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Evaluating waste incineration as treatment and energy recovery method from an environmental point of view

Mattias Olofsson*, Johan Sundberg and Jenny Sahlin
Department of Energy Technology
Chalmers University of Technology
Hörsalsvägen 7B
S-412 96 Göteborg, Sweden

*) Corresponding author
Phone: +46 31 772 1442
Fax: +46 31 772 3592
Email: mattias.olofsson@me.chalmers.se

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Abstract

During the last two decades, several research groups as well as consultants have been analysing the environmental impacts of incineration in comparison to other waste treatment options. Methods and models for describing these systems have been developed. Systems studies on local, regional and national level have been performed using a wide range of different modelling approaches. The aim of this paper is to describe the environmental performance of incineration with energy recovery in Europe in comparison with other options for waste treatment/recovery. This includes identifying key factors that largely affect the outcome from environmental systems studies where such comparisons are made. The paper focuses on mixed solid waste and on waste fractions where there has been a lot of controversy whether the material should be recycled, incinerated or treated biologically (e.g. paper, plastics, compostable material). The paper is based on a meta-study, where the above research field is mapped out in order to gather relevant systems studies made on local, regional and national levels in Europe. By thoroughly examining these studies, conclusions are drawn regarding the environmental performance of incineration with energy recovery and regarding key factors affecting the environmental results.

1. Introduction

1.1 Background

The role of waste incineration in the waste and energy systems is controversial from an environmental point of view. Today there are many research groups, companies, organisations etc., which have an opinion on whether waste incineration is a correct solution for the combustible waste or not. During the last 20-30 years, several research groups as well as consultants have been analysing the environmental impacts of incineration in comparison to other waste treatment options. Methods and models for describing these systems have been developed. System studies on local, regional and national level have been performed using a wide range of different modelling approaches. Results and suggestions of improvements have been presented. The most commonly used approach for the studies is LCA (Life Cycle Assessment) or LCA inspired techniques for describing the total environmental impact. However, there are also other types of approaches, e.g. cost-benefit analyses and use of systems engineering models.

Results from the system studies vary, although thoroughly done and considered objective. While many case studies indicate that incineration is an important option for reducing a number of pollutants and solving other goals (e.g. reducing the need for landfills), others show the opposite. There are obviously differences in the input to these studies (data, system boundaries, methods etc), which can explain the differences in the final results. Unfortunately, it is not an easy task to make these results transparent since they cover large technological systems such as waste management systems, energy systems (both electricity and heat) and material recovery systems.

1.2 Aim and scope

The aim of this paper is to describe the environmental performance of incineration with energy recovery in Europe in comparison with other options for waste treatment/recovery. This includes identifying key factors that largely affect the outcome from environmental systems studies where such comparisons are made. The paper focuses on mixed solid waste and on waste fractions where there has been a lot of controversy whether the material should be recycled, incinerated or treated biologically (e.g. paper, plastics, compostable material).

The paper is based on a meta-study (Profu 2004), where the above described research field is mapped out in order to gather relevant systems studies made on local, regional and national levels in Europe (this is further described in Section 2).

The paper is limited to environmental impacts of waste incineration in comparison to other treatment options. The economic consequences of different options are outside the scope of the study. Regarding waste-to-energy technologies, there are many possible concepts. In this paper, the focus is on waste incineration with energy recovery. The waste fractions are combusted in a grate or fluidised bed and the plants are specifically erected with the main purpose of treating the waste. Throughout this paper, all incineration is assumed to be conducted with energy recovery, i.e. incineration with no energy recovery where the sole purpose is destruction of the waste is not included.

2. Methodology

2.1 General

This paper is mainly based on a meta-study of earlier performed systems analyses of waste management (Profu 2004). In the systems analyses, incineration with energy recovery was at least one out of two or more options.

When performing the meta-study, it was essential to thoroughly map out the research field and the studies conducted. We did this through different approaches:

- As researchers and consultants, we have performed a large number of systems analyses of waste management. Beside the experiences and insights gained from the work, we have established extensive networks of both researchers and consultants worldwide, which we contacted for this work.

