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Working paper on the assessment of environmental pressures and potential environmental impacts from waste management

Prepared by:
European Topic Centre on Waste and Material Flows

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Project manager:
Dimitrios Tsotsos
European Environment Agency

European Environment Agency

This study has been conducted by the European Topic Centre on Waste and Material Flows under commission of the European Environment Agency. The participants of the project team were:

Alejandro Villanueva	ETC/WMF, Copenhagen Office
Roberto Zoboli Daniele Ferrero	CERIS-CNR - Milano. Department of Dynamics of Economic Systems
Maria Gabriella Simeone	APAT - Italian Environmental Protection Agency

Project management:

Rikke Carlsen	ETC/WMF, Copenhagen Office
Dimitrios Tsotsos	European Environment Agency

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1. Background, objectives and the approach of analysis

1.1. Background

The ETC/WMF has been requested by the EEA to develop indicators related to resource consumption and waste generation to be used in the EEA regular reporting activity. The goal is to identify a core set of indicators suitable for assessing the state of the environment, showing progress with respect to policy objectives and targets as set in EU policy documents.

This was the basis for the elaboration of the EEA document: "Towards a core set of indicators on waste and material flows" (ETC/WMF, 2002). In this document, the proposed indicators are organised following the DPSIR framework, developed and used by the EEA. The DPSIR (Driving force-Pressure-State-Impact-Response) is a tool describing in an integrated form the chain of links from the causes of environmental problems to their impacts, and society's responses to them. The tool is useful for organising environmental information and for developing, analysing and presenting environmental indicators to decision-makers.

For the description of the pressures derived from waste management, it has been decided to adopt a vision that allows relating the environmental pressures to the other elements of the DPSIR chain, in particular environmental impacts. An illustration of this is given in Figure 1.1. At present, the studies best adopting this perspective use environmental assessment tools such as EIA (Environmental Impact Assessment) and LCA (Life Cycle Assessment). Therefore, special emphasis is placed on the collection and analysis of existing EIA and LCA studies focusing on waste management as these may help in developing a link between environmental pressures and environmental impacts for waste management.

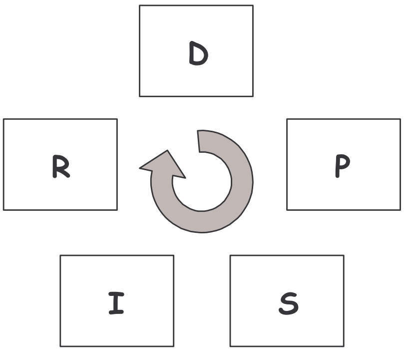
The vision of the present project is to refer the description of the environmental pressures to the EU policy objectives on waste and material flows, canalised by the use of the core set of indicators, against which policy performance can be monitored. The following three overall EU waste and material flow policy objectives have been identified in the ETC/WMF:

I. Sustainable use of natural resources
II. Prevention of waste generation
III. Sustainable waste management

In the development of the core set of indicators (ETC/WMF, 2002), three indicators were selected under (III) to represent the pressures from waste management:

III.3. Greenhouse gas emissions from waste recycling and disposal
III.4. Land use associated with waste recycling and disposal
III.5. Leachate emissions from landfills

The present technical paper responds to the request by EEA to define a methodology for linking pressure indicators and potential impact indicators of waste management activities in the framework of DPSIR (Driving Force-Pressure-State-Impact-Response), which the EEA uses in its integrated assessments. In the DPSIR framework, materials and energy flows that cross the borderline between the human economy and the environment constitute *pressures* influencing the *state* of the environment and leading to certain environmental *impacts*. In some environmental impact areas the cause-effect-chain from *pressures* over *state* to *impacts* is well developed (e.g. resource use, acidification, ozone depletion, global warming) but in other areas (e.g. toxicity to humans and ecosystems) it is still subject of scientific research.



DRIVING FORCES

Consumption /disposal behaviour, increasing material welfare, increasing use of resources and waste generation

PRESSURES

Larger amounts of waste generated

Need to minimise pressures (e.g. emissions) by finding technically and economically feasible and environmentally safe solutions for waste handling & disposal, e.g.:

- **Landfilling**:
  - air emissions (landfill gas)
  - soil & water emissions (leachate)
  - land use requirement
- **Incineration**:
  - air emissions (combustion gas)
  - solid & water emissions (ash, slag, wastewater)
  - land use requirement

STATE

- Percentage of land used for landfills / incineration plants
- Air quality, e.g. CO_2 concentration
- Groundwater quality, e.g. heavy metals concentration

IMPACTS

- Global warming
- Loss of land for other uses (e.g. recreational)
- Loss / dispersion of resources
- Human toxicity, ecotoxocity

RESPONSES

- Installation of flue gas cleaning technology
- Reduction of the landfilling of biodegradable waste

Figure 1.1 The DPSIR indicator framework using as a case study examples of some of the pressures and impacts derived from incineration and landfilling of waste

Source: adapted from Jesinghaus (1999).

The present project aims at establishing a knowledge basis of information on environmental pressures that supports the future work on the development of impact indicators. The present study focuses primarily on the description of the environmental pressures and potential impacts in a format that allows comparison between different waste management strategies. The collection of information in this format creates the basis that allows current and future work on exploring the causality chain between pressures (and pressure indicators) and potential impacts (and impact indicators).

1.2. Objectives

According to the Technical Annex 2003, the ETC/WMF was to elaborate a technical paper on possible frameworks, methodologies and indicators for the assessment of environmental pressures related to waste management and how these can be linked to environmental impacts.

The overall objective of the project is to evaluate the environmental pressures and the environmental impacts related to the generation and management of waste. The long-term objective of the project is to use the produced information to support the ongoing development of indicators for waste and material flows.

The following sub-objectives are defined:

1. To identify and characterise the environmental pressures related to the generation and management of wastes. Management of wastes encompasses in this context different

strategies for the collection, handling, reuse and final disposal of waste. Examples of environmental pressures are emissions to air, emissions to surface water and groundwater, emissions to soil, and use of land. In agreement with the EEA, it was decided by the project team to use as case studies incineration and landfilling. If considered convenient, the study can be extended in a later phase to also cover other waste disposal routes (e.g. recycling, composting).

2. To identify and describe the potential environmental impacts derived from the above-mentioned pressures. Particular emphasis is placed on the identification of environmental impacts that are specific or of special concern for waste generation and management. Examples of impacts are greenhouse effect, acidification, toxicity to humans, or scarcity of land. In agreement with the EEA, it was decided by the project team to focus on the pressures and impacts related to air emissions. If found convenient along the project, other pressures and impacts not related to these could also be described.

3. To describe established linkages between pressures and impacts, and how this is coupled with the ongoing projects of the ETC/WMF on the development of indicators.

2. Environmental pressures and potential impacts from landfilling and incineration of waste

2.1. Landfilling

Landfilling is one of the three existing final disposal routes for waste, the other two being utilisation into other products and the use on land for agriculture purposes. Landfill is the operation of depositing waste on a site, normally engineered and prepared for the storage of waste, and including in some cases systems for the collection of gaseous and liquid emissions. Landfilling is a managed disposal of waste on land. As such, it is distinguished from dumping, which is characterised by the absence of control of the disposal operations and lack of management of the dump site. At present, dumping of waste outside landfills is not allowed in the EU (European Council, 1999), but it still occurs in some parts of the EU.

MSW landfills may receive also other solid and semi-solid wastes, such as industrial waste, household hazardous waste, combustion ashes, construction and demolition waste, agricultural wastes, oil, or mining wastes.

2.1.1. Environmental Pressures

The pressures from establishing and operating a landfill depend on many factors, including the type of waste, and the location, design, operation and age of the landfill. The design of a landfill can vary from a simple hole in the ground where waste is deposited to modern, complex facilities where waste is encapsulated and leachate and gas are collected and treated. There is a huge variation in the characteristics of managed landfills across the EU, and also within member states (Smith et al, 2001).

