were then evaluated based on a set of quality criteria for selection of studies to be included in the review, the main criteria being that the study should be a holistic environmental study, preferably an LCA, meeting a set of methodological quality criteria, results of the study should be unambiguously ascribable to paper/cardboard, and the study should include a comparison of two or more options for management of paper/cardboard waste. The evaluation process led to the selection of 9 high quality studies finally comprised by the review. These studies are judged to represent the state-of-the-art knowledge on the environmental aspects of paper and cardboard waste management.

Each of the reviewed studies is a comparison between two or more of the following paper/cardboard waste management options: recycling (material recovery and re-use), incineration (with or without energy recovery) and landfilling. Each study comprises one or more scenarios of varying system boundary conditions and assumptions, and a total of 63 scenarios comparing the three main waste management options to each other is included in the review, each scenario being in fact an LCA of its own. The studies cover many different geographical regions including Sweden, Denmark, Finland, United Kingdom, Germany, other European countries, USA, and Australia. The review is, thus, comprehensive and quite ex-

haustive having captured the vast majority of existing studies and knowledge on the topic.

## Scenarios

An overview of the reviewed studies is presented in the table next page, including all scenarios and an overview of the waste management comparisons. The table, further, presents the overall conclusion on environmental preference between the compared waste management options.

Study no.	Country/region	Type of paper/cardboard studied	Scen. no.	Waste management comparison	Predominant environmental preference			
					Recycl.	Incin.	Landf.	Inc/land mix
1	Sweden	Corrugated board	1.1	Recycling vs. landfill	X			
			1.2	Recycling vs. incineration		X		
		Paper board	1.3	Recycling vs. landfill	X			
			1.4	Recycling vs. incineration		X		
2	Denmark	Corrugated board	2.1	Recycling vs. incineration	(X)	X		
			2.2	Recycling vs. landfill	X			
			2.3	Recycling vs. incineration	X			
			2.4	Recycling vs. landfill	X			
		Newspapers and magazines	2.5	Recycling vs. incineration	X			
			2.6	Recycling vs. an inc./landfill mix	X			
			2.7	Recycling vs. incineration	X			
			2.8	Recycling vs. an inc./landfill mix	X			
		Mixed paper	2.9	Recycling vs. incineration	(X)	X		
			2.10	Recycling vs. an inc./landfill mix	X			
			2.11	Recycling vs. incineration	X			
			2.12	Recycling vs. an inc./landfill mix	X			
3	AU, SF, F, I, NL, S, UK and D	Mixture of newsprint, writing paper and board	3.1	Recycling vs. incineration	X			
4	Germany and Finland	Newsprint	4.1	Recycling vs. incineration		X		
		Magazines	4.2	Recycling vs. incineration		X		
5	UK	Newspapers and magazines	5.1	Recycling vs. incineration	X			
6	Australia	Newsprint	6.1	Recycling vs. landfill	X			
			6.2	Recycling vs. landfill	X		X	
		Cardboard packaging	6.3	Recycling vs. landfill	X			
			6.4	Recycling vs. landfill	X			
7	Germany	Graphic paper	7.1	Recycling vs. an inc./landfill mix	X			
			7.2	Recycling vs. an inc./landfill mix	X			
			7.3	Incineration vs. landfill		X		

			7.4	Recycling vs. incineration	X	X			
			7.5	Recycling vs. incineration	X				
			7.6	Recycling vs. incineration	X				
8	USA	Newsprint	8.1	Recycling vs. landfill	X				
			8.2	Recycling vs. incineration	X				
			8.3	Recycling vs. an inc./landfill mix	X				
		Corrugated board	8.4	Recycling vs. landfill	X				
			8.5	Recycling vs. incineration		X			
			8.6	Recycling vs. an inc./landfill mix	X				
		CUK paperboard	8.7	Recycling vs. landfill	X				
			8.8	Recycling vs. incineration		X			
			8.9	Recycling vs. an inc./landfill mix	X				
		SBS paperboard	8.10	Recycling vs. landfill	X				
			8.11	Recycling vs. incineration	X	X			
			8.12	Recycling vs. an inc./landfill mix	X				
		Office paper	8.13	Recycling vs. landfill	X				
			8.14	Recycling vs. incineration	(X)	X			
			8.15	Recycling vs. an inc./landfill mix	X				
9	Denmark	Mixed paper	9.1	Recycling vs. incineration	X	X			
			9.2	Recycling vs. incineration	X				
			9.3	Recycling vs. incineration	X	X			
		Newspapers and magazines	9.4	Recycling vs. incineration	X				
			9.5	Recycling vs. incineration	X				
			9.6	Recycling vs. incineration	X				
		Corrugated board	9.7	Recycling vs. incineration		X			
			9.8	Recycling vs. incineration	X				
			9.9	Recycling vs. incineration		X			
		Mixed paper	9.10	Recycling vs. incineration	X				
			9.11	Recycling vs. incineration	X				
			9.12	Recycling vs. incineration	X				
		Newspapers and magazines	9.13	Recycling vs. incineration	X				
			9.14	Recycling vs. incineration	X				
			9.15	Recycling vs. incineration	X				
		Corrugated board	9.16	Recycling vs. incineration	X				
			9.17	Recycling vs. incineration	X				
			9.18	Recycling vs. incineration	X				