- We performed searches in databases for peer-reviewed papers and other relevant reports.

- We sent out an inquiry to members of various organisations, apart from CEWEP (Confederation of European Waste-to-Energy Plants), regarding relevant studies; FEAD (European Federation of waste management and Environmental Services), and ISWA (International Solid Waste Association). Furthermore, this inquiry was sent to the International Expert Group on Waste Management, the Joint Research Center Institute for Environment and Sustainability (IES) and participants of the international workshops "Systems Engineering Models for Waste Management" (Gothenburg, 1998), "Workshop on System Studies of Integrated Solid Waste Management" (Stockholm, 2001) and "Integrated Waste Management & Life Cycle Assessment Workshop and Conference" (Prague, 2004). In total, approximately 150 persons active in the waste management field in Europe, as researchers, consultants or practitioners, received this inquiry.

The mapping encompassed roughly 70 studies, which we found relevant to consider for the meta-study. Sections 2.2 describe the further division of the studies.

2.2 Studies included in the analysis

Out of the around 70 studies, we chose 31 case studies for a brief examination based on their relevance for this meta-study:

- In all studies, waste incineration was evaluated from an environmental perspective as one of two or more options for treatment of mixed waste or certain waste fractions, e.g. packaging, paper or plastic waste.
- The studies picked ensured a good geographical coverage, thus capturing discrepancies between the conditions in different European countries.
- Furthermore, only studies published after 1995 were considered. The studies are listed in Appendix A.

Out of these 31, we selected 12 for a detailed examination (see Table 2.1).

Table 2.1 Case studies included for a detailed examination. The number refers to the number in Appendix A, where the full references are written.

Nr	Country/region	Name of the study
1	Austria	Comparison of ecological effects and costs of communal waste management systems
2	Austria	Stoffliche Verwertung von Nichtverpackungs-kunststoffabfällen. Kosten-Nutzen-Analyse von Maßnahmen auf dem Weg zur Realisierung einer umfassenden Stoffbewirtschaftung von Kunststoffabfällen (in German)
5	Denmark	Madavfall fra storkøkkener (Waste food from catering canters) (in Danish)
8	Europe (EU-15)	Waste management options and climate change. Final report to the European Commission
11	France	Analysis of technical and environmental parameters for waste-to-energy and recycling: household waste case study
13	Germany	Comparison of plastic packaging waste management options – Feedstock recycling versus energy recovery in Germany
14	Germany	Grundlagen für eine ökologisch und ökonomisch sinnvolle Verwertung von Verkaufsverpackungen (Bases for an ecologically and economically reasonable recycling of sales packaging) (In German)
18	Italy	The environmental performance of alternative solid waste management options: a life cycle assessment study
20	Italy	Life cycle assessment of a plastic packaging recycling system
23	Sweden	Hur skall hushållsavfallet tas omhand? Utvärdering av olika behandlingsmetoder. (How should the household waste be treated? Evaluation of various treatment methods.) (in Swedish)
25	Sweden	Life Cycle Assessment of Energy from Solid Waste – Part 1: General Methodology and Results
28	Switzerland	Ecology, which technologies perform best?

We used the following criteria for the selection:

- Transparency and data availability must be high
- The study must be financed by a "neutral" player such as the EU, governments and/or national environmental agencies or authorities. If not, the study must be peer-reviewed in order to be included.
- Geographical discrepancies, e.g. regarding the infrastructure for waste management and energy supply, must be covered.
- As many waste fractions as possible should be included. However, we have also included studies only focusing of parts of the waste, e.g. packaging, food waste and paper.
- The number of environmental impact categories should be high. However, a few studies with only a limited amount of environmental impacts studied have also been included.

Beside the case studies, we also included a number of papers, reports etc, where general key factors affecting the choice between different waste treatment options were discussed. The majority of the studies are meta-studies, where the authors base their conclusions on overviews of earlier case studies. In Appendix B, we have listed these key factor studies.