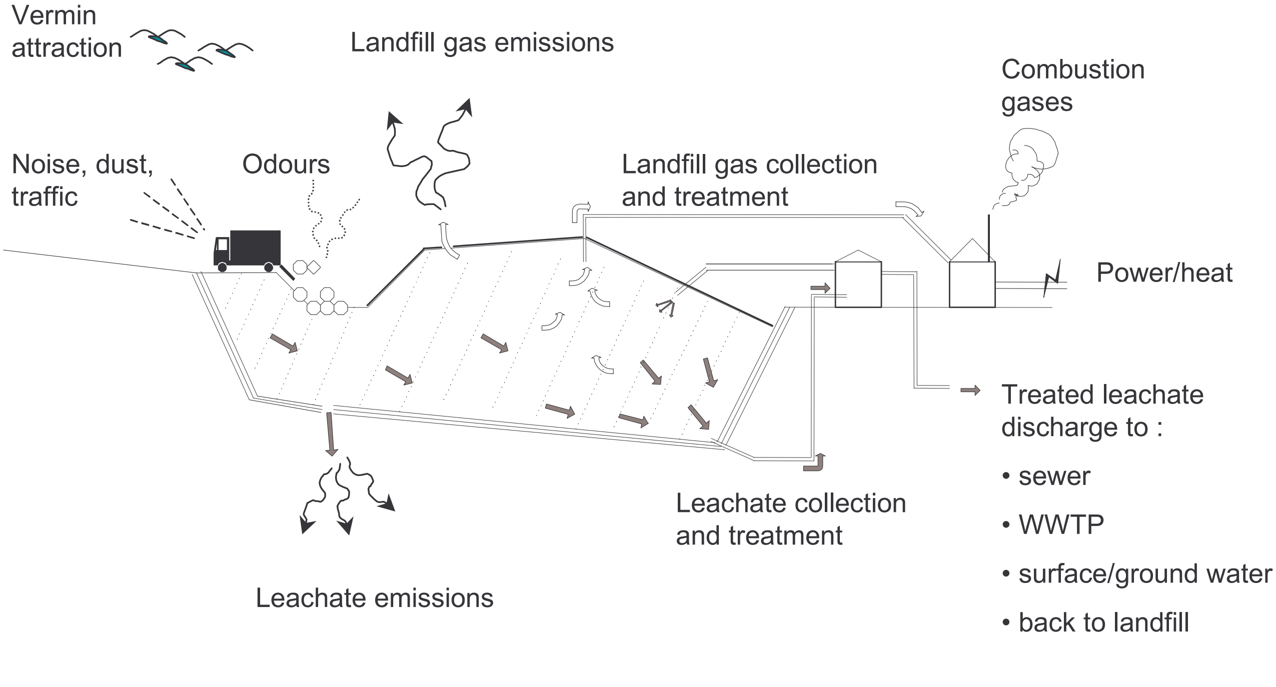


Figure 1.2 Illustration of some of the environmental pressures from a landfill

The pressures generated in a landfill can be classified into inputs and outputs (see also Figure 1.2):

The potential **inputs** to a landfill are:

- Land
- Civil works for construction (excavation, installation of liners, leachate and gas collection and treatment systems, and monitoring systems)
- Civil works for closedown (final capping and sealing, landscaping)
- Landfill on-site operation (energy for leachate treatment, routine works of compaction and topping)
- Collection and transportation of waste
- The loss of the resources contained in waste:
    - Energy content (if no system for energy recovery exists)
    - Inorganic content, e.g. of metals, glass, phosphates.

The potential **outputs** from a landfill are:

- Land released for use after closedown and restoration of the landfill
- Emission of treated leachate to groundwater, surface water, sewer system or wastewater treatment plant (WWTP)
- Emission of untreated leachate to groundwater or surface water through e.g. fractures in the bottom liner
- Emissions to the atmosphere from gas treatment/combustion of landfill gas
- Landfill gas emissions through the top and/or sides of the landfill
- Energy (if landfill gas is used for energy generation)
- Noise, traffic nuisance
- Dust
- Odours
- Vermin attraction
- Risk of accidents (explosions, traffic)

Some of these pressures from the construction, operation and closedown of landfills can result in environmental impacts. Table 1 gives an overview of the pressures and related impacts from waste landfilling

The most important potential environmental impacts are (Christensen and Kjeldsen, 1998):

- the risk of contamination of groundwater and surface water
- the release of gasses contributing to global warming
- the risk of explosion

These three potential impacts presented above are mainly originated from two pressures: landfill gas emissions and leachate emissions. These pressures can result in long-term impacts, whereas the other pressures (noise, vector attraction, dust, odour) only exist during the operation of the landfill. Leachate is produced both in landfills for organic and for inorganic waste. Gas release and explosion risks are only of concern in landfills containing organic waste.

Table 1.1. Overview of pressures from landfilling of waste and the related environmental impacts

	Impact Potential categories									
Pressures ↓	Example of emission / substance	Climate Change	Stratospheric Ozone Depletion	Acidification	Tropospheric Ozone formation (summer smog)	Eutrophication	Ecotoxicity	Toxicity / health effects / disamenity to humans	Depletion of resources (biological and non-biological)	Use and / or degradation of land
Air emissions	CH_4	X	(x)		X					
	CO_2	X								
	VOCs	X	X		X			(x)		
	Dust				(x)					
Leachate to groundwater and soil	Heavy metals						(x)	(x)		(x)
	Salts					X	(x)	(x)		
	Organic substances					X	(x)	(x)		(x)
Noise								X		
Risk of explosion risk	CH_4 accumulation							(x)		(x)
Odours								(x)		
Vermin attraction	Rats, birds						(-)	(x)		
Use/Loss of resources	Phosphorus, metals, paper, glass								X	
	Land									X

Notes:
X: measurable effect
(x): partly or non-measurable effect
(-): minor effect
blank: no known effect
Sources: Cowi (2000), Wenzel and Hauschild (1997), and ETC/WMF elaboration

The generation of gas and leachate from landfills is described in detail in the following.

2.1.2. Landfill gas emissions

A landfill generates during its lifetime gas containing substances from the waste and from the products of the biological and/or chemical reactions taking place inside the landfill. The amount and composition of the gas depends of the disposed waste composition and its age in the landfill. Landfill gas generation is thought to be at a maximum 5-15 years after waste deposition and reaches insignificant amounts after 25 to 35 years (Christensen and Kjeldsen, 1998).

Landfills containing organic waste and having reached steady state conditions emit gas containing mostly CO_2 (25-50%), CH_4 (30-65%) and N_2 (5%), see Table 2.2. CH_4 is formed in the anaerobic areas of a landfill. Most of the CO_2 emissions can be associated to carbon that was fixed by recent biological activity in plant and animal products (Christensen, 1998), and can therefore be considered neutral in a life-cycle perspective. The effects of CH_4 release to the environment are different, because the infrared reflection properties of CH_4 are ca 20-25 times larger than CO_2 on a carbon weight basis, and thereby its contribution to global warming is proportionally higher. Thorneole (1996) estimates that CH_4 contributes to ca 18% of the current global warming, and from this approximately 6-13% is originated in landfills, resulting in a global 1-2% of the global warming gas emissions being originated in landfills. In Europe, the European Commission estimates that landfills contribute to ca 30% of the total anthopogenic CH_4 emissions in 1999 (European Commission, 2001). For other substances emitted from landfills (CO, Volatile Organic Carbons), the share is under 0.1%.

In the absence of gas collection systems, all of the formed landfill gas will eventually be emitted to the atmosphere from the top and sides of the landfill, at quantities and composition varying over time. In landfills where gas collection occurs, different percentages of gas are collected:

- White et al. (1995), estimate the recovery at ca. 40% , whilst the remaining 60% still enters the atmosphere.
- In a recent study on greenhouse gas from solid waste, the US EPA estimates recovery to be from 60 to 80% (75% is most commonly assumed)(USEPA, 2001). From the ca 25% escaping, 10% is converted to CO_2 in the upper landfill layer
- Nielsen and Hauschild (1998) estimate this percentage to be 50% of the total formed.

In addition to CO_2 and CH_4, over 100 different types of other compounds have been identified in the gas from MSW landfills, but their total presence in the gas is less than 1%. Table 2.2. gives an overview of some of these constituents of landfill gas, which include e.g. nitrogen, hydrogen, H_2S, chlorine, argon and VOCs (Volatile Organic Carbons). Some of these gases (CFCs, HCFCs), released from halogenated organic solvents and refrigerants, are strongly reactive with stratospheric ozone. H_2S is potentially hazardous to humans, and benzene and vinylchloride are cancerogenic. In landfills where the landfill gas is collected and flared, CH_4 can be oxidised to CO_2 and the emissions of VOCs can be controlled. The profile of the combustion gases contained a completely different spectrum of substances, including CO_2 , NOx, SO_2, HCl, particulate matter and other combustion products. In some cases, other dioxins can be formed through combustion (Cowi, 2000).

Landfill gases from wastes other than MSW have a significantly different composition than the one described in Table 2.2.