The review finds that *recycling* is by practically all existing studies found to be environmentally preferable to *landfilling* and to the prevailing *mix of incineration and landfilling* in the studies and countries covered by the studies, which is around 20-30% incineration and 70-80% landfilling.

Only scenario comparing *incineration* to *landfilling* has been identified, and it shows a clear preference for incineration.

The immediate picture of the comparison between *recycling* and *incineration* is more varied. Within some impact categories, recycling is by the majority of studies found to lead to reduced impacts. This is the case for:

- overall energy consumption,
- energy related impacts of acidification, nutrient enrichment and photochemical ozone formation,
- toxicity, and
- other impacts (COD in wastewater effluents and land use)

Within other impact categories, the results of the reviewed studies show more evenly distributed advantages and disadvantages for recycling and incineration, i.e. the categories of:

- consumption of fossil fuels,
- global warming, and
- solid waste

for which global warming and fossil fuel consumption are strictly correlated. As global warming is of the highest interest, this impact category is given specific attention.

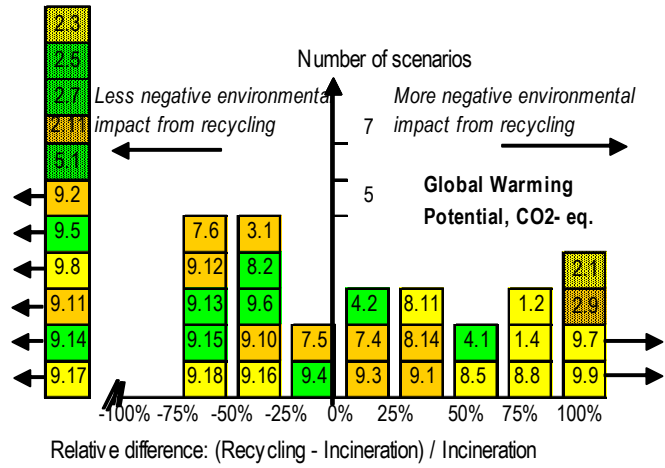
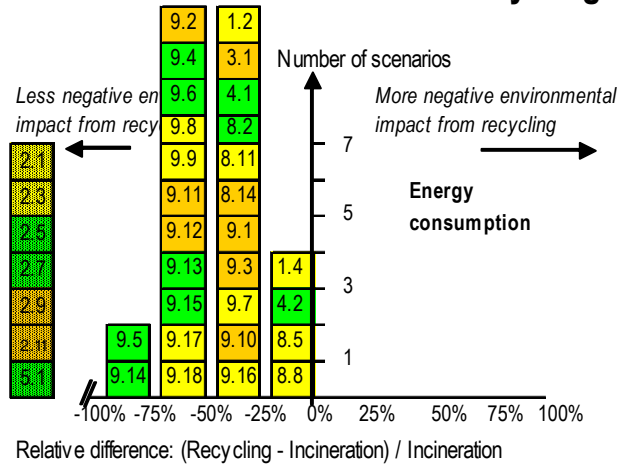
Results on overall energy consumption follow a very evenly distributed normal distribution with an average of 50% less energy consumption when recycling instead of incinerating paper and cardboard. In other words, the aggregation of results from the reviewed studies shows that:

*on average virgin production followed by incineration with energy recovery consumes twice as much energy as recycling*