3. Results and discussion

3.1 Brief examination

In the meta-study, we first completed a brief examination of 31 studies. When only making a brief examination of a systems analysis study, it is difficult to form conclusions on the importance of e.g. the quality of the input data, the system boundaries chosen and the modelling of different waste treatment options. For this, a detailed examination is necessary, which we have performed with 12 studies in Section 3.2. However, we have concluded some general observations based on the brief examination:

- On the choice of environmental impact categories, almost all studies included both Global Warming Potential (GWP) and energy use. This probably illustrates the importance of the enhanced greenhouse gas effect. Other impact categories that can be found in many studies are acidification and eutrophication and (to a lesser extent) toxicological impacts on nature and humans. Some studies have weighted the environmental impact into a total environmental cost or benefit that is also compared.

- The majority of the studies concentrates on separated fractions of the waste, e.g. food waste, paper, plastic, metals etc., but also studies including treatment of mixed waste (e.g. MSW) have been performed. Material recycling and biological treatment are normally compared to incineration for separated fractions. Very few studies examine how all parts of the mixed waste should be treated if incineration is replaced. This is mainly done for landfilling. Although material recycling and biological treatment could lead to lower impacts for the separated fractions, it is not obvious that the total environmental impact for mixed waste would be lower than for incineration, if the fractions that cannot be recycled or treated biologically must be landfilled.

- Regarding the main conclusions of these studies, we made the observation that for well source-separated and clean material fractions, material recycling generally leads to lower environmental impacts than incineration. For organic waste, the choice between incineration, composting and anaerobic digestion is not obvious. Landfilling is the worst option in almost all studies.

3.2 Detailed examination

In this section, we summarised results regarding the environmental impacts of incineration with energy recovery in comparison with other treatment options. We limited the comparison to the impact categories GWP, acidification and eutrophication as these are covered by most studies[1]. All studies do not include the same emissions in each impact category. This is marked in the tables below, as it has been defined in the studies. The results are summarised through colour-coded tables. The colours have the following meaning:

Colour	Meaning
	Incineration show lower emissions/lower environmental impact than the alternative treatment method
	The difference between incineration and the alternative treatment method is small
	Incineration show higher emissions/higher environmental impact than the alternative treatment method

[1] The meta-study (Profu 2004) also contains comparisons regarding photooxidants and toxicity. Other important evaluation criteria such as consumption of resources, required land space and costs are not considered.

By studying the dominating colour in each table, the idea is to give the reader an impression whether or not waste incineration is a better or worse treatment option than the alternative treatment option in each table. However, conclusions should be drawn with care, as each study includes specific assumptions and limitations that affect the environmental results.

Therefore, before moving on to the environmental results of specific studies, some comments on the uncertainties are necessary. In such comprehensive studies as the studies below, various types of uncertainties appear and have to be taken into consideration when evaluating the results and before drawing conclusions. Some of the most frequent uncertainties are: data gaps, uncertainties based on methodological issues, weighting uncertainties and uncertainties of the performance of new technologies.

In the case of gaps in input data, e.g. on the composition of the waste to be treated, the studies made assumptions based on other studies, earlier experiences or similar. Unless these assumptions had a key impact on the results, we did not consider the correctness of such assumptions, and thus we relied on them to be valid for the area in focus.

The uncertainties based on methodological issues were handled at an earlier stage of this study (see Section 2.2). Some studies use weighting methods in order to group the emissions with the same type of effect. This is the case when i.e. expressing total greenhouse gases as CO_2-equivalents etc. We did not study the used weighting methods, since they were developed through extensive international research, and therefore we rely on how they have been used in the studies. Performance of new technologies is further commented in Section 3.3.

Incineration vs. material recycling of paper waste

In the comparison of the environmental effects of incineration with energy recovery and material recycling of various types of waste paper and cardboard, results are varying (see Table 3.1 below).

For **GWP** more studies showed an advantage for material recycling than incineration. The studies that show better performance for incineration with energy recovery than for recycling, comment that the avoided burdens due to the energy recovery are important as well as the energy efficiency of the incineration process. Energy production from natural gas, oil or coal is avoided in these studies when energy is recovered at incineration.