Table 2.2 Composition ranges of gas from MSW reactor landfills.
Sources: Kjeldsen et al (1998); White et al. (1995)

Components of landfill gas		% (in volume) of the gas	
		Minimum	Maximum
Methane	CH_4	30	65
Carbon dioxide	CO_2	25	50
Nitrogen	N_2	5	30
Hydrogen	H_2	1	3
Oxygen	O_2	0	5
Argon	Ar	0	0,4
Hydrogen sulphide	H_2S	0	0,01
Chlorine	Cl	0	0,005
Total VOCs		0,0001	0,5
Ethene		0	0,018
Unsaturated hydrocarbons		0	0,009
Acetaldehyde		0	0,005
Other substances in gas		0	0,003
Vinyl chloride		0,000003	0,0044
Benzene		0,00006	0,0032
Trichloromethane		0,00002	0,0002
Dichloromethane		0,00009	0,049
Toluene		0,0004	0,0197
Xylene		0,00023	0,0139
Ethylenebenzene		0,00036	0,0049
Chloro-di-flouromehthane		0,0006	0,0602
Dichloroflouromethane		0,001	0,0486
TCE, tetrachloroethylene		0,00012	0,0116

Tetrachloroethylene	0,00003	0,011
Ethanole	0,0016	0,145
Propane	0,00041	0,063
Butane	0,00023	0,0626
Carbon disulphate	0,00005	0,0022
Methane ethiol	0,00001	0,043

2.1.3. Landfill leachate emissions

Leachate is generated in a landfill from the water contained in waste and the water from rainfall filtered through the landfill. In non-lined landfills, leachate percolates to the groundwater and may be transported to connected surface water bodies. This can also happen in lined landfills if the membrane has fractures. Depending on the landfill configuration, leachate can also be washed out with surface runoff.

Contamination of surface and groundwater can consist of oxygen depletion due to the high COD content of leachates, more acute in organic wastes, and the presence of high concentrations of salts and/or hazardous substances (e.g. high ammonium concentrations, heavy metal complexes, halogenated organic compounds).

The contamination of groundwater is believed to be limited to a few kilometres around landfill sites, mainly due to the geochemical reactions taking place in the migrating leachate below and in the proximity of the landfill, which oxidise and/or bind the substances from the leachate. This self-cleaning effect indicates that leachate percolation into groundwater may not necessarily result in the contamination of an aquifer (Christensen and Kjeldsen, 1998). When landfills are located in the vicinity of a surface water body or the sea, this self-cleaning effect may not be observed.

Leachate filtration can be avoided by:

(a) Limiting the deposition of wastes to inert wastes, i.e. wastes that do not react with water to form leachate
(b) Building physical, impermeable barriers on the landfill top to limit the filtration of rainwater and bottom impermeable liners to collect the leachate for treatment.
(c) In some existing landfills equipped with bottom membranes, the strategy adopted to avoid uncontrolled leachate filtration is the opposite: leachate formation is enhanced by collection, treatment and recirculation of the leachate within the landfill to accelerate the stabilisation of the waste (Christensen, 1998). This strategy may be combined with active landfill gas collection and treatment.

Leachate quality and especially quantity varies with time. Table 2.3 presents and example of the composition range of leachate from MSW. During the initial phases of the lifetime of a landfill, leachate from MSW contains high concentrations of dissolved organic compounds, salts (ammonia, chloride, sulphate), and heavy metals. However, in later phases (e.g. as a consequence of a pH change), the mobilisation of these substances changes, and the concentration of most substances falls. However, leachate composition data is only available for a period of about 30 years (Cowi, 2000), and the long-term behaviour of leachate generation and composition is unknown.

Table 2.3 Composition ranges of leachate from MSW landfills.

Sources:
/48/ Hjelmar and Christensen (1998), Kjeldsen et al, (1998)
/51/ WQI and CarlBro (1994)
/3/ White et al. (1995)

Constituent of leachate	Max-Min values (mg/l)	Comments	Ref.	Typical values (mg/l)	Comments	Ref.

Sodium	Na	70-7700	Reactor landfill	/48/	104-270	Leaching landfill	/48/
Potassium	K	50-3700	Reactor landfill	/48/	50	Leaching landfill	48/
Calcium	Ca	10-7200	Reactor landfill	/48/	200-340	Leaching landfill	/48/
Magnesium	Mg	30-15000	Reactor landfill	/48/	30-47	Leaching landfill	/48/
Ammonium-N	NH3-N	50-2200	Reactor landfill	/48/	13-28	Leaching landfill	/48/
Sulphate	SO4	8-22000	Reactor landfill	/48/, /51/	<5-450	Leaching landfill	/48/
Chloride	Cl	150-22100	Reactor landfill	/48/, /51/	100-600	Leaching landfill	/48/
BI5		20-57000	Reactor landfill	/48/			
BOD		27-33194		/51/	20	Leaching landfill	/48/
COD		140-152000	Reactor landfill	/48/	130-240	Leaching landfill	/48/
TOC		1-29000	Reactor landfill	/48/,/51/	40-93	Leaching landfill	/48/
EOX					0,010-0,02	Leaching landfill	/48/
Aluminium	Al	2,4		/3/			
Arsenic	As	0,01-1	Reactor landfill	/48/	0,009-0,037	Leaching landfill	/48/
Beryllium	Be	0,0048		/3/			
Cadmium	Cd	0,0001-0,4	Reactor landfill	/48/		Leaching landfill	/48/
Chromium	Cr	0,02-1,5	Reactor landfill	/48/	0,003-0,008	Leaching landfill	/48/
Cobalt	Co	0,005-1,5	Reactor landfill	/48/			/48/
Copper	Cu	0,005-10	Reactor landfill	/48/	0,001-0,011	Leaching landfill	/48/
Flourine	F	0,39		/3/			
Iron	Fe	3-5500	Reactor landfill	/48/	0,0035-0,260	Leaching landfill	/48/
Mercury	Hg	0,00005-0,16	Reactor landfill	/48/		Leaching landfill	/48/
Nickel	Ni	0,015-13	Reactor landfill	/48/	0,007	Leaching landfill	/48/
Lead	Pb	0,001-5	Reactor landfill	/48/	0,0002-0,006	Leaching landfill	/48/
Strontium	Sr	1		/51/			
Zinc	Zn	0,03-1000	Reactor landfill	/48/	0,1-0,6	Leaching landfill	/48/
Organic nitrogen		14-2500	Reactor landfill	/48/			
Total-P		0,1-23	Reactor landfill	/48/			
Hydrogen carbonate	HCO3	610-7320	Reactor landfill	/48/			
Manganese	Mn	0,03-1400	Reactor landfill	/48/			
Silicate	SiO3	4-70	Reactor landfill	/48/			
Aromatic hydrocarbons		up to 12300	Reactor landfill	/48/			
Chlorinated hydrocarbons		up to 3810	Reactor landfill	/48/			
Phenols		up to 2100	Reactor landfill	/48/			
Pesticides		1-90	Reactor landfill	/48/			

2.1.4. Other pressures from landfills

The most important pressures from landfills besides air and water emissions are described briefly in the following:

Land use
Landfill disposal needs land, which cannot be used for other purposes during the time of operation of the landfill. This land can be covered with soil and used again for certain purposes (e.g. recreation, landscape) after some decades, normally more than 50 years, when the monitoring of emissions shows that the waste is stabilised.
The use of land for landfilling is easily quantifiable.

Odour
Some of the gases generated in landfills such as SH_2 and organic sulphur compounds (e.g. mercaptanes, methylsulfides) have unpleasant odour. The release of these gases occurs mainly during transportation and disposal of the waste in the active front of the landfill and during the movement of waste within the landfill, when anaerobic areas get exposed to the atmosphere

(Christensen, 1998). The odours can be limited by (a) preventive measures, such as reduction of the organic content of wastes and (b) correction measures, such as re-location and reduction of the active deposition front.

Noise and traffic

Noise and traffic in landfills is generated by the waste transport and handling machinery. Noise can be limited by e.g. constructing noise barriers such as embankments and tree fronts and by locating the active deposition front at convenient distance from inhabited areas. Noise disturbances caused by landfilling are easily quantifiable.

Vermin attraction

Some animals such as rodents, birds and insects are attracted by the possibility of feeding from organic wastes in landfills. Some of these can spread and/or transmit illnesses, in particular from infected waste, and are therefore a potential hygienic problem.

Explosion risks

Landfill gas can be inflammable when methane mixes with air at percentages exceeding 5-10%, and there is a spark that triggers the explosion, e.g. in close-located buildings or from the machinery (Christensen et al, 1998). The inflammability is relatively insensitive to the presence of other gas constituents. The risk of explosion can be reduced by limiting the deposition of organic waste and installing a gas collection system.