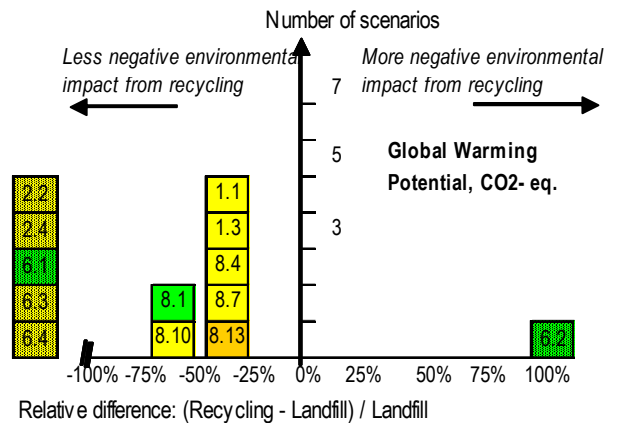
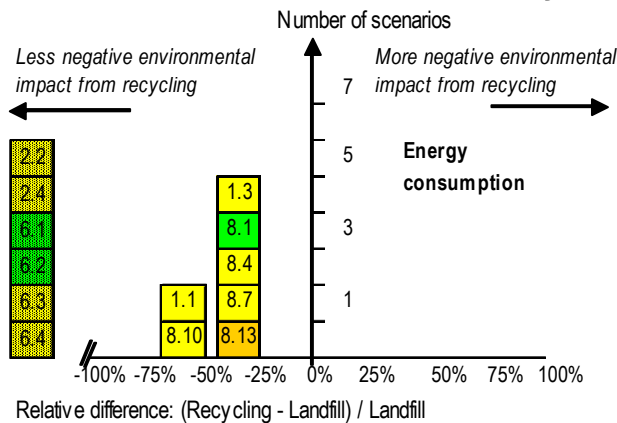
see the Figure next page. The reason that this result does not reproduce itself for the energy related impacts is that the energy systems behind virgin paper/cardboard production and paper/cardboard recovery are different: whereas the energy underlying virgin production is to some extent based on CO<sub>2</sub>-neutral fuels, the paper/cardboard recovery operations are typically solely based on fossil fuels.



### Recycling vs. Incineration



### Recycling vs. Landfill



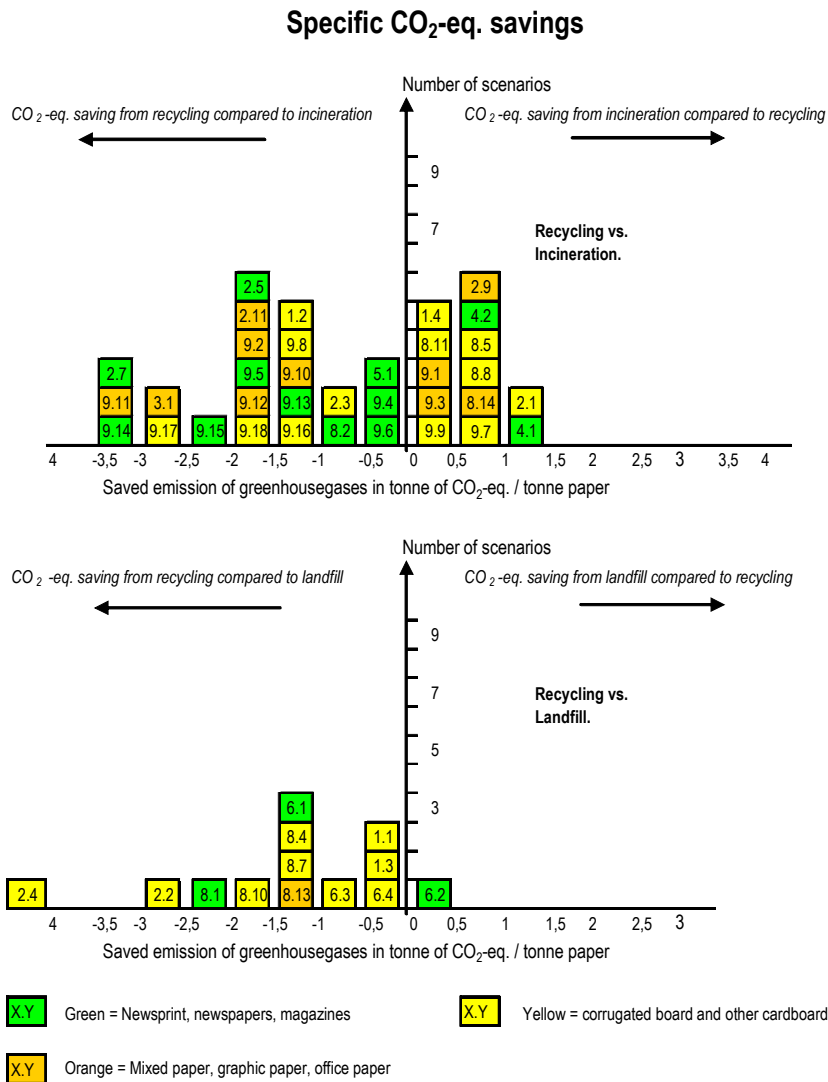
- X:Y The LCA covers the entire life cycle, i.e. relative difference in percentage can be calculated
- X:Y The LCA covers only waste management end-of-life. The quantification in percentage is, therefore, not possible, and the environmental preference is shown qualitatively out of scale
- X:Y → Means that this value lies outside of the scale.