According to these studies, **acidification** is generally prevented when paper and cardboard is recycled instead of incinerated. This is mainly due to the prevention of emissions of SOx and NOx, when the production from virgin materials is prevented.

Regarding **eutrophication** the results show that recycling can be preferred. The study that shows the opposite (for newsprint paper only) does not include emissions of NOx, which could explain this discrepancy.

Table 3.1 Incineration with energy recovery in comparison to material recycling. Studies including separated fractions: paper, cardboard etc.

Ref	Waste fractions	Alternatives	GWP	Acidification	Eutrophication
1	Paper				-
11	Paper			a	-
14	Paper carton composites	Current technology[b]			c
		New technology[d]			c
	Carton for liquids				c
23	Paper packaging				
25	Newspaper			e	f
	Corrugated cardboard			e	f
	Mixed cardboard			e	f

a) SOx and NOx mainly, b) Current sorting/recycling technology (Status Quo), c) Terrestrial and aquatic, d) New automatic sorting technology (SORTEC), e) Excl SOx and NOx, f) Aquatic (excl NOx)

Incineration vs. material recycling of plastic waste

In the comparison of the environmental effects of incineration with energy recovery and material recycling of various types of waste plastics, results are also varying (see Table 3.2 below). Collection and separation of plastic waste are included in the evaluations.

GWP: Recycling of plastic is mainly preferred. One study shows the opposite in one scenario, due to the assumption that the plastic recycled does not substitute virgin plastic production but wood.

Acidification: The results are not definite but may show that recycling is preferred. However, the results vary with the type of plastic compared, but also if SOx and NOx are included or not in the substances causing acidification.

Eutrophication: No definite conclusions can be drawn, except that it is important for the results if virgin plastic or wood is assumed to be avoided.

Table 3.2 Incineration with energy recovery in comparison to material recycling Studies including separated fractions: plastics

Ref	Waste fractions	Alternatives	GWP	Acidification	Eutrophication
1	Plastics				-
2	Plastics (non-pack.)			-	-
11	Plastics			-	-
14	Plastic pack. (bulk)				a
	Plastic packaging, small items	Current technology			a
		New technology			a
19	Plastics			-	-
23	Plastic packaging				
25	PE			b	c
	PP			b	c
	PS			b	c
	PET			b	c
	PVC			b	c
	Mix of the plastics	Wood palisades[d]		b	c

a) Terrestrial, b) Excl SOx and NOx, c) Aquatic (excl NOx), d) Palisades made of recycled, mixed plastics are assumed to replace palisades made from impregnated wood.

Incineration vs. anaerobic digestion
For **GWP** it is difficult to say which option is to be preferred when comparing incineration with anaerobic digestion. Anaerobic digestion (see Table 3.3 below) could or could not be preferred, depending on various factors; i.e. if the fuel is used for district heating (dh), electricity (el) or refined to a transportation fuel, or whether biomass or oil is assumed to be the alternative fuel for the alternative production of district heat. In both cases, where oil is the alternative for district heat production instead of biomass, incineration is favoured. If natural gas is the alternative source for district heating, the difference is small between the treatment options.

Regarding **acidification** and **eutrophication**, anaerobic digestion is likely the best alternative according to the results of these studies. The difference is small, though, if the gas from the anaerobic digestion is used as a fuel for transportation instead of for district heating and electricity. It should also be noted that in study 23 and 25, the energy recovery from incineration does only generate district heating and no electricity. In study 5, both electricity and district heating are generated from incineration.

Table 3.3 Incineration with energy recovery in comparison to anaerobic digestion
Studies including biodegradable waste fractions

Ref	Waste fractions	Alternatives	GWP	Acidification	Eutrophication
5	Food waste	El + dh[a]			
23	Easily biodegradable	Fuel[b], biomass			
		Fuel, oil[c]			
	Easily biodegradable	El + dh, biomass			
		El + dh, oil			
25	Food waste	El + dh, biomass[d]		e	f
		Fuel, natural gas[g]		e	f

a) Biogas is used for production of electricity and district heat, b) Biogas is upgraded to vehicle fuel, c) In the base scenario, biomass is the alternative fuel for district heat production. Here, oil is the alternative, d) Waste incineration produces district heat and biomass is saved in the base scenario. Gas from the anaerobic digestion is used in a combined heat and power plant (CHP). The heat and electricity is assumed to substitute the fuels biomass and coal condensing power, respectively, e) Excl SOx/NOx, f) Aquatic (excl NOx), g) Natural gas is assumed to be the avoided heat source for district heating.