Besides air emissions, all the pressures from landfills are characterised by being local, i.e. they mainly affect the surroundings (normally up to 1-2 km) of the landfill sites. Opposition from residents is the major reason for the difficulties that the authorities of most EU countries find for the designation of new landfill sites. In the designation of new sites, the not always quantifiable pressures mentioned above will exert the dominant influence, whereas air emissions of greenhouse gasses and ozone depleting gases do not score so high (Smith et al, 2001).

In the context of the life-cycle perspective encouraged by the recent EU policies on waste, an important (and quantifiable) impact from landfilling is the loss of the resources contained in waste. The energy content, mainly stored in the form of carbon compounds (fossil such as plastics and non-fossil such as paper and biomass) may be partially recovered in landfills equipped with systems for energy recovery from gas. On the other hand, the inorganic content, e.g. of metals, glass or phosphates, is lost. Very few studies exist which encompass the loss of resources in landfilling of MSW. An attempt to develop indicators to make quantitative estimations of the loss of resources due to landfilling of waste in Denmark is described in Dall et al (2003).

2.1.5. State of the art of the estimation (modelling) of landfill gas and leachate emissions

The estimation of the emissions from landfills is complicated, and reliable data on the emissions from a given product when it is landfilled are lacking. One of the research fora where there is a demand for such information is the international LCA research community. In this community, it is acknowledged that the currently existing LCA models lack a description of the emissions from waste management of products (Nielsen and Hauschild, 1998). LCA models aim at following the emissions of a product's life "from cradle to grave", but the currently existing models currently describe very poorly "the grave", i.e. the processes and emissions occurring when a product (waste) is handled by e.g. incineration or landfilling.

Unfortunately, the emissions from a product in e.g. a landfill cannot be determined by measurements, because the emissions from different products in a landfill are mixed, and in addition are emitted at an unknown time in the future. To estimate such emissions it is necessary to create mathematical models of the physical, biological and chemical processes (evaporation, leachate formation) occurring inside a landfill along its lifetime.

Various models have been developed from the early 1990's which attempt to quantify the landfill gas and leachate generation from different products and mixtures of wastes These models have different degrees of complexity and incorporate a different number of the variables that are believed to influence the gas and leachate formation processes. The variables that determine the amount and composition from waste products disposed at landfills can be merged in two groups:

- The physical, chemical and biological conditions in the landfill
- The composition of the waste product, and the physical and chemical properties of its components

For example, the most important factor affecting the production of landfill gas are (Bates and Haworth, 2001):

- the waste composition, and in particular:
    - the amount of biodegradable carbon
    - presence / absence of growth promoting and growth inhibiting compounds

- the characteristics of the landfill, including:
    - rainfall/evaporation balance and resulting moisture content of the waste
    - atmospheric pressure
    - temperature
    - pH
    - oxygen content and infiltration
    - depth of waste in the landfill site
    - age of the landfill
    - presence, type and operation of capping and landfill gas collection system.

The generation of landfill leachate has also been modelled using different approaches, from simple massbalances to complex hydrogeological models (Christensen, 1998). Leachate formation is believed to be governed, among others, by the following variables:

- waste composition

- characteristics of the landfill and the underground layers, including:
    - depth of waste in the landfill site
    - age of the landfill
    - soil geophysical parameters such as porosity and permeability
    - soil geochemistry
    - rainfall/evaporation balance and resulting moisture content of the waste
    - location and movement of groundwater
    - groundwater composition atmospheric pressure, oxygen content and infiltration
    - temperature
    - pH

The existing models are able to estimate emissions for a time frame of about 100 years. Beyond this horizon there are large uncertainties about the processes and behaviour of landfills, and the estimates produced by models are not as reliable (Gabriel and Nielsen, 1998). The estimation is made more complex by the changes in the composition of the waste landfilled.

Simple models require a modest effort of collection of information from the specific waste and the landfill studied, but are characterised by the need to establish important assumptions (% of capture of formed gas, % of precipitation entering the waste, % degradation of organic compounds, efficiency of leachate treatment, etc.) and the results have large uncertainty ranges. More sophisticated models demand information which is hardly available and/or expensive to obtain.

2.2. Incineration

Incineration is an intermediate treatment technology for waste. Incineration has certain advantages, which can be the reason for its implementation:

- The volume of waste is reduced to ca 10% of the original, and the weight to ca 20-30% of the original. This reduces the costs of further handling and disposal.
- The final solid residue is sterile (although not inert, since it still can leak dissolved inorganic substances)
- Incineration ovens have the possibility of generation of heat and power

Incineration of waste in the EU is followed by thorough aftercare of the gaseous, liquid and solid emissions from combustion, in the terms established in the EU Directive 2000/76/EC.

Incineration facilities exist for most waste streams, sometimes MSW may receive also other solid and semi-solid wastes, such as sewage sludge, industrial waste, household hazardous waste, hospital wastes, agricultural wastes, or waste oil. Hazardous waste is normally incinerated in special incineration plants. In order to obtain good combustion conditions and an efficient flue gas cleaning, it is necessary that the composition of the waste mixture is stable. Strong deviations from the average heating value of the waste may result in malfunctioning of the plant.

2.2.1. *Environmental Pressures*

The pressures from establishing and operating a MSW incineration plant depend on many factors, including the composition of the waste, the design of the oven, its operation and age, and the facilities for flue gas treatment.

The pressures generated in a landfill can be classified into inputs and outputs (see also Figure 2.2):

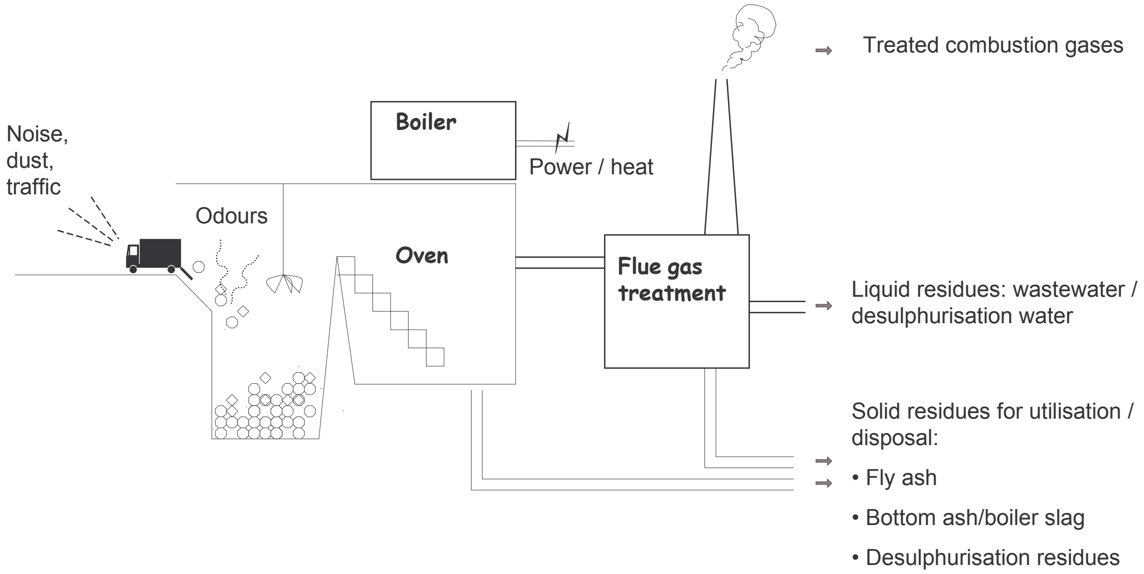


Figure 2.2 Illustration of some of the environmental pressures from an incineration plant

The potential **inputs** to an incinerator are:

- Land
- Civil works for construction (excavation, buildings, equipment)
- Operation (energy, labour, maintenance, materials for flue gas cleaning)

- Collection and transportation of waste to the plant
- The loss of the resources contained in waste:
  - Inorganic content, e.g. of metals, glass, phosphates.
  - Energy content (if no system for energy recovery exists)

The potential **outputs** from an incineration plant are:

- Land released for use after closedown and restoration of the plant site
- Emissions to the atmosphere of treated combustion gas
- Emission of treated wastewater to sewer or surface water
- Generation of solid residues: ashes, slag, desulphurisation residues
- Energy (if energy generation equipment is installed)
- Noise, traffic nuisance
- Dust
- Odours

Some of these pressures from the construction, operation and closedown of incineration plants can result in environmental impacts. Table 2.4 below gives an overview of the pressures and related potential impacts from waste incineration.