- X:Y Green = Newsprint, newspapers, magazines
- X:Y Orange = Mixed paper, graphic paper, office paper
- X:Y Yellow = corrugated board and other cardboard

The reason that results on global warming and fossil fuel consumption show a large variation and an unclear preference shall be found in the way in which the studies handle the above mentioned differences in the underlying energy systems in their system boundary settings within their various scenarios. This variation is to be expected, as the many scenarios

of some of the studies were set up for the exact reason of showing the dependency of results and conclusions on variations in key assumptions.

Specific account has been made of results on the quantitative difference in the emissions of greenhouse gases measured as CO<sub>2</sub>-equivalents between the compared waste management options. The picture is the same as shown for the relative difference above, see the Figure below.



## Discussion and conclusion

Based on experience and on the results of the reviewed studies, a number of system boundary issues have been identified that are decisive to the results and conclusions of the comparison. In this way, the review is not solely a compilation of results and conclusions of existing studies, it is further an analysis of which assumptions and boundary conditions lead to which results and conclusions. This has been done to allow for a qualified discussion and to enable the target group of this report to cut through the debate on environmental aspects of paper and cardboard waste management. In all, 15 essential boundary issues and assumptions have been identified, and all reviewed studies have been assessed with respect to their choices of assumptions and mode of handling these issues.

The overall conclusion is that the reviewed studies represent a fair handling of the system boundary issues.

In the table below, a brief overview on this is presented.

Code	System boundary conditions		Number of studies	% of the studies that consider the given boundary condition
1	Alternative use of land/wood considered?	Considered	3	33%
		n.i.	6	-
2	Saved wood used for energy considered?	Considered	3	33%
		n.i.	6	-
3	Wood marginal considered?	Considered	3	33%
		n.i.	6	-
4	Virgin paper - Electricity marginal considered?	Considered	9	100%
		n.i.	0	-
5	- Steam marginal considered?	Considered	8	89%
		n.i.	1	-
6	Recovered paper - Electricity marginal considered?	Considered	8	89%
		n.i.	1	-
7	- Steam marginal considered?	Considered	6	67%
		n.i.	3	-
8	Energy export from virgin paper considered?	Considered	3	33%
		n.i.	6	-
10	Emissions from landfill considered?	Considered	7	78%
		n.i.	2	-
11	Energy from incineration substitutes heat- considered?	Considered	5	56%
		n.i.	4	-
12	Energy from incineration substitutes electricity – considered?	Considered	7	78%
		n.i.	2	-

13	Alternative use of incineration /landfilling capacity considered?	Considered	3	33%
		n.i.	6	-
14	Data on the substitution ratio recycled/virgin paper considered (1:1 or 1:0.8 or 1:0.5 or other)?	Considered	5	56%
		n.i.	4	-
15	De-inking sludge considered?	Considered	6	67%
		n.i.	3	-

NOTES: n.i.: no information

As the table shows, however, there is some variation in the extent to which the various system boundary issues are considered in the studies. In most cases, the key issues are considered and the assumptions presented transparently. In the cases, where assumptions are not transparently shown, moreover, the issues are probably considered and dealt with anyway, but just not transparently documented in the report. On a few issues, however, there is judged to be a real lack of awareness, especially the issue of alternative use of wood (issue 1-3) and the issue of alternative use of incineration capacity (issue 13).