Incineration vs. composting
Compared to composting (see Table 3.4 below), incineration shows better results regarding **GWP**. This is not the case, however, if biomass is the alternative fuel for heat production as in the base case of study 25.

Incineration is to be preferred regarding the **acidification** potential compared to composting.
In the case of the potential for **eutrophication** the studies show different results.

Table 3.4 Incineration with energy recovery in comparison to composting
Studies including biodegradable waste fractions

Ref	Waste fractions	Alternatives	GWP	Acidification	Eutrophication
5	Food waste				
23	Easily biodegrad.				
25	Food waste	Biomass for dh		a	b
		Natural gas for dh[c]		a	b

a) Excl SOx / NOx, b) Aquatic (excl NOx), c) In the base scenario, biomass is the alternative fuel for district heating. Here, natural gas is the alternative.

Incineration vs. landfilling
For mixed waste (see Table 3.5), all categories (**GWP, acidification, eutrophication**) are better for incineration than landfilling.

Table 3.5 Incineration with energy recovery in comparison to landfilling
Studies including mixed waste

Ref	Waste fractions	Alternatives	GWP	Acidification	Eutrophication
18	Rest waste				-
23	MSW				
28	MSW	Mechanical-biol.[a]			
		Landfilling			

a) Mechanical-biological pre-treatment does in this case consist of a iron scrap recovery, separation of high-calorific value waste for incineration and biological treatment of the rest waste followed by landfilling.

For separated waste fractions, however, landfilling can show better results than incineration with energy recovery (Profu 2004). From the studies regarding plastics (Profu 2004), it is not possible to say which treatment option is the best regarding GWP. The cases with negative outcome for incineration are due to the time perspective used for landfilling. In the short term, the GWP is lower for landfilling than for incineration, as only a small fraction of the plastic is assumed to be degraded (see also Section 3.3).

Regarding treatment of paper and cardboard (Profu 2004), negative results for incineration compared to landfilling in the GWP category are also due to the time perspective considered. In the short term, if the landfill is considered as a carbon sink, the GWP is lower for landfilling than for incineration, as a fraction of the paper (constituted of hemicellulose, cellulose and lignin) is only partly degraded. In the short term, there are no GHG-emissions from the landfilling from this non-degraded fraction, and emissions are thus avoided in comparison to incineration where this fraction is oxidised into CO_2 (see also Section 3.3).

3.3 Key factors
In this section, we present identified key factors that can change the environmental ranking (for one or more emissions/impacts) between incineration and the other treatment/recovery methods. This section starts with key factors that are of general importance, i.e. that are important for all treatment methods. Then we continue with incineration and the other treatment/recovery methods that were compared to incineration in Section 3.2. The key factors have been identified mainly by using two sources: a) the systems analyses in Section 3.2, and b) so called key factor studies (as listed in Appendix B).

General key factors
The following key factors, we found to be of general importance for the environmental ranking of treatment methods:

- Time perspective
- Technology development
- Local conditions
- Alternative electricity and heat generation
- Renewable energy supply in Europe
- Waste transports by passenger car

The **time perspective** is fundamental for the modelling of the processes in the waste management system as well as for the assumptions/modelling of surrounding systems (e.g. the energy system or the material production system) that are affecting the results. Furthermore, the time perspective can also affect the choice of data in LCAs. The choice of time perspective might affect what technologies are available. On a short term, only existing facilities are available, which can lead to certain technologies being omitted due to lack of capacity.