Table 2.4 Overview of pressures from incineration of waste and the related environmental impacts

	Impact Potential categories									
Pressures ↓	Example of emission /substance	Climate Change	Stratospheric Ozone Depletion	Acidification	Tropospheric Ozone formation (summer smog)	Eutrophication	Ecotoxicity	Toxicity / health effects / dissamenity to humans	Depletion of resources (biological and non-biological)	Use and / or degradation of land
Air emissions	CO_2	X								
	CO	X			X			(x)		
	SO_2	(x)		X				X		
	VOCs	X	(x)		X		(x)	X		
	Dioxins						X	X		
	NO_x	(x)		X	(x)	X		X		
	Dust, particulates				(x)			X		
	HCl,HF			X				X		
	Heavy metals						X	X		
Wastewater emissions to sewers / water bodies	Salts									
	Heavy metals						(x)	(x)		(x)
	Organic substances (e.g. dioxins)					X	(x)	(x)		(x)
Noise								X		
Odours								(X)		
Generation of solid residues	Stable (e.g. slag)								(if landfilled)	
	Potentially leaking (ashes, desulphurisation residues)						(x)	x	(if landfilled)	(x)
Use/Loss of resources	Phosphorus, metals, paper, glass								X	
	Land									X

Notes:
X: measurable effect
(x): partly or non-measurable effect
(-): minor effect

blank: no known effect
Sources: Cowi (2000), Wenzel and Hauschild (1997) and ETC/WMF elaboration

The most important potential environmental impacts from incineration are (Hjelmar, 1998, Dalager, 1998):

- The release of gasses to the atmosphere:
    - Contributing to global warming (e.g. CO_2, CO)
    - Contributing to stratospheric ozone depletion (e.g. CFCs)
    - Contributing to acidification (e.g. SO_2, NOx, HCl)
    - Contributing to tropospheric ozone formation (e.g. particulates, CO)
    - That are potentially hazardous to humans (e.g. heavy metals, VOCs, dioxins)

- The risk of contamination of groundwater and surface water from inappropriate storage / landfilling of flue gas cleaning residues solid residues with leaching potential, e.g.:
    - Fly ashes
    - Desulphurisation residues

  If well managed, the potential environmental impact from these residues can be controlled.

An important difference between the potential impacts derived from these two pressures is the time dimension: whereas air pollutants are released in the moment of incineration, the release of the substances contained in incineration ashes and desulphurisation residues does not happen until water penetrates in the residue.

Most of the potential impacts from the other pressures in Table 2.4 (noise, dust, odour, loss of resources) stop at the very moment incineration stops.

Some incineration plants, particularly those of recent construction, have the possibility of using the energy of waste for heat and / or power generation. Energy is mainly stored in the form of carbon compounds (fossil such as plastics and non-fossil such as paper and biomass). On the other hand, the inorganic content, e.g. of metals, glass or phosphates, is lost. Some of the materials in waste are partially utilised in applications such as the use of incineration slag as filling material for road construction. This utilisation is based on the bulk volume and low leachability of slag, but not on the intrinsic value of the substances it contains.

2.2.2. Air emissions from waste incineration

Air emissions are not the only pressure generated from incineration, but they are associated to the main public concerns and relatively extensive information and data are available for them. Abundant information of high quality is available on e.g. the emitted substances, and the equipment necessary to control the emissions.

An emission catalogue has been made based on the existing combinations of combustion technologies:

- M1= Mass burn excess air combustors
- M2= Modular excess air combustors
- M3= Mass burn waterwall combustors
- M4= Refuse derived fuel-fired combustors

and flue gas cleaning equipment:

- I1 = particle removal by electrostatic precipitator (EPS)
- I2 = particle removal (EPS) and dry/semidry flue gas cleaning
- I3 = particle removal (ESP) and wet flue gas cleaning
- I4 = particle removal (ESP), dry/semidry flue gas cleaning, DeNOx and dioxin removal
- I5 = particle removal (ESP), wet flue gas cleaning and DeNOx
- I6 = particle removal (ESP), wet flue gas cleaning and dioxin removal

- I7 = particle removal (ESP), wet flue gas cleaning, DeNOx and dioxin removal

The seven different combinations of flue gas treatment technologies are illustrated in Figure 2.3 (Erichsen and Hauschild, 2000).

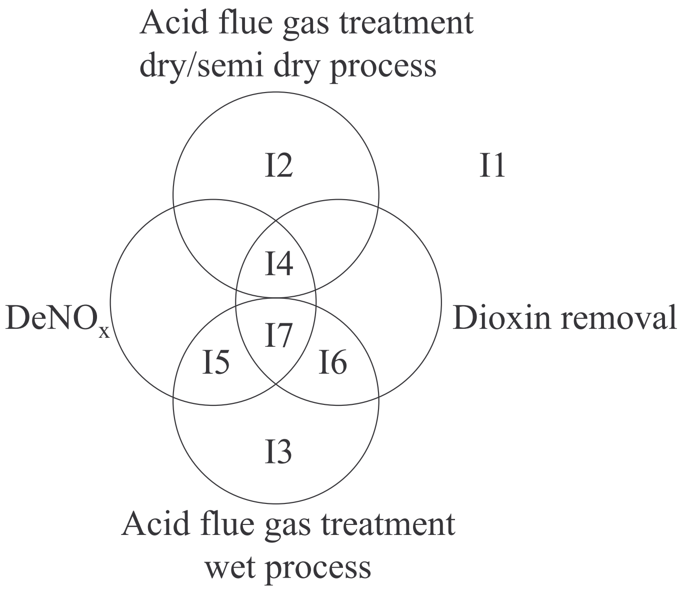


Figure 2.3 The different combinations of flue gas treatment technologies for waste incineration
Source: Erichsen and Hauschild (2000)

In the following, a series of tables is presented including air emission factors for MSW Incineration plants. There is a large amount of data available on emissions, and many of the emission factors are usually of high quality. Categories with only limited data and low quality data have not been considered. Two main sources of information have been used:

- EEA (1997) Emission Inventory Guidebook, Waste treatment and disposal- CORINAIR - SNAP 97. European Environment Agency
- USEPA (1993) Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: Stationary Point and Area Sources, Chapter 2 Solid Waste Disposal-Incineration
- IPCC- Intergovernative Panel on Climate Change (1996a) Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories & Guidelines for National Greenhouse Gas Inventories: the Workbook (Volume 2), Module 6 – Waste

The overall mass balance is in general terms similar for all conventional types of incineration plants. Of every tonne of MSW incinerated (containing in average 70% of humidity), ca ¾ of its weight goes to the atmosphere as water vapour and CO_2 and ca ¼ is kept as a solid residue, which has to be utilised or disposed of, depending on its characteristics. The incineration of one tonne of MSW requires the use of 6 tonnes of air (1.26 tonnes of O_2) and produces 6.7 tonnes of flue gases (Dalager, 1998).

The main substances of interest in the flue gas are (see also Table 2.4 above):

- Particulate Matter (PM)
- Greenhouse gases: CO_2, and in much smaller amounts CO, N_2O, CH_4
- NOx
- SOx and other acid gases (HCl, HF)
- Heavy metals
- Organic pollutants (PCBs, Dioxins)

Particulate Matter (PM)

The amount of PM exiting the furnace of an MSW combustor depends on the waste characteristics, the physical nature of the combustor design, and the combustor's operation. Under normal combustion conditions, solid fly ash particulates formed from inorganic, non combustible constituents of MSW are released into the flue gas. Most of this particulate is captured by the facility's Air Pollution Control Devices (APCD) and are not emitted to the atmosphere.

Particulate matter can vary greatly in size with diameters ranging from less than 1 micrometer to hundreds of micrometers (µm). Fine particulates, having diameters less than 10µm (known as PM-10), are of increased concern because a greater potential for inhalation and passage into the pulmonary region. Furthermore, acid gases, metals, and toxic organics may preferentially adsorb onto particulates in this size range.

The level of PM emissions at the inlet of the APCD will vary according the combustor design, air distribution, and waste characteristics. For example, facilities that operate with high underfire/overfire air ratios or relatively high excess air levels may entrain greater quantities of PM and have high PM levels at the APCD inlet. For combustors with multiple-pass boilers that change the direction of the flue gas flow, part of the PM may be removed prior to the APCD. Lastly, the physical properties of the waste being fed and the method of feeding influences PM levels in the flue gas. Typically, RDF units have higher PM carryover from the furnace due to the suspension-feeding of the RDF. However, controlled PM emissions from RDF plants do not vary substantially from other combustors, because the PM is efficiently collected in the APCD.