The review includes an analysis of the sensitivity of the results and conclusions of the reviewed studies to the system boundary assumptions, and it is found that the following four main system boundary issues and assumptions are especially:

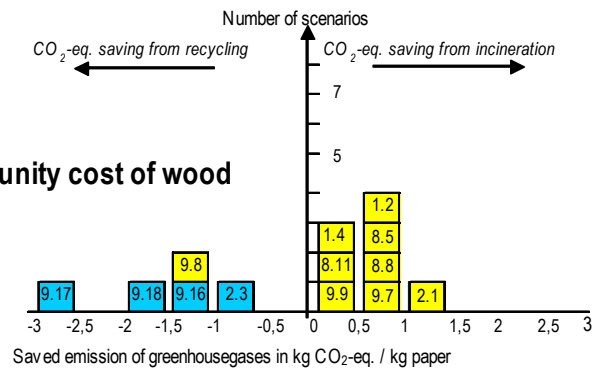
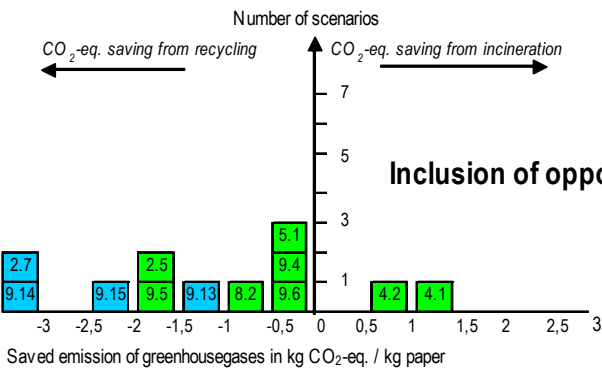
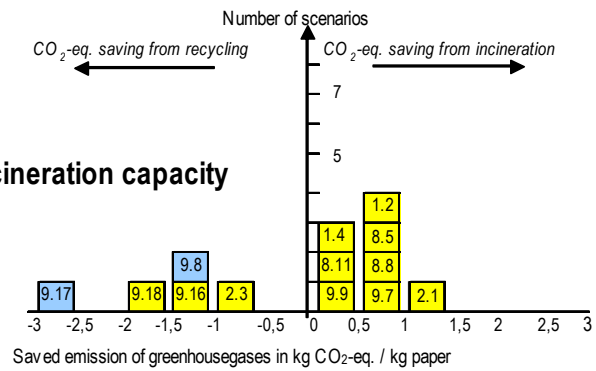
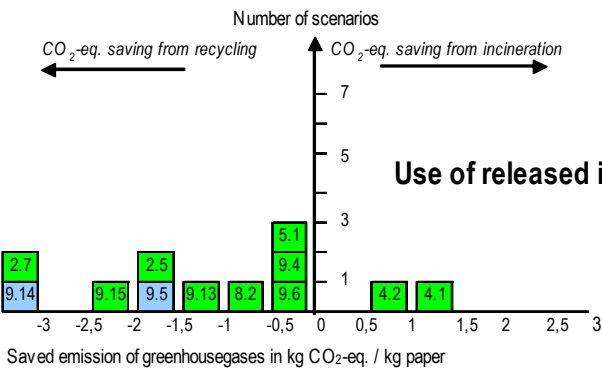
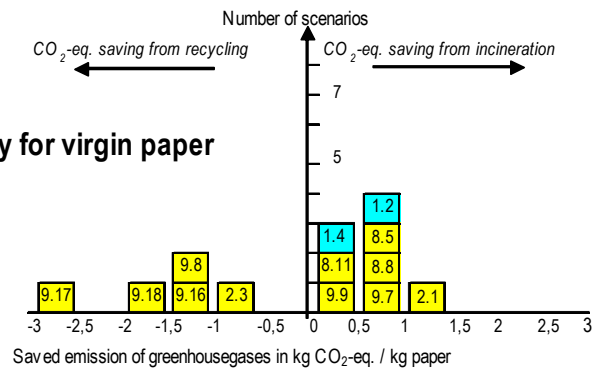
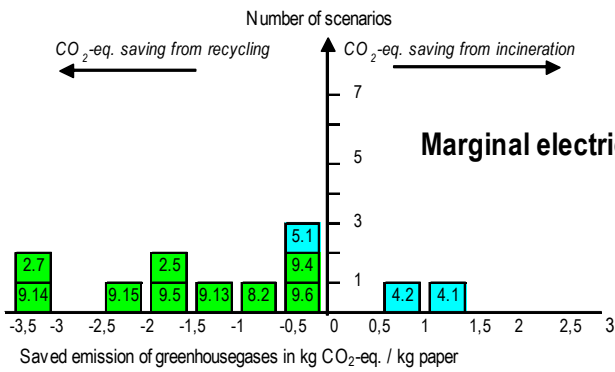
1. The energy split between electricity and thermal energy of the various paper and cardboard types.
2. The marginal electricity assumed for virgin paper/cardboard production
3. The considering of the utilisation of the extra incineration capacity created by recycling to reduce landfilling
4. The inclusion of an opportunity cost of using wood for virgin paper/cardboard production