The choice of time perspective is also an underlying factor behind assumptions made for **technology development.** These assumptions, based e.g. on promising results from pilot plants, can crucially improve the efficiency of the technologies both regarding emissions and the quality and amount of the end products. In Christiani et al (2001) for example, the new sorting technology for light-weight packaging in Germany, meant an improved result for material recycling compared to the technology used at the time of the study (1998). For some of the environmental impacts evaluated, this changed the ranking between material recycling and incineration (see study 14, Tables 3.1 and 3.2 in Section 3.2).

The **local conditions** strongly affect the environmental value of different treatment options. For example, if there is no market/demand for compost due to strong requirements on a low level of heavy metals in fertilizers, composting is not a viable option. In the case of incineration, the existence of a district heating system enables a higher energy recovery compared to the case where only electricity production is possible. Furthermore, the local conditions can also decisively influence the importance of different environmental parameters. For example, for some regions acidification might be of larger relevance than eutrophication and vice versa. This can change the overall environmental ranking between different options.

The choice of **alternative electricity and heat generation** has a large impact on the results where energy is either recovered directly (e.g. waste incineration) or indirectly[2] (material recycling), but also generally for the all treatment options where electricity and heat are consumed. The assumptions in the studies range from use of fossil fuels (predominantly coal or natural gas) to renewable fuels (solid biofuels or wind). In between these options, national or EU averages both for electricity and heat production have been used. The choice depends on the time perspective and on the local conditions. For example, if the study is change-orientated, marginal data should be used instead of average data, thus reflecting the effects of the change. The local conditions are more important for the alternative heat generation, which unlike electricity cannot be transmitted over large distances. For example, in the case of district heating, mainly fossil fuels are used in Germany, while in Sweden a large share of the district heat production is based on biofuels.

Considering the goals of the Kyoto protocol and its implications on waste management, **the renewable energy supply in Europe** is also a relevant key factor. In Section 3.2, only the systems analyses made for Sweden assume that the alternative heat production can come from solid biofuels. For the other countries, fossil fuels are generally assumed both for electricity and heat production. In long term studies, it is relevant to evaluate whether fossil fuels or renewable fuels (predominantly biofuels) will be the alternative heat production. For example, could the Kyoto targets stimulate a development of domestic resources of biofuels in Europe?

Finally, in principle all evaluated systems studies have shown that the large-scale collection and transportation of waste by truck is of less environmental importance

[2] At the material recycling, energy is consumed. But the material recycling replaces virgin production, leading to energy savings. The net is normally an energy reduction.

than the choice of treatment option. However, there is one type of transport that can change the ranking of different treatment options. Due to the low fuel efficiency, **waste transports by passenger car** mean large emissions per tonne of waste transported, if the sole purpose of the transport is to deliver the waste (and not do other errands such as shopping etc, to which the emissions could be allocated). In some studies, an assumed increase in waste transports by passenger car has been very negative for the environmental performance of material recycling and incineration.

Key factors for incineration

Besides the general key factors above, we have found the following key factors to be of relevance for incineration:

- Emission level
- Energy recovery
- Time perspective and fate of landfilled residue

The **emission level** is mainly dependent on the waste incinerated, the waste incineration technology and the flue-gas treatment. The Waste Incineration Directive means harder restrictions on emissions from incineration throughout the whole EU. The directive regulates a large amount of different emissions, and will lead to better environmental performance, when fully implemented and followed. The more efficiently the process works, the less are the environmental impacts from regulated as well as unregulated emissions.

Another key factor for incineration is the efficiency of the **energy recovery**, i.e. the amount of energy in the waste that can be transformed into useful energy such as electricity, steam for industrial purposes or heat for residential heating. When electricity is produced, the energy efficiency ranges between 20 and 30 %. However, if it is possible to produce district heat, the energy efficiency can amount to around 90 %[3] (based on LHV, excluding district heating distribution losses). This fact, in combination with the local conditions regarding alternative electricity and heat generation, has a large impact on the environmental performance of waste incineration.