Table 2.5 Emission factors for PM

Tipology of plant	Pollutant control lay-out	Emission factor (kg/t)	Source
Mass burn and modular excess air combustors	Spray dryer + Electrostatic Precipitator	0,0352	US EPA (1997)
	Spray dryer + Fabric Filter	0,0311	
Refuse derived fuel-fired combustors	Spray dryer + Electrostatic Precipitator	0,0482	
	Spray dryer + Fabric Filter	0,0664	
Not specified	Particle abatement only	0,3000	CORINAIR, EEA (1997)

Greenhouse gases

Waste incineration, like other types of combustion, is a source of greenhouse gases (GHG) emissions. Few data have been compiled on the global emissions from waste incineration.

Carbon dioxide

Waste incineration produces CO_2, but it is difficult to identify the portion that should be considered net emissions. A large fraction of the carbon in waste combusted (e.g. paper, food waste) is derived from biomass raw materials which are replaced by regrowth. These emissions should not be considered net anthropogenic CO_2 emissions in the IPCC Methodology (IPCC, 1996a). On the other hand, some carbon in waste is in the form of plastics or other products based on fossil fuels. Combustion of these materials, like fossil fuel combustion, releases net CO_2 emissions. In estimating emissions from waste incineration, the desired approach is to separate carbon in the incinerated waste into biomass and fossil fuel based fractions. Only the fossil-based portion should be considered net carbon emissions.

Table 2.6 Emission factors for CO_2 - Baseline emission factor (no NOx abatement)

Tipology of plant	Emission factor (kg/t)	Source
Mass burn waterwall combustors	985	US EPA (1993)
Not specified	560	IPCC (1996c)(*)

(*) Calculated assuming carbon quote in MSW=40%, biogenic carbon quote=40% and combustion efficiency = 95%

Methane
Emissions of CH_4 are not likely to be significant because of the aerobic combustion conditions in incinerators (e.g. high temperatures, excess of oxygen and long residence times). Emissions of CH_4 from waste incineration are highly uncertain. An expert working group recognised waste incineration as a source of methane production, but was not able to give global estimates or default emissions factors. Although this source is considered to be relatively small compared to the other CH_4 sources in waste (e.g. landfilling), it was recognised as an area for further research in the future

Nitrous Oxide
Recent studies have also shown that N_2O may be an important GHG produced from incineration. Table 2.7 provides data from studies of several incineration plants and the N_2O produced from the waste incineration. Normally, emissions of CO_2 from waste incineration are significantly greater than N_2O emissions.

Table 2.7 Emission factors for N_2O

Tipology of plant	Emission factor (g/t)	Source
Not specified	100	CORINAIR, EEA (1997)
Not specified	11-293	IPCC(1996c)

Carbon monoxide (CO)
Carbon monoxide emissions result when all of the carbon in the waste is not oxidized to carbon dioxide (CO_2). High levels of CO indicate that the combustion gases were not held at a sufficiently high temperature in the presence of oxygen (O_2) for a long enough time to convert CO to CO_2. As waste burns in a fuel bed, it releases CO, hydrogen (H_2), and unburned hydrocarbons. Additional air then reacts with the gases escaping from the fuel bed to convert CO and H_2 to CO_2 and H_2O. Adding too much air to the combustion zone will lower the local gas temperature and retard the oxidation reactions. If too little air is added, the probability of incomplete mixing increases, allowing greater quantities of unburned hydrocarbons to escape the furnace. Both of the conditions would result in increased emissions of CO.

Because O_2 levels and air distributions vary among combustor types, CO levels also vary among combustor types. For example, semi-suspension-fired RDF units generally have higher CO levels than mass burn units, due to the effects of carryover of incompletely combusted materials into low temperature portions of the combustor, and, in some cases, due to instabilities that result from fuel feed characteristics. Carbon monoxide concentration is a good indicator of combustion efficiency, and is an important criterion for indicating instabilities and nonuniformities in the combustion process. It is during unstable combustion conditions that more carbonaceous material is available and higher CDD/CDF and organic hazardous air pollutant levels occur. The relationship between emissions of CDD/CDF and CO indicates that high levels of CO (several hundred parts per million by volume [ppmv]), corresponding to poor combustion conditions, frequently correlate with high CDD/CDF emissions. When CO levels are low, however, correlations between CO and CDDs/CDFs are not well defined (due to the fact that many mechanisms may contribute to CDD/CDF formation), but CDD/CDF emissions are generally lower. Emissions of carbon monoxide do not depend on pollutant control lay-out.

Table 2.8 Emission factors for CO

Tipology of plant	Emission factor (kg/t)	Source
Refuse derived fuel-fired combustors	0,960	US EPA (1993)
Mass burn waterwall combustors	0,232	US EPA (1993)

Not specified	0,700	CORINAIR , EEA (1997)

Nitrogen oxides (NO_X)

Nitrogen oxides are products of all fuel/air combustion processes. Nitric oxide (NO) is the primary component of NO_X ; however, nitrogen dioxide (NO_2) and nitrous oxide (N_2O) are also formed in smaller amounts. The combination of the compounds is referred to as NO_X . Nitrogen oxides are formed during combustion through oxidation of nitrogen in the waste, and fixation of atmospheric nitrogen. Conversion of nitrogen in the waste occurs at relatively low temperatures (less than 1.090 °C), while fixation of atmospheric nitrogen occurs at higher temperatures. Because of the relatively low temperatures at which furnaces operate, 70 to 80 percent of NOx formed in MSW incineration plants is associated with nitrogen in the waste.

Table 2.9 Emission factors for NO_X - Baseline emission factor (no NOx abatement)

Tipology of plant	Emission factor (kg/t)	Source
Refuse derived fuel-fired combustors	2,51	US EPA (1993)
Mass burn waterwall combustors	1,83	US EPA (1993)
Not specified	1,80	CORINAIR, EEA (1997)

Acid gases

The main acid gases of concern from the combustion of MSW are HCl and SO_2 . Hydrogen fluoride (HF), hydrogen bromide (HBr), and sulphur trioxide (SO_3) are also generally present, but at much lower concentrations. Concentrations of HCl and SO_2 in MSW combustor flue gases directly relate to the chlorine and sulphur content in the waste. The chlorine and sulphur content vary considerably based on seasonal and local waste variations. Emissions of SO_2 and HCl from municipal waste incinerators depend on the chemical form of sulphur and chlorine in the waste, the availability of alkali materials in combustion-generated fly ash that act as sorbents, and the type of emission control system used. Acid gas concentrations are considered to be independent of combustion conditions. The major sources of chlorine in MSW are paper and plastics. Sulphur is contained in many constituents of MSW, such as asphalt shingles, gypsum wallboard, and tires. Because refuse derived fuel (RDF) processing does not generally impact the distribution of combustible materials in the waste fuel, HCl and SO_2 concentrations for mass burn and refuse derived fuel units are similar.

Table 2.10 Emission factors for acid gases

Tipology of plant	Pollutant control lay-out	Emission factor (kg/t)		Source
		SO2	HCl	
Refuse derived fuel-fired combustors	Spray dryer + Fabric Filter	0,221	0,0264	US EPA (1993)
	Spray dryer + Electrostatic Precipitator	0,799	ND	
Mass burn and modular excess air combustors	Spray dryer + Fabric Filter	0,277	0,106	US EPA (1993)
	Spray dryer + Electrostatic Precipitator	0,327	0,079	
Not specified	Acid gas abatement	0,400	0,500	CORINAIR EEA (1997)

Toxic pollutants

Toxic pollutant includes inorganic (mainly metals) and inorganic compounds.

Metals

Metals are present in a variety of MSW streams, including paper, newsprint, wood, batteries, and metal cans. The metals present in MSW are emitted from incinerators either in association with particulate matter (e.g., As, Cd, Cr, and Pb) and as vapours, such as Hg. Due to the variability in MSW composition, metal concentrations are highly variable and are essentially independent of the combustor type. If the vapor pressure of a metal is such that condensation onto particulates in the flue gas is possible, the metal can be effectively removed by the particulate matter control device. With the exception of Hg and sometimes Cd, most metals have sufficiently low vapour pressures to result in almost all of the metals being condensed. Therefore, removal in the particulate matter control device for these metals is generally greater than 98 %. Mercury, on the other hand, has a high vapour pressure at typical abatement system operating temperatures, and capture by the particulate matter control device is highly variable.