For this reason, results and conclusions from these groups are distinguished from each other in the presentation and discussion of the analyses of the review. The Figure below presents some of the key findings in the form of frequency functions of results from the reviewed studies for global warming.

Some of the essential cause-effect relationships between assumptions on these issues and results/conclusions on global warming are transparent from the Figure. It shows, that for newsprint, for which the energy for virgin paper production is mainly electricity, recycling is clearly favourable. Only a few scenarios, which, probably incorrectly, assume that the marginal electricity on the grid is based partly or fully on wood, find

### Newsprint

### Cardboard



- X.Y Green = Newsprint, newspapers, magazines
- X.Y Light blue = Marginal electricity partly or fully based on wood
- X.Y Dark blue = An opportunity cost of using wood included
- X.Y Yellow = Corrugated cardboard and other cardboard
- X.Y Medium blue = Incineration capacity released by recycling used to reduce landfilling

incineration to be preferable. With the proper use of marginal electricity there seems to be no doubt that recycling is preferable for newsprint on global warming and other impact categories – as well as any other paper and cardboard category being made from thermo-mechanical pulp, TMP or chemical-thermo-mechanical pulp, CTMP.

For paper and cardboard categories on the other hand, for which the underlying energy system of virgin production is mainly thermal energy being produced from wood, like for craft pulp, the conclusion on global warming remains conditional to a few key assumptions for which no clear right or wrong can be identified without a closer analysis. It has, thus,

been found that recycling will lead to huge CO<sub>2</sub>-eq. savings, *if* either of the two following assumptions is made:

- the extra capacity of waste incinerators being released on recycling can be utilised to reduce landfilling of burnable waste *or*
- that society is facing a future in which there will be an opportunity cost of using wood in the sense that it deprives society the opportunity of using it in the energy sector.

Likewise, it has been found that incineration will lead to CO<sub>2</sub>-eq. savings, *if* it is assumed that the above mentioned conditions are *not* fulfilled.

#### Scope of interpretation and potential knowledge improvements

A very wide variety of paper and cardboard types are covered by the reviewed studies, i.e. with the terminology used in the studies themselves: newsprint, newspapers, magazines, mixed paper, office paper, writing paper, graphic paper, corrugated cardboard, paper board, CUK paper board, and SBS paperboard. Moreover, the studies cover many different geographical countries/regions worldwide. In general, therefore, the conclusions of this review are believed to be robust.

To further improve the knowledge on the environmental aspects of waste management options of paper and cardboard, the priority is, thus, not to do more LCAs on more paper and cardboard types in more countries or regions in the world. Neither is it to improve the quality of underlying data and methods used, because this is not where the uncertainty lies.

The remaining uncertainty lies with the identified system boundary assumptions that are decisive to conclusions on global warming and fossil fuel consumption. On these issues, however, stakeholders in the environmental aspects of waste management of paper and cardboard would benefit much from a deeper analysis of the future developments and probabilities of which system boundaries will in fact exist, i.e.:

- What is the incineration and landfill capacities in the country/region in question, what is the short and long term match of these capacities with the waste flows, and what is the waste management policy. Will in fact a release of incineration capacity due to more recycling be used to take in more burnable waste from landfills? What are the short term and long term aspects of this?
- Does society face a future in which wood and other biomass becomes a priority fuel in the energy sector, e.g. because of

CO<sub>2</sub> reduction measures, fuel scarcity or economic relations in general? Will there be an opportunity cost of using wood?

It is possible to do a meaningful analysis of these issues, and this is the highest priority to further qualify future statements on the environmental aspects of waste management of paper and cardboard.

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