Waste incineration generates slag and flue-gas cleaning residues. While the former can be sorted and reused to a large extent, the latter normally needs to be landfilled due to a high level of substances such as heavy metals, dioxins etc. When modelling incineration, it is essential to include the direct and future impacts of this landfilled residue. **The time perspective and fate of the landfilled residue** can differ from study to study. The longer the time perspective, the larger the amount of substances leaching out of the landfill into the environment. Some studies assume an infinite perspective where all substances leach out to the environment (e.g. Finnveden et al 2005), while other only include the emissions during a "surveyable" time of around one century (Sundqvist et al 2002)[4]. Hellweg et al (2003) comment that the time perspective is important when analysing the performance of normal versus newer incineration technologies. In the short-time perspective, the newer incineration technologies with recovery of heavy metals from the slag are not credited for their prevention of emissions that would have appeared from the landfill in the long run. Furthermore, it is also important to assess how sensitive the recipient of the leachate is. The evaluation of the sensitivity of the recipient is seldom done. Instead, emissions are added together without

[3] However, the exergy value of electricity is higher than heat, which means that electricity is a more "valuable" energy form than heat. To make them equal, one has to consider the effort of producing them with alternative methods.

[4] See also below where key factors for landfilling are discussed.

consideration of background levels and recipient buffer capacity.
It should also be considered that several operators of WtE plants, e.g. from Austria, Switzerland, The Netherlands and Germany bring their residues to salt mines which could be considered as an environmentally sound storage on the long term as no aftercare is considered necessary due to the final exclusion from the biosphere. Sometimes the residues are used as filler and thus replace natural resources, which otherwise would have been used to refill the salt mine.

Key factors for material recycling
For material recycling, we have found the following key factors to be of importance when compared to incineration:

- Market/demand for recycled material
- Substitution factor
- Energy consumption and emissions at material production from virgin and from recycled materials
- Fate of saved biomass in the forest (paper and cardboard recycling)

Ideally, the recycled material can replace virgin material for the same product. Even though there is a **market/demand for the recycled material**, due to qualitative reasons some of the recycled material cannot be used, leading to a lower **substitution factor**. In effect, more recycled material must then be used to replace a certain amount of virgin material. Furthermore, if there is an international market for collection and sales of recyclables, as for instance for paper, increased collection in one place might partially lead to decreased collection in another place (see e.g. Ekvall 1999 and Olofsson 2004). The virgin production would thus only be partially affected, and the net effect would be; increased recycling in one place leads to a combination of replaced virgin production and increased alternative treatment in another place.
Due to high quality standards, the recycled material might not meet the demands of the market, and thus the material might be "down-cycled", replacing virgin material to some other products (e.g. recycled plastics in plastics palisades replacing wooden palisades).

The choice above has large impacts since it decides what alternative production from virgin materials is avoided. The net benefit of material recycling is also dependent on what **the energy consumption and the emissions are from the production from recycled and virgin material respectively**. The larger the reduction of energy consumption and emissions through recycling, the better the environmental performance of material recycling compared to incineration.

For paper and cardboard recycling specifically, it is also relevant to note the **fate of saved biomass in the forest.** When these waste fractions are recycled, virgin production of paper and cardboard can be replaced, thus leading to a lower consumption of biomass in the forest. The fate of this saved biomass can be different: it can be left in the forest, it can be cut down and used for other material production, or it can be used for energy production, thus replacing alternative electricity and/or heat generation.
Depending on the choice made, the environmental performance of material recycling in comparison to incineration is clearly affected (see e.g. Ekvall 1999 and Finnveden et al 2005).

Key factors for biological treatment (anaerobic digestion, composting)
For biological treatment, we have found the following key factors to be of importance when compared to incineration:

- Emission level
- Market/demand for digestion residue/compost
- Topsoil value of digestion residue/compost

Compared to incineration, the **emission level** for biological treatment facilities is less regulated, and there is thus a larger probability for variations throughout Europe compared to incineration. Today, the processing and the spreading of the rest products on farmland lead to methane and nitrogen emissions (as N_2O and NH_3). These emissions contribute negatively on the environmental performance.