Table 2.11 Emission factors for metals

Pollutant	Emission factor (g/t)				
	Source: US EPA (1993)				Source: CORINAIR, EEA (1997)
	Mass burn and modular excess air combustors		Refuse derived fuel-fired combustors		Particle and acid gas abatement
	Spray dryer + Fabric Filter	Spray dryer + Electrostatic Precipitator	Spray dryer + Fabric Filter	Spray dryer + Electrostatic Precipitator	Not specified
As	0,0212	0,00685	0,00259	0,00541	
Cd	0,0136	0,00376	0,01660	0,04180	0,10000
Cr	0,0500	0,13000	0,02040	0,05440	
Hg	1,1000	1,63000	0,14600	0,21000	1,10000
Ni	0,0258	0,13500	0,03150	0,09640	
Pb	0,1310	0,45800	0,51900	0,57700	0,80000

Organic toxic pollutants
A variety of organic compounds, including dioxins and furans (CDDs/CDFs), chlorobenzene (CB), polychlorinated biphenyls (PCBs), chlorophenols (CPs), and polyaromatic hydrocarbons (PAHs), are present in MSW or can be formed during the combustion and post-combination processes. Organics in the flue gas can exist in the vapor phase or can be condensed or absorbed on fine particulates. Control of organics is accomplished through proper design and operation of both the combustor and the APCDs. Based on potential health effects, dioxin has been a focus of many research and regulatory activities. Due to toxicity levels, attention is most often placed on levels of dioxins in the tetra-through octa- homolog groups and specific isomers within those groups that have chlorine substituted in the 2, 3, 7, and 8 positions. So dioxin and furan concentrations are usually expressed in term of so-called "TEF": a weighed average of concentrations of various kind of dioxins, related with most toxic one (2,3,7,8 TCDD).

Table 2.12 Emission factors for dioxins

Tipology of plant	Pollutant control lay-out	Emission factor		
		US EPA (1993)	CORINAIR, EEA (1997)	EU MSW incineration Directive (*)
Mass burn waterwall combustors	Spray dryer + Fabric Filter	0, 0331 mg/t		
	Spray dryer + Electrostatic Precipitator	0, 3110 mg/t		
Refuse derived fuel-fired combustors	Spray dryer + Fabric Filter	0,01220 mg/t		
	Spray dryer + Electrostatic Precipitator	0,05310 mg/t		
Not specified	Particle and acid gas abatement		0,5 μg TEF(**)/t	<0.6 μg TEF/t

(*) The emission factor is estimates assuming dioxins concentration minus or equal to legal concentration requirements (0,1 ng TEF/m^3).
(**) TEF: weighed average of concentration of various kind of dioxins, related with most toxic one (2,3,7,8 TCDD).

With the aim to completeness, the following table shows emission factor for other organic toxic pollutants. The only source is CORINAIR – SNAP 97 (EEA, 1997). The abatement type is "Particle and acid gas abatement" in all cases.

Table 2.13 Emission factors for dioxins

Compound	Emission factor
PCB (IUPAC No. 77)	1,6 µg/t
PCB (IUPAC No. 126)	1,7 µg/t
PCB (IUPAC No. 169)	1,2 µg/t
Fluoranthene	145 mg/t
Benz[a]anthracene	4,2 mg/t
Benzo[bk]fluoranthene	6,3 mg/t
Benzo[a]pyrene	0,7 mg/t
Dibenzo[ah]anthracene	3,5 mg/t

Source: EEA (1997)

2.2.3. Solid and liquid emissions from incineration

Waste incineration results in a volume reduction to ca 10% of the original, and the weight reduction to ca 20-30% of the original. Various final residues are generated, and these have to be handled appropriately. The residues generated are (Hjelmar, 1998):

- Residues of combustion, i.e. non-combusted material, for example:
    - Slag / bottom ash
    - Grate residue

- Flue gas cleaning residues for removal of certain substances from the gas, for example:
    - Boiler ash
    - Fly ash
    - Residues from acid gas cleaning (e.g. desulphurisation gypsum)
    - Wastewater (from wet flue gas cleaning)

The amounts and characteristics of the residues depend on the composition of the waste, the flue gas cleaning technology used, the age of the plant and the operation conditions of the plant. A brief description of the residue types is given in the following, and a summary of the generation factors is given in Table 2.14.

Table 2.14 Typical order of magnitude of the generation of residues from waste incineration

Residue	Kg/tonne incinerated waste	Notes
Slag/bottom ash	250-400	
Grate residue	5	Data from only one plant
Boiler ash	2-12	
Economiser ash	No data	
Fly ash	10-30	
Residues from acid gas cleaning		
Dry process	20-50	Including 10-30 kg fly ash/tonne waste
Semi-Dry process	15-40	
Wet process	1-3	Dry weight of the sludge from the wastewater

Source: Hjelmar (1998)

Slag / bottom ash

Is by large the most voluminous residue stream, with approximately 250-400 kg/tonne waste. Is a very inhomogeneous material, and depending on the technology used and the way it is cooled down, it can be a granulate or consist of large clumps with attached iron scrap and non-combusted material. The non-combusted material does not normally exceed a few percent.

Grate residue

Consists of combusted and non-combusted particles and melted material (e.g. lead, tin) falling through the grate system in the furnace. In some places it is mixed with the slag, in other incinerators it is collected separately and fed again to the furnace. This last practice is becoming more and more common, since higher quality standards are required to slag to be utilised and not disposed of.

Boiler ash

Consists of coarse ash particles that deposit from the flue gas stream shortly after combustion, and in some cases can cover completely the internal surface of the boiler. It accounts for ca 1-3% of the total ash generated. Sometimes is collected separately, and sometimes mixed with the slag.

Fly ash

In incinerators with dry flue gas cleaning systems, fly ash is collected in the energy economiser and the flue gas filters for particulate matter (electrostatic filter or bag filter). Normally, 10-30 kg/tonne waste are generated. In systems with wet scrubbers, it has the form of sludge, otherwise is has the consistency of a fine powder.

Residues from acid gas cleaning

In incinerators with dry and semidry flue gas cleaning systems, pulverised lime is used to adsorb the acid gases. The reaction products are mostly calcium chloride (from removal of HCl) and gypsum (from removal of SO_2). In incineration plants where the fly ash removal system is not installed before the acid gas cleaning, a mixed residue containing fly ash, calcium chloride and gypsum is obtained. Other substances contained in the gas of attached to the ash particles (e.g. dioxins, heavy metals) are also found in this residue.

Wastewater (from wet flue gas cleaning)

Wastewater is obtained in wet flue gas cleaning for acid gases. There are several possible combinations of wet, semi-dry and dry processes for flue gas cleaning, where the corresponding residues are wastewater, sludge or solid residues. Depending on local conditions such as the feasibility to discharge wastewater to a sewer or dispose of solid residues in a landfill, wastewater can e.g. be sprayed into the flue gas to obtain a dry residue. Wastewater, sludge and fly ash are in some locations mixed and landfilled together as a mixture.

In some countries (e.g. USA) slag is mixed with the rest of residues and the mixture is landfilled. In other countries, e.g. Denmark, Netherlands and Germany, the utilisation of the residues is prioritised. Slag has a large potential for utilisation as a filling material in construction, in some cases after some treatment, but fly ashes and acid gas residues contain much higher concentrations of soluble salts and heavy metals, and therefore it is preferred to handle these streams separately. In most cases, a comprehensive treatment would be required in order to be able to utilise fly ashes and /or acid gas treatment residues. The residues for which no utilisation route has been found are currently landfilled.

In some countries, one of the reasons for mixing the residues and disposing of them in a combined form is that e.g. fly ash has high concentrations of hazardous substances and therefore it is classified as hazardous waste. In a mixture with slag, these substances are “diluted” to a concentration in the mixed residue that makes it not being classified as hazardous waste, and can be landfilled as generic waste.

The physical, chemical and geotechnical characteristics of residues are important parameters in connection to the utilisation and disposal of residues. In connection with the risks of environmental impact, the major concern is related to the leaking of e.g. salts and heavy metals, either in a landfill or in e.g. a road where slag has been used as filling material. An investigation of the leachability of substances from a given residue is normally performed in the laboratory, accelerating the natural wash-out processes occurring in the full scale scenario.

2.2.4. Other pressures from waste incineration

The most important pressures from waste incineration besides air and solid emissions are described briefly in the following:

Land use
Incineration plants need land, which cannot be used for other purposes during the time of operation of the plant. The land occupied by the incineration plants is easily quantifiable.