Analogous to material recycling, the environmental performance of biological treatment is dependent on a **market/demand for digestion residue/compost**. Only when there is a demand from the farmers to use the products is it possible to close the loop for recycling of the nutrients in the waste, leading to replacement of other fertilizer production. When there is no market/demand, the digestion residue/compost must be used for other purposes (e.g. land reclamation or as a top layer when old landfills are covered), where the environmental benefits are much smaller.

Normally the digestion residue/compost is credited after its content of phosphorous and nitrogen and sometimes for the content of potassium. The emissions for industrial production of the same amount of these fertilisers are thus deducted from the overall emission. However, in southern Europe there are examples of soils where the topsoil layer is very thin. For these conditions, it might be relevant to attribute a **topsoil value of digestion residue/compost**, since they contribute to thicken the topsoil layer. Sundqvist et al (2002) shows through a simplified example that the energy balance would be significantly improved for anaerobic digestion compared to incineration, if it was assumed that the use of digestion residue would replace peat as soil improver.

Key factors for landfilling

For landfilling, we have found the following key factors to be of importance when compared to incineration:

- The modelling of the landfill (time frame)
- Mechanical-biological pre-treatment
- Carbon sink

Compared to other treatment methods, landfilling is harder to model since the emissions are occurring over a long time period. For example, while CO_2 is emitted directly from incineration, methane from landfilling is mainly emitted during 40-80 years. The task of measuring the emissions is also much harder. One of the specific interests in the **modelling of landfills is the time frame chosen**. This decides how much of the environmentally harming substances will leave the landfill as gas or with the leachate water. There is no general international agreement on how to choose the time frame when modelling landfills. Some modellers use a practical time frame which might range from a couple of decades up to around a century. Others use a so-called surveyable time period. This is the period until the landfill has reached a pseudo steady state, a time period corresponding to approximately one century. As a "worst case" some modellers also use a hypothetical infinite time period, where a complete degradation and spreading of all landfilled material is assumed (Moberg et al 2005). As an example, if only degradation during a century is accounted for, only a small fraction of the plastics are degraded. The major part remains in the landfill unaffected. From a GWP perspective, this makes landfilling of plastics a better option than incineration. However, if a hypothetical infinite time period is chosen, all plastics in the landfill is degraded and emitted as CO_2, thus making incineration the better option as energy is recovered at incineration.

Another key factor for landfilling is if there is **mechanical-biological pre-treatment.** This clearly reduces the possible future emissions from the landfill, e.g. the methane formation is significantly reduced. In Hellweg et al (2003) the mechanical-biological pre-treatment improves the performance of landfilling, but not as much as the ranking between the alternative treatment options is changed.

Finally, another key factor is whether the landfill can be regarded as a **carbon sink.** This is of relevance for the landfilling of renewable material, e.g. paper, wood etc. During a surveyable time period, the cellulose, hemicellulose and lignin in these waste fractions are only partly degraded. The rest of the carbon is thus "stored" in the landfill. In comparison to incineration, where the carbon directly is oxidised to CO_2, this means that CO_2-emissions are avoided during the surveyable time. This could change the order between landfilling and incineration from a GWP perspective. Of course, it is important to stress that this way of modelling emissions contributing to GWP, is only valid when a surveyable time period or shorter is evaluated. For a longer time period, the cellulose, hemicellulose and lignin will degrade into CH_4 and CO_2, thus leading to higher GWP for landfilling than incineration.

4. Conclusions

Based on the findings in the meta-study, we have come to the following conclusions regarding the environmental performance of incineration with energy recovery in comparison to other treatment/recovery methods in Europe:

- Landfilling is the main treatment option in Europe. It is also clearly the worst environmental option according to the system studies.
- Material recycling, waste incineration and biological treatment are *complementary* options that all need to be expanded in order to replace landfilling.
- To reach the best environmental results for material recycling and biological treatment of organic combustible material, waste incineration is necessary for treating residues arising during pre-treatment and processing at the material recycling facilities and the biological treatment plants.
- Due to different local conditions and opportunities for development, the distribution of waste being treated by material recycling, waste incineration and biological treatment must be allowed to vary.
- Regional differences will lead to different distributions being optimal for different regions in Europe.

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