Odour
Waste emits SH_2 and organic sulphur compounds (e.g. mercaptanes, methylsulfides), which have unpleasant odour. The release of these gases occurs mainly during transportation and storage of the waste before incineration and during the movement of waste to feed the oven. The combustion gas, if not properly treated, can also be odorous. The odours can be limited by (a) preventive measures, such as reduction of the organic content of wastes and (b) correction measures, such as enclosure of the discharge areas of the plant.

Noise and traffic
Noise and traffic is generated by the waste transport and handling machinery. Enclosure and isolation of the machinery and the waste receiving areas can limit noise. Noise disturbances caused by operation of incineration is easily quantifiable.

Vermin attraction
Some animals such as rodents, birds and insects are attracted by the possibility of feeding from organic wastes. In general, their presence is much less important than in landfills, because of the short time that waste is stored in the plant before incineration.

2.3. Information quality

The information available on the emissions from waste treatment options (including incineration and landfills with/without gas or leachate collection) must be estimated from statistical information and literature data, which is often incomplete. Emission data are typically based on models, but these models have typically uncertainties which vary for different waste treatment options and for different materials (Weidema et al, 2003).

For incineration, the largest uncertainties are (Nielsen and Hauschild, 1998):

- Extent of heat recovery and efficiency of energy conversion in the municipal waste incinerators.
- Extent and efficiency of flue gas cleaning.
- Fate of most substances from waste in the different incineration processes existing.

For landfills, the largest uncertainties are due to (Nielsen and Hauschild, 1998; Sundqvist, 1998):

- Lack of knowledge of the composition of the waste landfilled, especially in old landfills
- Lack of knowledge about the decomposition and transport behaviour and fate of substances within the landfill i.e. how much goes to the air, water and soil phases as a function of time (most important for specific organic chemicals, metals, chlorine, sulphur and nitrogen).
- Lack of knowledge about the extent and efficiency of gas collection (estimated to +/- 60%).

- Lack of knowledge about the extent and efficiency of leachate collection and treatment (+/- 100%).

The mentioned data uncertainties make it difficult to be able to establish a causal relationship between wastes and the related emissions, and it is considered (Sundqvist, 1998) that more important than establishing a correct causal correlation is to ensure good quality of the waste and emission data.

A difficulty of special interest in characterising the emissions from landfills is how to handle time aspects, i.e. how to model that waste that is disposed of today will generate emissions for several centuries in the future at a rate which is non-linear. In waste incineration, this issue is not so relevant because emissions to the atmosphere take place instantaneously. Finnveden (1998) suggests defining several time frames, including among others:

1. a shorter time period e.g. 15, 30, 50 or 100 years, until a landfill reaches an almost steady, stabilised state
2. a longer time period, e.g. 1 million years, until the emissions reach the "background level". The inclusion of this time period allows estimating the magnitude of the emissions during the shorter time period, as compared to the total potential emissions of all substances landfilled. In this longer time period, other emission pathways than gas and leachate may become relevant, e.g. erosion.

In their contribution to the Communication from the European Community on Climate Change, Bates and Haworth (2001) indicate that estimates of landfill emissions generally have a fairly high level of uncertainty, mainly because of the difficulties in estimating accurately emissions from what is a complex emissions mechanism. In addition, accurate waste statistics can be difficult to collect especially when waste management is unregulated, and an improvement in the collection of statistics often reveals that previous figures were underestimates.

3. Main results and proposals for future developments

The main findings from the literature analysed and the collection of pressures and impacts from landfilling and incineration presented in this technical paper are summarised in the following:

- Landfilling and incineration have very different profiles of environmental pressures and the derived potential impacts. The time dimension is one of the factors making this difference, but in general the physicochemical reactions taking place in both disposal routes are very different.
- The available information on the pressures from landfills and incineration plants depends on the actual measurements carried out on the pressures, and this information is at present of variable quality. There are still knowledge gaps in the description of the relationships between waste composition and emissions. This is especially true for landfills, because composition of the waste deposited on landfills some decades ago is in most cases difficult or impossible to determine. A good estimation of the emissions from landfills requires the use of a mathematical model, and one of the fundamental inputs to such a model is the composition of waste. The description of the emissions from incineration plants is less uncertain, partly due to the existence of important records of emissions, and partly because of the fact that it is easier to find the link between waste composition and emissions when both occur within a short time frame.
- The most well documented environmental pressure from incinerators and landfills are the emissions of greenhouse gasses. Other pressures such as the production of leachate in landfills and the emissions from incineration residues are less well documented.
- Information exists describing emission factors in waste incinerators using different technologies. Landfills are more difficult to classify in such discrete technology types.
- Very few studies analyse quantitatively the link between the pressures from incineration and landfilling of waste and their actual environmental impact. Some of the environmental impacts (global warming, loss of resources, use of land, stratospheric ozone depletion, nutrient enrichment, acidification) are well described in the literature. Other impacts (toxicity on humans and the environment) are more difficult to describe in quantitative terms, especially for landfilling, where toxicity may be actually manifested after several decades.

The above results have various implications for describing the ‘potential impacts’ from waste management:

- Emission factors (per unit of waste input) exist for certain categories within landfilling nad incineration. Some of these factors are subject of low uncertainty (e.g. air emissions from certain incineration plant types) and others are largely uncertain (e.g. current generation of leachate from old landfills, future leachate generation from current landfills, leachability of incineration residues in certain utilisation routes). Mathematical models exist that attempt to describe these pressures, and their use is necessary to incorporate all the variables which are thought to play a role in the emissions.
- The definition of reference emission factors for the different pollutants from incineration and, much more, landfill can be very difficult and of limited reliability, the latter being also different for different pollutants; available emission factors can have, for some pollutants, a range from zero to a very high level depending on operational conditions of the facilities, their location, the composition of inputs, etc.; incineration seems to be in a relatively better position due to the lower variability of estimated factors.
- The description of the link between pressures and impacts is mature in certain areas (e.g. air emissions and derived impacts) but it is too complex and in its infancy in other areas (e.g. determination of toxicity impacts). The LCA approach and the existing software

available using this approach is one possible way of describing quantitatively the link between pressures and impacts.

- Impact on global warming is probably the impact category for which the most reliable emission factors can be found and the most reliable pressure/impact relationship is found. The use of land and loss of resources are also well described. Land use is only easily described in terms of surface because the measurement of soil quality is more difficult.
- The large variability of emission factors for most pollutants depending on the technology used locally (e.g. type of furnace, type of landfill) poses an important question mark to the possibility of generalising this information and create meta-data at e.g. European level of total emissions. Such generalisation requires a series of very important assumptions on the "average technology" used in each country.

In the following, some options are given for the future development of the explorations of the pressures and impacts from waste disposal. Some of these options would require specialised collaboration from e.g. environmental research centres or LCA centres, given the technical nature of the analysis required.

The three suggested options are to be taken as tentative proposals, and need to be further discussed, re-elaborated and connected to e.g. the goals and target groups of existing EEA projects.

3.1.1. First option: Selection of reference values and mapping of European facilities

- The available literature list can be expanded and further explored to define "average emission factors" representing average European conditions. This requires to map facilities in order to identify which kinds of facilities are actually under operation across European countries.
- Additional analysis with the same aim can be performed on other waste management technologies, e.g. recycling, composting, application of wastes on land.
- The three main macro-categories of potential impacts can be selected, e.g. global warming, energy use, landfill capacity need, or long-term toxicity.

3.1.2. Second option: Developing models of the emission factors and potential Impacts

- This option can focus on investigating and if possible also testing existing software application that describe:
    - Emissions from waste handling and disposal options
    - Impacts from the above emissions

  The ultimate goal is to arrive at an estimation of European emission factors and potential impacts.
- The identified modelling tools can also be useful for e.g. simulating scenarios of diffusion of best available technologies for landfilling and incineration, or the requirement of innovation/diffusion posed by the landfill directive and other directives on waste management;
- This development implies a systematic monitoring of what is produced by technical universities and other private and public bodies working of waste management technologies in the European countries, in particular innovations and advances in LCA approaches to quantify the impacts.

3.1.3. Third option: Case studies

- A certain number of facilities which are considered to be representative of the "average technology" in each European country can be selected. These facilities can be the object of specific studies in to determine their emission factors and their potential environmental impacts (or a selected group of impacts such as the above mentioned global warming, toxicity, resource loss, land use and energy use).

- The calculated factors can be multiplied by the quantities of waste landfilled and incinerated in the countries for arriving at an indicator of potential impact; the indicator will vary with the quantities of waste.
- The approach by case studies can be also used to go beyond potential impacts or pressures in terms of pollutants and to arrive at analysing actual impacts on the state of the environment and human health; this development requires a very specific scientific effort which continuity during time is a condition for the updating of the indicators.

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